Environmental Impacts and Hazardous Characteristics of LED Lamps Waste

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ผลกระทบทางสิ่งแวดล้อมและลักษณะสมบัติที่เป็นอันตรายของหลอดไฟแอลอีดีที่ใช้แล้ว

น.ส.เดลปวิตา โคราเลเก ลักชนี ดิลุกา คุณะวัฒนา

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เดลปวิตา โคราเลเก ลักชนี ดิลุกา คุณะวัฒนา : ผลกระทบทางสิ่งแวดล้อมและลักษณะสมบัติที่เป็นอันตรายของหลอดไฟแอลอีดีที่ใช้แล้ว. (Environmental Impacts and Hazardous Characteristics of LED Lamps Waste) อ.ที่ปรึกษาหลัก : วัชราภรณ์ สุนสิน

เทคโนโลยีหลอดไฟแอลอีดีมีบทบาทอย่างมากในธุรกิจด้านแสงสว่างของประเทศไทยเนื่องจากปริมาณการใช้หลอดไฟที่สูงขึ้นทั้งในภาคครัวเรือน ภาคอุตสาหกรรมและภาคธุรกิจ ดังนั้นการคำนึงถึงความยั่งยืนของห่วงโซ่หลอดไฟแอลอีดีในประเทศไทยจึงเป็นปัจจัยสำคัญยิ่ง หลอดไฟแอลอีดีที่ใช้แล้วประกอบด้วยโลหะที่มีความเป็นพิษดังนั้นการกำจัดโดยการฝังกลบที่ไม่เหมาะสมจึงมีโอกาสสูงในการเกิดผลกระทบเชิงลบต่อสิ่งแวดล้อมและสุขภาพของมนุษย์เนื่องจากการปนเปื้อนของโลหะที่มีความเป็นพิษสู่สิ่งแวดล้อม ดังนั้นการศึกษาวิจัยนี้จึงมุ่งเน้นเพื่อ (1) การประเมินผลกระทบต่อสิ่งแวดล้อมอันเนื่องมาจากพฤติกรรมการใช้งานหลอดไฟแอลอีดีในโรงงานอุตสาหกรรม (2) การระบุลักษณะความเป็นอันตรายและการประมาณการความเป็นพิษจากการฝังกลบหลอดไฟแอลอีดีที่ใช้แล้วที่ไม่เหมาะสม การประเมินผลกระทบต่อสิ่งแวดล้อมเนื่องจากการใช้หลอดไฟแอลอีดีรุ่นสำหรับที่อยู่อาศัยในภาคอุตสาหกรรมโดยใช้วิธีการประเมินวัฏจักรชีวิตเปรียบเทียบ 6 สถานการณ์ของช่วงชีวิตที่เป็นไปได้และการผสมผสานพลังงาน พบว่าการใช้หลอดไฟแอลอีดีรุ่นสำหรับที่อยู่อาศัยเพื่อการส่องสว่างในอุตสาหกรรมส่งผลกระทบมากขึ้น 25% ทั้ง 6 สถานการณ์ และผลกระทบต่อสุขภาพของมนุษย์เป็นปัจจัยที่สำคัญสูงสุดสำหรับตัวบ่งชี้ปลายทางทั้ง 6 สถานการณ์

นอกจากนี้มีการตรวจหาปริมาณโลหะที่มีความเป็นพิษจากเศษโลหะในหลอดไฟแอลอีดีที่ใช้แล้วโดยกระบวนการชะล้างและทำการเปรียบเทียบกับข้อกำหนดของประเทศไทยและข้อกำหนดความเข้มข้นทั้งหมดของสิ่งเจือปน และทำการวิเคราะห์ผลกระทบต่อสิ่งแวดล้อมและความเป็นพิษต่อมนุษย์โดยใช้แบบจำลอง USEtox จากการศึกษาพบว่าไดร์เวอร์หลอดไฟแอลอีดีและแหล่งกำเนิดมีลักษณะสมบัติที่เป็นอันตรายตามข้อกำหนดของประเทศไทย เนื่องจากมีโลหะทองแดง ตะกั่ว สังกะสี และเงิน ที่มีความเข้มข้นสูงเกินกว่าค่ามาตรฐานความเข้มข้นทั้งหมดของสิ่งเจือปน สำหรับผลกระทบต่อสิ่งแวดล้อมและความเป็นพิษต่อมนุษย์ พบว่า อะลูมิเนียมจากไดรเวอร์หลอดไฟแอลอีดีมีระดับความเป็นพิษต่อสิ่งแวดล้อมสูงสุดในทั้งสามองค์ประกอบ ได้แก่ ดิน อากาศ และน้ำ ตะกั่วจากไดรเวอร์หลอดไฟแอลอีดีมีผลกระทบด้านความเป็นพิษต่อมนุษย์ในองค์ประกอบดินเกษตรกรรมและอากาศ นอกจากนี้ยังพบว่าสังกะสีจากแหล่งกำเนิดหลอดไฟแอลอีดีมีผลกระทบด้านความเป็นพิษต่อมนุษย์ในองค์ประกอบน้ำเป็นหลัก จากผลการศึกษาแนวทางปฏิบัติในการใช้หลอดไฟแอลอีดีของผู้ใช้ในภาคอุตสาหกรรมและทางเลือกในการกำจัดควรได้รับการประเมินใหม่เพื่อการใช้งานหลอดไฟแอลอีดีที่ยั่งยืนในประเทศไทย

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KEYWORD: LED lamp waste, Environmental Impact, Life Cycle Assessment, Hazardous Characteristics, USEtox Model, Total Threshold Limit Concentration (TTLC)

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LED lighting technology has strongly taken the Thai lighting market due to the high consumption in residential, industrial and commercial sectors so the sustainability of LED lamps chain is considered as a critical factor for Thai lighting market. Additionally LED lamps waste consist of toxic metals hence improper landfilling has high potential to create negative environment and human health impact due to toxic metals contamination to environment. Therefore, this study focused on (1) quantifying environmental impact due to consumption behaviors among industrial lighting consumers and (2) hazard characterization and toxicity estimation of improper landfilling of LED lamps waste. Environmental impact due to the consumption of residential LED lamps for industrial purpose were compared by using Life Cycle Assessment (LCA) methodology via 6 scenarios based on possible lifespans and two energy mixes. Results identified that using residential LED models for industrial lighting purpose generates 25% greater impact in all six scenarios and human health impact is the highest contributing factor for endpoint indicators of all six scenarios.

In addition, toxic metal contents in LED lamp waste were examined by leaching process and compared with Thai and TTLC regulatory limits. Later the environmental and human toxicity impacts were investigated by applying USEtox model. From this study, the LED driver and source exhibited hazard characteristics under Thai regulations. Due to the presence of Copper (Cu), Lead (Pb), Zinc (Zn) and Silver (Ag) metals in exceeding concentrations compared to TTLC standard. For the environmental and human toxicity impacts, Aluminum (Al) leaching from LED driver showed the highest eco-toxicity level in all three compartments: soil, air, and water. The highest human toxicity impact from LED driver occurred due to Pb leaching to agricultural soil and air compartments. Only in water compartment, LED source was responsible for the human health toxicity impact from Zn leaching. Based on research findings, LED lamps consumption practices among industrial users and disposal options should be reevaluated for sustainable LED lighting applications in Thailand.

Field of Study:	Hazardous Substance and Environmental Management	Student's Signature ....
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CHAPTER 1

INTRODUCTION

1.1 Background

Industrial sector in Thailand has taken the prior urge to take actions toward energy conservation from year 2011 under the Thailand 20-Year Energy Efficiency Development Plan (2011 - 2030). According to the Ministry of Energy, 866 Gigawatt Hour (GWh) have distributed among industrial users in 2019. Industrial consumers use the second highest amount of electricity units among residential and commercial users (Ministry of Energy, 2016).

Out of total electric energy consumption, 30% of electricity consumed for lighting purpose in Thailand. Average monthly electricity rate in Thailand is expected to increase by 50% within next 10 years (EGAT, 2019). Industrial sector has the highest value for electricity consumed for lighting purpose about 58% out of total electrical energy use for lighting in Thailand (PAMA model, UN). Authorities have been conducting and implementing energy saving plan to decrease unnecessary electric consuming equipment from household and commercial sector. Numerous types of lighting technologies have been available in Thailand lighting market throughout the years. Fluorescent Lamp (FL) and High Intensity Discharge (Uchida *et al.*) Lamp have been used intensively in Thailand for the lighting purpose in the past decade. In 2010, the

Pollution Control Department (PCD) and the Electricity Generating Authority of Thailand (EGAT) introduced Light Emitting Diode (LED) lamp to Thailand lighting market to replace fluorescent and incandescent lamps due to the policy drive toward energy conservation and mercury reduction in lighting application. Currently, LED lighting has owned 10 - 15 % from Thailand lighting market and expected to take control over whole lighting market in 2036 (Ministry of Energy, 2015). Due to the influence from the EGAT, amount of LED usage is rapidly increasing in residential and commercial sectors in Thailand.

LED lamps are semiconductors that follow simple theory of energy conversion. LED lamp emit light by consuming electricity. Mainly two types of metals contain in LED lamps (heavy metals and rare-earth metals). There is a significant difference between residential and industrial lighting products in terms of product performances or product designs. Industrial LED lighting products have been commercialized to improve performances, such as high efficacy (brightness per power (lumens per watt: lm/W)), longer lifespan (50,000 hrs.) and high efficiency. On the other hand, residential LED lamps have low efficacy, short lifespan and lower resistance to harsh environmental conditions which make them completely suitable for residential lighting applications.

Within the period of 2012-2019, LED lighting equipment has been going through intense technological advances. Industrial LED lamp models in local market evolved significantly from low to high performances, cost effective and durable product. Due to the consumer attraction toward green economy and environmental friendly regulations, major LED lamp manufactures launched eco-friendly LED lamps into the market.

Life Cycle Analysis studies have estimated that environmental impact from End of Life LED (EoL LED) is responsible for only 0.4 - 1% from total environmental impact of entire LED lamp life cycle (Kumar *et al.*, 2019). Longer lifespan of industrial LED lamps is reason to postponed handling of LED waste stream since industrial LED lamp waste is yet inconsiderable amount compared to other solid waste. LED lamp waste has two different options when it comes to disposal, landfill and recycling. Selection of disposal scenario of EoL LED lamp strictly based on country regulations and consumer behavior.

1.2 Problem statement of this research

Industrial LED lamps offer many advantages over residential models such as high durability, strong ability to withstand workplace hazard conditions, and reparability. On the other hand, higher installment cost related with industrial LED models (Scholand & Dillon, 2012). Therefore, industrial consumers prefer to purchase residential models as their lighting source. This practice creates wastage of electricity. Improving energy efficiency within a country generates a positive impact on its economy, environment, and human health. Currently, life cycle assessment is the most common practice to identify the environmental impacts related with each life cycle stage of a product. Comparative environmental impact assessment of products that have the same functional unit is intended to identify the best available appliance for a specific application. A cradle to grave life cycle assessment of Eco designed and general LED lamp model was conducted in 2017 (Casamayor *et al.*, 2017). Results revealed that the subjected eco-design LED lamp has 60% reduced environmental impact compared to the general model. The United States Department of Energy conducted a life cycle assessment to estimate the environmental impacts of LED models manufactured in two different years (2012 and 2017) from a cradle to grave perspective. Fifteen impact categories were selected to evaluate impacts on air, water, soil, and resource consumption. Results revealed that input energy in use phase has the highest impact on each selected category compared to other life cycle phases. Dillon *et al.* (2020) applied an LCA methodology to four LED samples manufactured in four different years to estimate improvements in energy and environmental impacts of LED models over time. Newer LED models showed least impact on energy and environment during use phase. This study focused mainly on the environmental impacts related to the energy in use phase of LED lamp. Several impact assessment methods, such as ECO-I-99, ReCiPe, and ILCD (European) methods, have been applied in previous studies. The scenario analysis method has been used in several LED related research/works to select the most sustainable option for the policy planning and product development process. Since the consumption phase plays a major role in the final environmental impact result, most researchers are concerned about factors that attribute to energy in use of LED lamps. Scenarios have been made to represent different lifespans and electricity mixes (Dale *et al.*, 2011; Principi & Fioretti, 2014). Tahkamo and Halonen (2015) assumed two different lifespans (15 000 hr. and 36 000 hr.) and two different electricity mixes (French and European).

This study aims to conduct a comparative environmental impact assessment between residential and industrial LED lamp models. Assessment was performed based on six use stage related scenarios to give recommendations to consumers and policy makers

In the next few years amount of LED waste will be a major threat in solid waste management process (Machacek *et al.*, 2015). LEDs will comprise about 30 - 40 % of the waste within the next 10 years (Nigel Harvey, CEO of UK lamp recycler and Eucolight founding member).

In Thailand, LED lamp waste has not been treated as hazardous waste but e-waste under the section of universal waste. According to the Pollution Control Department (PCD) and the Department of Industrial Works (DIW), current e-waste recovery/recycling process is not applying on LED lamps waste.

Landfilling is the most prominent solid waste management practice in Thailand (Pollution Control Department, 2019). Even though LED lamp waste has permission from authorities to be disposed in landfill, LED lamps still include eco-toxic materials that can leach through soil layers and pollute the environment. LED chips can contain arsenic, gallium, indium, and antimony that have linkage with human health and environmental impact. Several research papers have exposed the limit of toxic materials in LED lamp waste and scientific experiments to predict the pollution when it is disposed off in a landfill without pre-treatment. In Thailand, LED lamps are treated as universal waste. According to the Ministry of Industry, Waste that contains impurities equal to or greater than Total Threshold Limit Concentration (TTLC) or Soluble Threshold Limit Concentration (STLC) will be labeled as hazardous and prohibited to landfill without pretreatment.

Therefore, this research will focus on conducting science based evidence generation for solid-hazard waste policy planning approach to consider LED lamps waste to give recommendations for manufactures on eco-friendly product designing and for policy makers to consider about improper landfilling of LED lamp waste.

1.3 Research Objectives

The overall objective in this research is to greening the LED lamps within product's lifecycle in national level. Due to the difficulty of collecting data on LED lamp assembling in Thailand, research is limited to consumption and end of life phases.

- To evaluate the environmental impact of the LED lamp consumption phases in industrial facilities in Thailand.

- To identify the metal concentration in LED lamps waste

- To characterize the LED lamp waste based on the toxic metal concentrations compared to regulatory limits

- To evaluate eco-toxicity and human-toxicity associate with contain metals in LED lamp waste.

1.4 Scope of the study

1. Survey was distributed to only electronic and electrical appliances manufacturing facilities in Thailand.

2. During the LCA study, environmental impact from LED lamp manufacturing, distribution and installation phases excluded due to the data limitation.

CHAPTER 2

LITERATURE REVIEW

2.1 Light Emitting Diode Lamps (LED)

Light Emitting Diode (LED) are semiconductors that emit light when electricity flows through it. LEDs occupied for different duties in numerous electrical equipment such as lamps, television screen to remote controls. The color of LED can be altered by changing the composition. LEDs are made of elements from group III and group V of the periodic table. Gallium arsenide (GaAs) combination is the most prominent one among LED lighting technology. Manufacturing of LED package is highly complex procedure that have three specific steps,

- Substrate production
- LED die fabrication
- Packaged LED assembly

Upon the completion of these three steps, LED package combined with optics, heat sink and LED enclosure to finalize the design of LED lamp.

2.1.1 Working principle and components of general LED lamp

LED lamp connected to the current, driver is controlling the current flow that flow through the LED module. This controlled electric flow illuminate the LED pieces that attached to the metal piece. Lens uniformly distributes the light that produced in the middle of the LED lamp. Heat generation controlled by aluminum heat sink.

Figure 2.1 : Basic components of LED bulb (Philips, 2019)

Description and function of basic components in LED have stated in Table 2.1.

Table 2.1 : Basic Components in LED Lamp (OSRAM Opto Semiconductors GmbH, 2009; Tahkamo & Halonen, 2015)

Component	Description	Building material	Function
LED module (Chip)	LED pieces attached to metal piece. This part is stated as printed circuit board. Type of PCB depend on the number of LED pieces that attached to its metal piece.	LED, Silicon and Aluminum	Source of light.
Driver	Combination of integrated diodes, transformers to multiply the output capacity.	Printed circuit board, Capacitors, Diodes, Resistors, Steel, Plastic	LED output in an LED lamp is strictly related to the flowing current through LED. Driver is the component controlling the current flow.
Heat sink	Piece of metal that LED attached.	Aluminum, Acrylic and Polycarbonate	Remove heat from internal LED pieces and transfer into outer parts of the lamp.
Lens/ Optics	Plastic lens that cover the LED chip.	Plastic and Phosphor cover	To distribute brightness from light source uniformly.
LED enclosure	Piece that cover the inner LED components, Cover and End cap.	Steel, Plastic	Protect LED chip and driver from outer environment.

2.2 LED lamp market evolution and policy drivers in Thailand

Pressure on global lighting market from LED influenced Thailand lighting market especially in 2010 due to LED technology introduction by the government and the energy saving program by the PCD. LED lamps are gaining increased market share in new building projects and are widely used as replacements for Compact Fluorescent Lamps (CFLs) and halogen lamps due to the government support for the lighting technology shifting (ASEAN Regional Efficient Lighting Market Assessment, UNEP). LED market share in Thailand increased by 17% during 2010 – 2015. Thailand have generated strategy plans along with the international laws and regulations to protect the environment and improve the sustainability.

Thailand climate change master plan 2011-2050 is the current practice of government agencies to promote the make national sustainability goals related to global. According to the Thailand climate change master plan, the specific goals justifying the LED lamp shift in Thailand are presented in Table 2.2. Market share of LED lighting in Thai lighting market is 38% in the year of 2015. These LED friendly policy drivers are the main reason behind USD 823.2 Million worth LED lighting market in 2019, Thailand (Imarc, 2020).

Table 2.2 : LED lamp waste shift and climate change master plan (EGAT, 2019)

Action	Relationship with LED lamp shift
To work with the global community in solving the issue of climate change without producing negative impacts on the country's economic, social and environmental progress (development).	LED lamp introduction in 2012.
To promote Thailand's sustainable development in a way that is in line with the international endeavor in solving the climate change problem.	Introducing eco-labels for LED lamps.
To motivate every sector and level to be able to create operational plans/implementation plans for climate change properly, appropriately, efficiently, and with concrete effectiveness.	Energy saving LED lamp replacement in public sector.

Most of the industrial workspaces have high ceilings and larger area. General lighting with low efficacy LED lamp will be insufficient to illuminate these warehouses and factories. High efficacy powerful LED lighting advances such as high capacity heat sink, longer lifespan and energy efficiency are crucial for industrial applications.

2.3 LED lamp product design moderations

Government initiated energy efficiency and eco labeling program for LED lamp in 2014. Table 2.3 has stated the official green label LED lamp products available in Thailand.

Table 2.3 : ECO labeled LED lamp products (Pollution Control Department, 2019)

Type	Manufacturer	Certification	Expire date
LED bulb with built-in lamp driver, type G13, voltage 220-240 V, rated power 16 W and 18 W	TOSHIBA	green label	30 November 2020
LED bulb with built-in tube driver, T8 type, cap type G13, power 18 W	L&E	green label	27 February 2021
LED with built-in T8 tube driver, lamp cap type G13, rated voltage 220-240V, rated power 16W, daylight type, warm white, cool white	L&E	green label	27 February 2021

2.4 Life Cycle Assessment and LED lamps

Life Cycle Assessment (LCA) is a tool to evaluate environmental impact that related with complete life cycle of a product or a service (Raw material extraction, manufacturing phase, distribution, consumption phase and end of life). LCA follows ISO 14040 and ISO 14044. According to these standards, inventory of input material and emissions should be estimated. After that, the related environmental impact will be evaluated via specific impact categories and finally the results will be manifested along with the research objectives (Tahkamo & Halonen, 2015).

Purpose of using LCA on a product or service can be vary, such as product improvement, comparison and marketing. General LCA framework proceed through 4 sectors.

1. Goal and scope definition: the most influential step in the entire LCA procedure. Purpose of the study, system boundaries, assumptions and limitations and functional unit will be identified in the selected product LCA process. Along with the process goal and scope can be redefine to bring more clarity to the research.

2. Inventory analysis: material, energy input and emissions to the environment will listed in bill of materials of the product in inventory analysis. Data on quantity and category of natural resources that used within the total lifespan of a product will be mapped by researchers with the support of manufactures, literature reviews and databases (Simapro, Eco invent).

3. Impact assessment: Inventory data will be converted to environmental load via environmental impact categories. Three main areas of protection will be subjected to assess (eco system quality, human health and natural resources). To conduct impact assessment there are compulsory (definition and characterization, classification) and optional (characterization, normalization, weighting, grouping, evaluating and reporting Life Cycle Impact Assessment-LCIA results) steps in LCA as shown in Table 2.4.

Table 2.4 : Description of impact assessment steps (Oney, 2019)

Category	**Description**
Definition and characterization	The three main areas of protection are described with several impact indicators (midpoint, endpoint) that express the impact on the environment.
Classification	To calculate the relative contribution, multiply the results of the inventory obtained in the classification phase by the characterization factors of each substance within each impact category.

4. Interpretation: Impact assessment results will be analyzed and explained in order to draw conclusions from the LCA. Critical environmental issues and resource consumption hotspots will be recognized. To verify the data accuracy, statistical checking procedures should be taken by researchers in following perspectives,

There are visible technological and compositional moderations have been applied to LED lamps from 2012 onwards. Energy effectiveness, environmental impact and lamp lifespan are most considerable factors for LED lamp manufactures over the time.

There was a complete life cycle assessment to evaluate energy and environmental improvement in domestic LED lamp models from 2012 to 2017.

Researchers have selected A-19 general low efficacy LED lamp model from 2012 and three samples from 2017 (11 W, 815 lm). Results prove that each new LED lamp samples show less environmental impact compared to 2011 model and noticeable change heat transfer system. Lower amount of metals and higher amount of light plastics included in 2017 model. The most outstanding movement in terms of product design in 2017 model is separate printed board for LED engines to increase effectiveness (Dillon H, 2019). Detailed description of LED related LCA studies shown in Table 2.5.

Table 2.5 : LED lamps related LCA studies in literature

Reference	Sample LED lamp model	Characteristics				Goal and scope	Func. Unit	System boundary
		Power (W)	Brightness (Julander *et al.*)	Brightness Efficacy (lm/W)	Lifespan (hr.)			
Hartley et al., 2009	Street light	105	-	-	59,000	Comparative life cycle assessment of street lighting technologies	100,000 hr.	Cradle to grave
Abdul Hadi et al., 2013	Street light	180	15,000	60	30,000	Assess the life cycle environmental impacts of ceramic metal halide and LED.	60,000 hr.	Cradle to grave
Tahkamo et al., 2013	Indoor	19	1,140	60	15,000	Determine the life cycle stages that exhibits the highest environment impact.	50,000 hr.	Cradle to grave

Remark: Func. Unit = Functional Unit

Past several years green consuming has become one of the major factors that affect consumer demand in the market. It is a compulsory step to proceed LCA studies to evaluate the environmental impact of eco-design and commercialized LED lighting products.

- Past LCA studies - Sensitivity analysis of LED lamps

Due to the uncertain nature of LED lighting technology, sensitivity analysis has been conducted to identify optimum solution for sustainable use of LED lamps. In 2017, scenario analysis conducted via 6 scenarios based on lifespan and disposal options. 3 lifespans (1000, 15,000 and 40,000 hrs.) and 2 disposal options (dumped off into the household bin and recycling center) were selected. Results showed that 1000 hrs. – Domestic bin disposal option (Scenario 1) exhibited the highest environmental impact while 40,000 hrs. – Domestic bin disposal option (Scenario 6) labeled as the lowest environmental impact scenario (Casamayor *et al.*, 2017). In past studies, scenario analysis has conducted also based on the different energy mixes (Indian energy mix and Swiss energy mix). This energy mix difference initiated different environmental impact results. Using Indian energy mix for the LED lamps generate the highest environmental impact due to the increased use of coal as main energy source on the other hand using Swiss energy mix generate lower environmental impact because of the clean energy sources (Sangwan *et al.*, 2014).

2.5 Toxicity of LED lamps

Pollution Control Department requires that hazardous waste refers to any hazardous waste that has composition of various hazardous substances which may cause danger to people, animals, plants, the environment (Pollution Control Department, 2003)

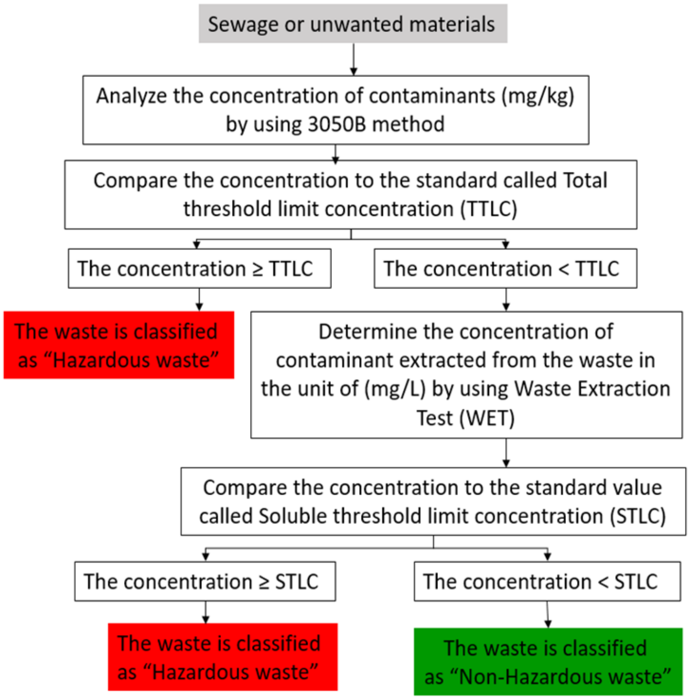

Figure 2.2 : Hazardous waste analysis procedures in accordance with the notification of the Ministry of Industry (Ministry of Industry, 2005).

2.5.1 Human health impact from building materials of LED lamps

Many researches have done to prove that environmental and human health impact from LED lamps is less than fluorescent and indecent lamps. Mass of toxic chemicals in LED lamp should be below hazardous limit and safe to landfill. Description of toxic materials included in LED lamps and environmental and human health impact stated in Table 2.6.

Table 2.6 : Possible Environmental and Human health impact from LED building materials

Substance	Human health impact	Environmental impact	Reference
Lead (Pb)	Disruption of the biosynthesis of hemoglobin and anemia	Bioaccumulation capability Aquatic toxicity	(World Health Organization, 2019)
Copper (Cu)	Dysfunction in digestive system	Reduce reproductive capacity of aquatic organisms	(Bui *et al.*, 2015)
Aluminum (Al)	Neurotoxicity	Inhibition of plant root growth	(Lione, 1985)
Antimony (Sb)	Carcinogenic	Increase oxidative stress in plant cells and destroy the plant cell structure	(Wolff, 1995)
Arsenic (As)	Vomiting, reduction of bone marrow production	Toxic for reproduction system of fish	(Hughes, 2002)
Zinc (Zn)	Nausea, vomiting	Aquatic toxicity	(Fosmire, 1990)
Nickel (Ni)	Kidney dysfunction, carcinogenic	Reduce the level of protein production in fresh water organisms	(Denkhaus & Salnikow, 2002)

2.5.2 Studies related with Hazard Characterization of LED lamps.

Hazard potential of LED lamp waste concerned in past studies using several toxicity evaluating experimental procedures. Table 2.7 stated metal detection of LED lamps waste in literature.

Table 2.7 : TTLC / WET leachate analysis for different types of LED lamps.

Reference	LED lamp model	Tested lamp component	Tested metal/ Hazard amount (mg/l)						
			As	Cu	Cd	Pb	Cr^{6+}	Ni	Y
DoE US, 2013	Low efficacy, General LED lamp	Full lamp	-	exceed TTLC limit	exceed TTLC limit	exceed STLC limit	exceed TTLC limit	exceed TTLC limit	-
Choi Y, 2019	LED linear	Full lamp	0.095	1.249	0.024	1.689	ND	-	-
		LED	8.701	0.055	0.212	6.207	ND	-	-
		Driver	ND	11.925	0.217	15.858	0.069	-	-
		Other	ND	0.084	0.056	0.007	ND	-	-

Remark: ND = Not Detected

2.6 End of Life LED lamp management in Thailand

Currently, LED lamp waste has categorized as hazard waste under Hazardous Substance Act B.E. 2535 (Waste List No. 5.3) due to the electronic nature of the product. Unfortunately, consumer awareness on toxicity of LED lamp waste is insignificant compared to florescent lamp waste. Lack of science based evidences on hazard metal concentration levels in LED lamps. Metal toxicity information of waste mobile phones, televisions and personal computers readily available to the public while LED waste is praising as eco-friendly product compared to fluorescent lamps due to the absence of mercury Hg and high energy efficiency values.

2.6.1 LED lamp waste characterization

The Pollution Control Department (PCD), Thailand has categorized waste into several groups. Among these groups there are some specific waste that interface with industrial – hazard – solid waste and contained similar but different characteristics. Industrial LED lamp waste is one of the major type of waste that shows mixed qualities between these types. Industrial LED lamp waste in Thailand can include under policies and regulations that control industrial solid waste, Hazardous waste and E- waste.

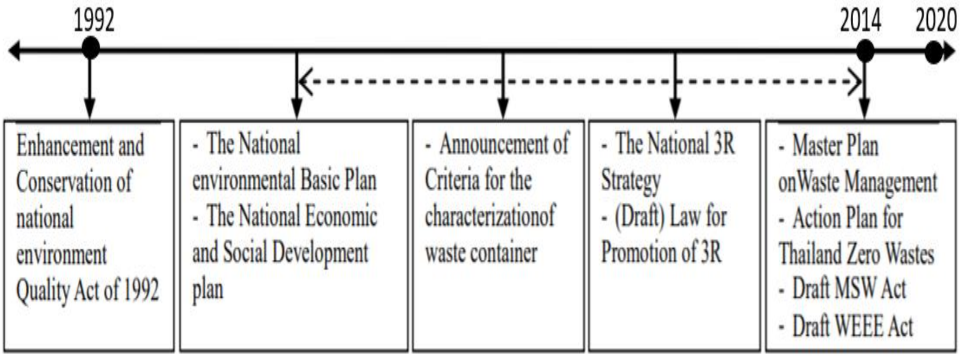

Figure 2.3 : Flow diagram of Solid Waste Management (Pollution Control Department, 2020)

Currently, LED lamp waste excluded from the list of metal recovering and recycling waste generated by Department of Primary Industries and Mining (Pollution Control Department). There is a significant difference between waste management policy acts and reality. According to the PCD, 60% of industrial and household hazardous waste managed improperly in Thailand (2018).

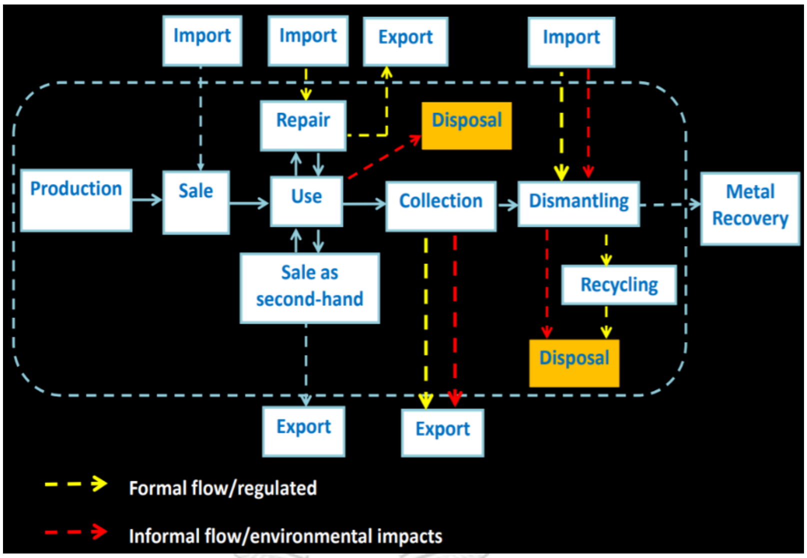

Figure 2.4 : Current E-waste flow in Thailand (Pollution Control Department, 2016)

Policies on solid waste management in Thailand has been started from Enhancement and Conservation of national environment Quality Act of 1992. The amount of E-waste was insignificant in 1992 therefor no policy has considered on E-waste until 2014. Draft act on waste electrical and electronic equipment (WEEE) has been proposed along with Master Plan on Waste Management and Action Plan for Thailand Zero Wastes in 2014. E-waste collection and dismantling activities mainly run by private waste dealers. Lack of research and development in the sections such as mechanical preprocessing and metallurgical metal from e-waste challenge the proper e-waste management practices in Thailand. Investors hesitate to invest on research and developments of recovery and recycling of e-waste due to unsettled status of policy act on WEEE. LED lamp has stated under E-waste due to the component materials of the lamp. Therefore, current and proposed WEEE management plans can be applied to LED lamp waste.

2.6.2.1 (Draft) National Integrated E-waste Management Strategy Phase II: 2012-2016

Strategy description

Thailand has developed several strategies to overcome e-waste issue in Thailand. Below table 2.8 discuss proposed strategies.

Table 2.8 : *Content description of (draft) E-waste management plan*

Strategy	**Concerned section**
Strategy 1:	Strengthening of import/export control
Strategy 2:	Promotion of eco-friendly e-products with the focus on public procurement
Strategy 3:	Development of E-waste database
Strategy 4:	Development of e-waste segregation, collection, storage and transport for local government
Strategy 5:	Upgrade of dismantling and recycling facility
Strategy 6:	Promotion of public awareness on e-waste

Possible policy options for e-waste under considerations (Pollution Control Department, 2020)

(1) Formulate a new law (Act) by Ministry of Natural Resources and Environment

– Establish a new fund to support buy-back, collection, transportation, recycling and disposal

(2) Formulate a new law similar to Extended Producers' Responsibility (EPR)

– Setting collection and recycling target for producers to comply with and private sectors manage their own collection and recycling system

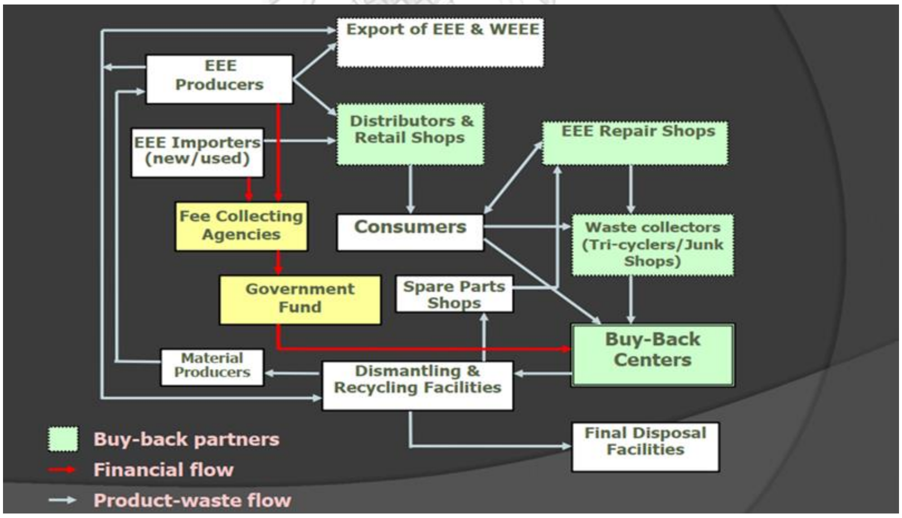

Figure 2.5 : Proposed E-waste management plan in 2016 (Pollution Control Department, 2016)

2.7 Environmental testing of LED lamps

The amount of electronic and electrical waste that are flowing into solid waste stream is increasing gradually with the time due to consumer behaviors and technological advancements. Lighting technology has taken a great turn with LED lighting technology. LED lamps contain various types of metals to enhance energy efficiency and product lifespan. Building chemicals could leach into the ecosystem in the disposal phase. LED lamps end up in landfills due to low concerns over hazard potential of LED lamp waste. Amount of toxic chemical substituents leaching from waste to landfills have been regulated via standards originated by national and international environmental related agencies. Chemical analysis conduct through different testing procedures to evaluate the metal leaching concentration under various environmental conditions. Environmental testing supports to find the amount of toxic metal concentrations and compare with the regulated safe limits for landfilling. Several testing procedures present to stimulate metal leaching from waste under specific environmental conditions.

2.7.1 Leaching tests in solid waste: Potential risk of waste to release toxic substances into the environment

EPA method 1311 - Toxicity Characteristic Leaching Procedure

TCLP (Toxicity Characteristic Leaching Procedure) EPA method 1311designed to identify mobility of both organic and inorganic analytes present in liquid, solid, and multiphasic wastes. Environmental Protection Authority (EPA) US has published several leaching tests (SPLP- Synthetic Precipitation Leaching Procedure, MEP-Multiple

Extraction Procedure) to simulate different natural conditions. Table 2.9 describes selected leaching processes.

Table 2.9 : EPA test methods for toxicity leaching process

TEST METHOD	TCLP (EPA METHOD 1311)	SPLP (EPA METHOD 1312)	MEP (EPA METHOD 1320)
Leaching Solution	Acetic Acid	60% Sulfuric Acid, 40% Nitric Acid	60% Sulfuric Acid, 40% Nitric Acid
Leaching Solution pH	As low as 2.88	As low as 4.2	3.0
Extraction Cycles	1	1	10
Time in Acid Bath	18 Hours	18 Hours	240 Hours
Simulated Weathering	100 Years in a Landfill	100 Years Exposure to Acid Rain	1,000 Years in a Landfill

EPA 3050B - Acid digestion of sediments, sludge, and soils

EPA 3050b (Acid digestion of) apply to waste to compare metal concentration limits against TTLC standard. In this method, waste will applied to almost complete digestion except elements that not environmentally available such as metals that not mobile in ecosystem will not leach via this digestion method. EPA 3050B capable for the detection of 24 metals (Aluminum, Magnesium, Arsenic, Antimony, Manganese, Beryllium, Barium, Molybdenum, Cadmium, Nickel, Chromium, Cadmium, Potassium, Cobalt, Calcium, Silver, Iron, Sodium, Lead, Copper, Vanadium, Selenium, Thallium, Zinc

Waste Extraction Test (State of California)

WET procedure will apply into waste to compare contain metals with Soluble Threshold Limit Concentration (STLC). 17 types of metals consider in WET procedure (Antimony, Arsenic, Barium, Beryllium, Cadmium, Chromium, Cobalt, Copper, Lead, Mercury, Molybdenum, Nickel, Selenium, Silver, Thallium, Vanadium, and Zinc)

TCLP, TTLC and WET testing procedures are simulating worst case scenario within the laboratory. Therefor leaching tests related with specific digestive requirements.

According to Thai regulations, hazard waste testing procedure has two steps. First is to apply total constituent test to check chemical concentration against TTLC standards. Then waste that have higher level of toxic constituents than TTLC, will labeled as hazard. But waste that has concentration levels between 10 x STLC – TTLC will be applied further for WET procedure. If resulting values are higher than STLC standards, waste will be labeled as hazard.

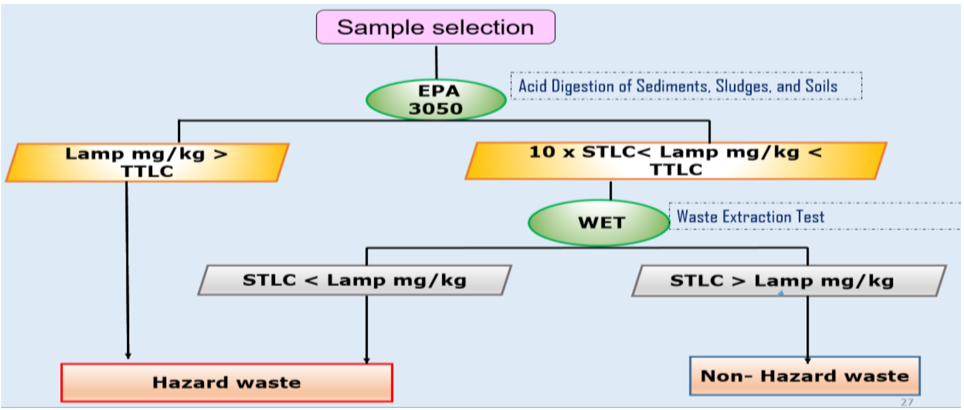

Figure 2.6 : Waste characterization flowchart

2.7.2 Thai hazard waste characterization test

According to Thai regulations, following characteristics have been listed as wastes that are ignitable, corrosive, reactive, contain chemical substances that exhibits toxic qualities such as human health impact (carcinogenic, chronic and acute) and environmental impact (bioaccumulation and persistent) and finally waste that has following stated inorganic chemicals in a high concentration exceeding regulatory limits.

Metals containing in LED lamp components detailed in table 2.10 and 2.11 along with the regulatory limits published in hazard waste document, Ministry of Industry.

Table 2.10 : TTLC limits for chemical concentrations in waste (Ministry of Industry, 2016)

Element	**Regulatory limit (mg/kg)**
Arsenic and/or arsenic compounds	500
Cadmium and/or cadmium compounds	100
Chromium and/or chromium (III) compounds	2,500
Copper and/or copper compounds	2,500
Lead and/or lead compounds	1,000
Mercury and/or mercury compounds	20
Nickel and/or nickel compounds	2,000
Silver and/or silver compounds	500
Zinc and/or zinc compounds	5,000

Table 2.11 : STLC limit for waste hazard characterization (Ministry of Industry, 2016)

Element	Regulatory limit (mg/kg)
Arsenic and/or arsenic compounds	5
Cadmium and/or cadmium compounds	1
Chromium and/or chromium (III) compounds	5
Copper and/or copper compounds	25
Lead and/or lead compounds	5
Mercury and/or mercury compounds	0.2
Nickel and/or nickel compounds	20
Silver and/or silver compounds	5
Zinc and/or zinc compounds	250

2.8 Environmental and human health impact assessment

Sustainable e-waste management process should be initiated with the assessments of impact on human health and environment by improper disposal scenarios. Currently, there are numerous models for identifying and quantifying of impact to stimulate ecofriendly waste management plan. Currently, there are other impact assessment models present. Such as Impact 2002, USES-LCA, Eco indicator 99 and CalTox.

USEtox model apply to estimate human health and environmental impact from specific life cycle phase of a product or service. This model was created in 2002 by UNEP/SETAC scientist team to support researchers with chemical toxicities estimation. Resulting output from USEtox model is identification of magnitude of impact from specific product's or service's lifespan. USEtox model capable of transferring toxic chemical concentrations in e-waste into the measured impact on human health and ecosystem.

USEtox model quantify the toxicological effects of a substance on human health and ecosystem. It follows the major principle of cause – effect chain. Cause – effect has converted into elision – impact via three consequence steps, chemical fate, exposure and effect. Figure 2.7 illustrated a short description of USEtox model.

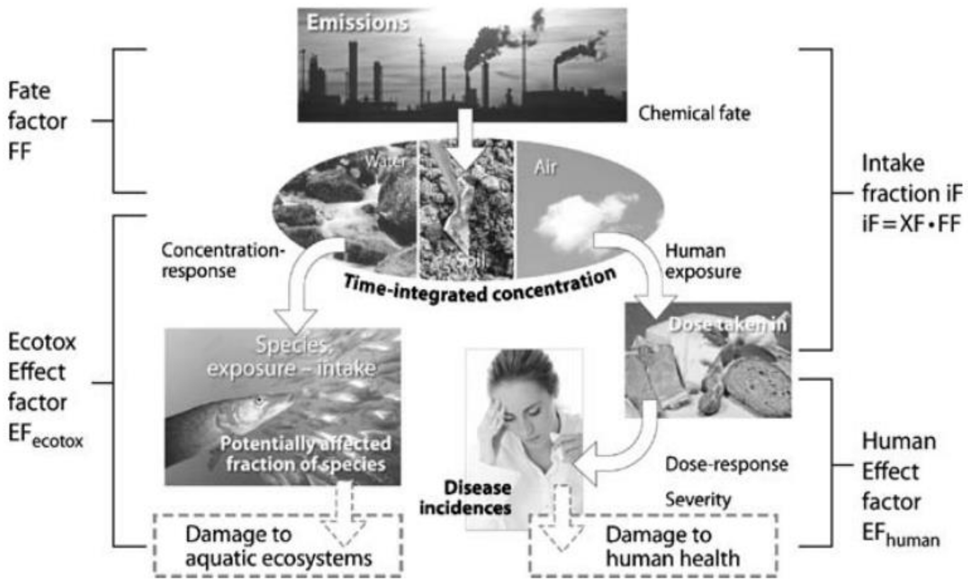

Figure 2.7 : USEtox model description

Toxic impact on human health and ecosystem modeled based on matrix algebra with related factors. Eq. 1 has shown the factors based impact calculation.

$$\overline{CF} = \overline{EF} \times \overline{XF} \times \overline{FF} = \overline{EF} \times \overline{iF} \qquad (1)$$

Whereas;

$\overline{CF}$: Characterization factor [(cases/ $kg_{emitted}$) or (PAF. m^3.day/$kg_{emitted}$).

$\overline{EF}$: Effects factor [(cases/kg_{intake}) or (PAF.m^3/$kg_{emitted}$)]

$\overline{FF}$: Fate factor [$kg_{in\ compartment}$ per $kg_{emitted}$/day]

$\overline{iF}$: intake fraction [kg_{intake}/$kg_{emitted}$]

Characterization factors for human toxicity and eco toxicity calculate in USEtox model. Impact assessment conduct via two different scales, global and continental. Where global scale has divided into 6 environmental compartments such as air: urban, rural, soil: industrial, agricultural and water: freshwater, coastal marine scale. In USEtox, human exposure model calculates the increment of chemical concentration that transferred into human population based on the concentration difference in different media.

USEtox database

USEtox model contain 3 types of databases specifically designed for inorganic and organic substances. Since this study applied for metal toxicity to human health and eco system, only inorganic databases will be discussed in following section.

1. Physio-chemical properties of substances: inorganic substances

Properties such as, molecular weight (extracted from periodic table), the Henry coefficient stated as 1.10-20 $Pa.m^3.mol^{-1}$ by assuming the volatilization rate of inorganic substances from soil and water compartments to air compartment negligible, and Partition coefficients values for soil, sediment, suspended solids and dissolved organic carbon collected from (IAEA International Atomic Energy Agency, 2010). Degradation rates of metals has stated as 1E-20 in the library indicating that the possibility of metals to degrade is almost zero.

2. Toxicological effect data on laboratory animals as a surrogate to humans

Human toxicity data related to main toxicokinetic processes which reform toxicity of metals to human. Parameters such as, bioaccumulation factor for fish (taken from (IAEA International Atomic Energy Agency, 2010). For metals Be and Cd values taken from (US-EPA, 2002), values of biotransfer factor for food items (milk and eggs) taken from IAEA International Atomic Energy Agency (2010), and data for bioconcentration factor for root crops and leaf crops collected from IAEA International Atomic Energy Agency (2010) and US-EPA (2002).

3. Eco toxicological effect data for freshwater organisms

Eco-toxicity data modeled based on EC50-data (Half maximal effective concentration). Currently, in the model 2 datasets available: (1) acute EC50 values from the National

Institute for Public Health and the Environment (RIVM) etoxBase and, (2) chronic and acute EC50-data mainly from ECOTOX Knowledgebase and International Uniform Chemical Information Database (IUCLID).

USEtox precision is different for human health and ecosystem respectively within factor 100-1000, 10-100. Limitations in USEtox model can be listed as, lack of data on the section of human exposure routes such as indoor air and dermal exposure. Currently no experimental data contain in USEtox model in the topics of marine / terrestrial ecosystems.

CHAPTER 3

METHODOLOGY

3.1 Survey for industrial LED lamp consumers

Survey was conducted to identify the most consumed LED models in 35 electronic and electric appliance manufacturing factories, 9 industrial estates Thailand. Survey concerned whether purchased LED lamp models have changed with the time and lifespans of consumed LED lamp models. And also the disposal procedure for used LED lamps. Factories were selected according to stratified sampling method to increase the data reliability. Sampling procedure, distributed survey (Thai and English) and factory list attached in appendix A and appendix B. Based on survey answers, 68% consumers use T8 LED lamp as their lighting source which classified as general lighting model. While 32% apply high bay LED lamp. This raised the question on energy efficiency of industrial lighting. Therefore, T8 tube and high bay models were selected to represent residential and industrial sectors. Both of lamps manufactured by Philips, Thailand.

3.2 Life Cycle Assessment

Complete methodology of life cycle assessment process have been stated in this section. This research has followed the standard of ISO 14040 and ISO 14044 series.

Audience for this study are lighting manufactures and consumers, policy makers, and future researchers. Simapro version 8.2 used as the analyzing software in this research.

LCA is a scientific tool that quantify the environmental impact from a product or process by accounting inputs (materials and energy) and emissions to environment along the complete life cycle (cradle to grave) or selected stage (cradle to cradle) in the life cycle of a subjected product. LCA is consists of 4 steps, which are,

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

3.2.1 Goal and scope selection

This study was designed to estimate environmental impact related with two actions. The way LED lamp purchasing patterns has changed along the time from 2012 to 2020. Compare and estimate the environmental impact between general T8 tube LED model and industrial high bay LED model. LCA study focused on the consumption phase. Maintainers of LED lamps during the use phase has also excluded.

3.2.2 Functional unit

Function of both LED lamp models is generating a specific amount of light during particular time period. Several parameters related with the light quality and quantity. Quality of light mainly depend on CCT (correlated color temperature) and CRI (color rendering index) while quantity indicate via luminous flux (Julander *et al.*). Light quantity is the crucial factor for the electricity consumption in use phase (Casamayor *et al.*, 2017). Therefore, assumption made that slight difference of light quality (CRI) between these two models show minor impact on its electricity consumption values. Lifespan of the selected models obtained from product datasheets (Philips, 2020). Hence functional unit of this study is generating of 10,000 lm of light for 50,000 hr. (500,000,000 lm.hr.). T8 model multiplied by ***41.7 ≈ 42*** to equal the luminous output as high bay model.

Table 3.1 : Luminous performances of selected LED models

Parameter	T8 tube lamp	High bay lamp
Light quality		
CCT (K)	4,000	4,000
CRI	73	>80
Power consumption	8w	85w
Light quantity (Julander *et al.*)	800	10,000
Durability (hr.)	15,000	50,000
No. of lamps per Functional Unit	41.7 ≈ 42	1

3.2.3 Life cycle inventory

Input data for the electricity generation collected from Ecoinvent version 3 databases. All input data are specific to Thailand. Amount of electric energy consumed by LED models measured according to the manufacture data on power consumption per lamp (W) and lifetime (hr.).

3.2.4 Life cycle impact assessment and scenario analysis

Recipe V1.12 method applied to estimate comparative environmental impact from selected LED models. In this method results manifested through 18 midpoint impact categories which are climate change, ozone depletion, terrestrial acidification, freshwater acidification, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter foundation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion and fossil depletion. Midpoint impacts aggregated into three endpoint impact categories human health, ecosystem quality and resource depletion. Midpoint and endpoint approaches were applied based on the Hierarchist (H) version and excluded long term emissions to correlate with policy principles as regards of time frame. Impact assessment conducted based on six scenarios to discover the sensitivity of results. The most common practice selected as the base case scenario, where both LED lamp models complete ideal lifespan and consume electricity generated in accordance with 2020 energy mix. Three possible lifespans were built based on the principle of bathtub curve of electronic products lifetime (Osram, 2008). Fuel source and percentage for the 2020 energy generation added form on EGAT data while values for the energy mix in 2036 extracted from Thailand power development plan 2015-2036. Table 3.2 describes the factors that influence scenario generation.

Table 3.2 : Description of influence factors for scenario analysis

<table>
<tr><td rowspan="4">Lifespan</td><td></td><td colspan="2">Use time for residential LED model (hr.)</td><td>Required electricity input (MJ)</td><td>Use time for industrial LED model (hr.)</td><td>Required electricity input (MJ)</td></tr>
<tr><td>Early failure</td><td colspan="2">375</td><td>453.6</td><td>1,250</td><td>382.5</td></tr>
<tr><td>Random failure</td><td colspan="2">5,625</td><td>6,804</td><td>18,750</td><td>5,737.5</td></tr>
<tr><td>Ideal</td><td colspan="2">15,000</td><td>18,144</td><td>50,000</td><td>15,300</td></tr>
<tr><td rowspan="3">Energy mix</td><td></td><td>Natural gas</td><td>Import Hydro</td><td>Lignite</td><td>Domestic Hydro</td><td>Nuclear</td></tr>
<tr><td>% of energy generated in 2020</td><td>57</td><td>22</td><td>18</td><td>3</td><td>0</td></tr>
<tr><td>% of energy generated in 2036</td><td>40</td><td>20</td><td>20</td><td>15</td><td>5</td></tr>
</table>

3.2.5 Interpretation

Life cycle assessment results could interpret to the audience in numerous ways. There are 4 major ways that included in LCA ISO 10440 standard, as stated here

1. Uncertainty analysis
2. Sensitivity analysis

3. Contribution analysis
4. Inventory analysis.

In this research, scenario analysis which is a type of sensitivity analysis had chosen to interpret the result to the audience. How different choices in input data change the impact of the output results within the selected system boundary. Environmental impact of electronic appliances mainly correlates with the use phase. Factors such as lifespan and energy mix in use that affect use phase have high potential to change the environmental impact from the electronic product. Therefore, results described under several different scenarios based on the different input data.

3.3 Environmental Testing

3.3.1 Sample selection and preparation

Before the sample model selection process, 70 small scale electronic and electrical appliance manufacturing factories selected from 9 industrial estates in Thailand. Survey was distributed among LED lamp consumers to discover the most used LED lamp models among them. Based on the survey answers, E27, T8 models from different brands were purchased from the shops. Structure of selected sample models present in figure 3.1. Unused LED lamps were subjected to the experiment assuming that metal content will stay same regardless of the consumption period. Metal concentration of LED lamps responsible for the luminous efficacy, color and color temperature. Detailed information of selected brand and models have included in table 01. LED lamp samples were manually disassembled into six components (LED source, driver, metal base, plastic cover, luminous) and separated LED source and driver for the metal detection procedure. Thus mixture of drivers and sources from selected models were used for this study. LED sources and drivers used for the experiment presented in Figure 3.2.

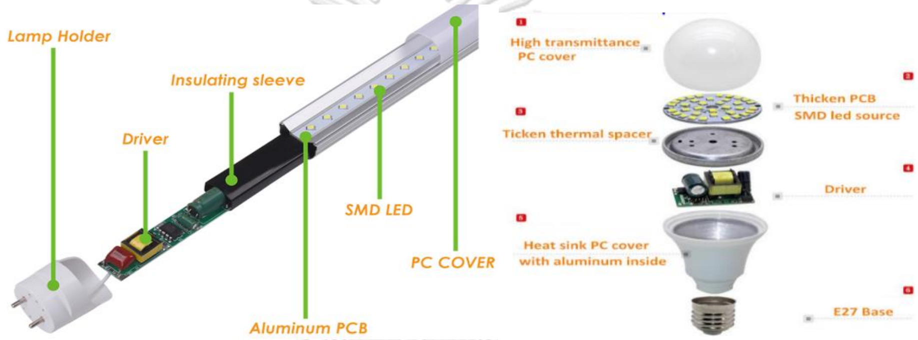

Figure 3.1 : Structure of selected LED models

Table 3.3 : Characteristics of selected LED models for the environmental testing procedure

Model	Brand	Power (W)	Lifespan (hrs.)	Color temperature (K)	Brightness (Julander *et al.*)
T8	A1	18	25,000	6,500	1,840
	A2	16	15,000	-	1,600
	A3	16	25,000	6,500	1,760
E27	B1	12	30,000	3,000	1,050
	B2	7.5	15,000	2,700	600
	B3	13	20,000	6,500	1,300
	B4	14.5	10,000	-	1,800

Figure 3.2 : LED drivers and sources from selected models.

3.3.2 Metallic content detection and hazard waste characterization

According to Thai regulations, solid waste must go through two hazard testing procedures to categorize waste as hazardous. EPA 3050b (SW-846 Test Method 3050B: Acid Digestion of Sediments, Sludge, and Soils) and Waste Extraction Test (WET). First, prepared samples went through Environmental Protection Authority (EPA) 3050b procedure. Resulted concentration values from EPA 3050b compared with listed total threshold limit concentration (TTLC). The detected metal concentrations are higher than TTLC standard measures for Cu, Ag, Pb and ZN, therefor WET did not apply to samples.

As illustrated in Figure 3.3, LED drivers milled using industrial grinder for particles less than 2mm but for LED sources crushed by a hammer to obtain 2 mm pieces. In next step, 10ml of HNO_3 (1:1) solution were added into1g of milled sample. Mixture should cover with a watch glass and repeatedly heat up to 95°C ± 5°C with addition of concentrated nitric acid to complete the oxidation reaction of contain metals. After then, hydrogen peroxide added to initiate the peroxide reaction. Finally, concentrated hydrochloric acid added to the sample and heat it up to 95±5°C for 15 minutes. Leachate from the acid digestion was filtered through whatman no 41 filter paper. EPA method 6010B (ICP-AES) used for the metal concentration analyzing in filtrate. Experimental procedure.

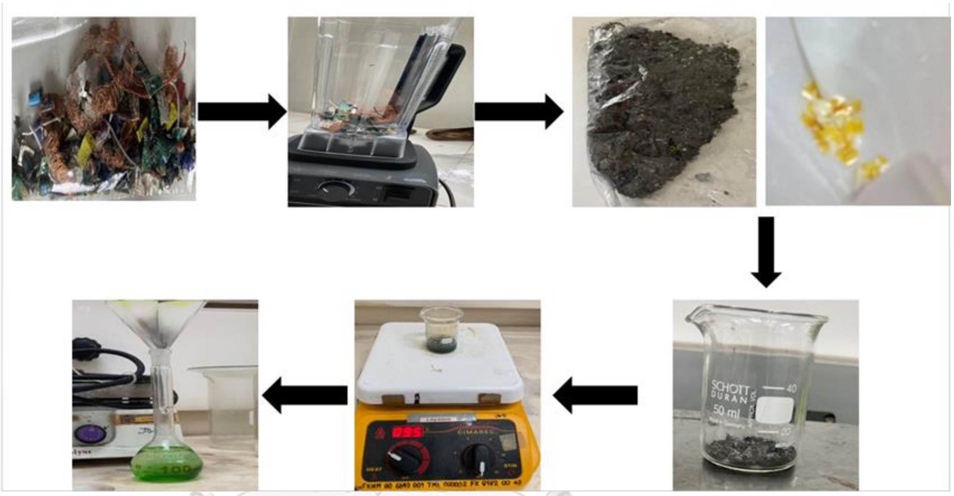

Figure 3.3 : Experimental procedure for TTLC test

Sample blanks and spikes were tested for both of testing procedures to ensure quality control measures. Resulted metal concentration is an average value of triplicate measured values. This study compares toxic metal concentration limits from driver and LED sources from most used LED lamps in Thailand 2019/ 2020 with regulatory limits

3.3.3 Applying USEtox model for toxicity evaluation

USEtox is a scientific environmental model designed by UNEP (United Nations Environmental Program) / SETAC (Society for Environmental Toxicity and Chemistry) for the purpose of estimating life cycle environmental performance of products/ organizations.

In this research, USEtox 2.12 version applied to analyze the impact on human health and ecosystem from LED lamp waste in Thailand. Human Toxicity (Carcinogenic/ non-carcinogenic) & Eco toxicity calculated for each metal detected in LED lamp waste via Eq. 2.

$$IS_x = (CF_x) . (C_x) . (M) \quad (2)$$

Whereas,

Impact Score (IS_x) of metal x in waste LED lamps for Human and Eco toxicity is based on factors such as, $CF_{x,i}$ Characterization factor of metal x (cases/kg); C_x is the concentration of metal x in waste LED lamps while M is the mass of selected waste LED lamps (kg). Concentration of metals in waste LED lamps were determined via chemical digestion of the samples. Characterization factors can be human toxicity (cases/$kg_{emitted}$) divided into carcinogenic and non-carcinogenic and Eco toxicity (PAF. m^3.day/$kg_{emitted}$). Characterization factors related with detected metals of waste LED lamps that emit into air: urban air, rural air, water: fresh water, soil: agricultural soil, natural soil.

Human toxicity characterization factor [cases/$kg_{emitted}$] and Eco toxicity Characterization factor [PAF.m^3.day.kg^{-1}] calculated based on the metal type, emission compartment, setting (landscape or indoor environment) stated in Table 3.4 and Table 3.5 and data also illustrated in Figure 3.4 and Figure 3.5.

Table 3.4 : Calculated Human toxicity characterization factor [cases/$kg_{emitted}$]

Metal name	Human toxicity characterization factor [cases/$kg_{emitted}$]				
	Emission to natural soil	Emission to agricultural soil	Emission to rural air	Emission to urban air	Emission to freshwater
Aluminum (Al)	n/a	n/a	n/a	n/a	n/a
Barium (Ba)	6.68E-05	6.71E-05	5.44E-05	8.88E-05	1.35E-04
Cadmium (Cd)	8.57E-03	8.32E-01	6.09E-02	5.85E-02	1.72E-02
Chromium (Cr)	6.64E-03	7.00E-03	4.71E-03	1.08E-02	1.34E-02
Copper (Cu)	8.37E-07	3.72E-04	2.53E-05	2.48E-05	1.65E-06
Iron (Cesaro *et al.*)	n/a	n/a	n/a	n/a	n/a
Lead (Pb)	4.00E-04	2.01E-01	1.36E-02	1.38E-02	7.42E-04
Nickel (Ni)	7.68E-05	8.43E-04	1.06E-04	1.59E-04	1.53E-04
Silver (Ag)	1.24E-03	3.60E-01	2.48E-02	2.43E-02	2.47E-03
Zinc (Zn)	6.43E-04	6.82E-02	4.95E-03	4.66E-03	1.25E-03

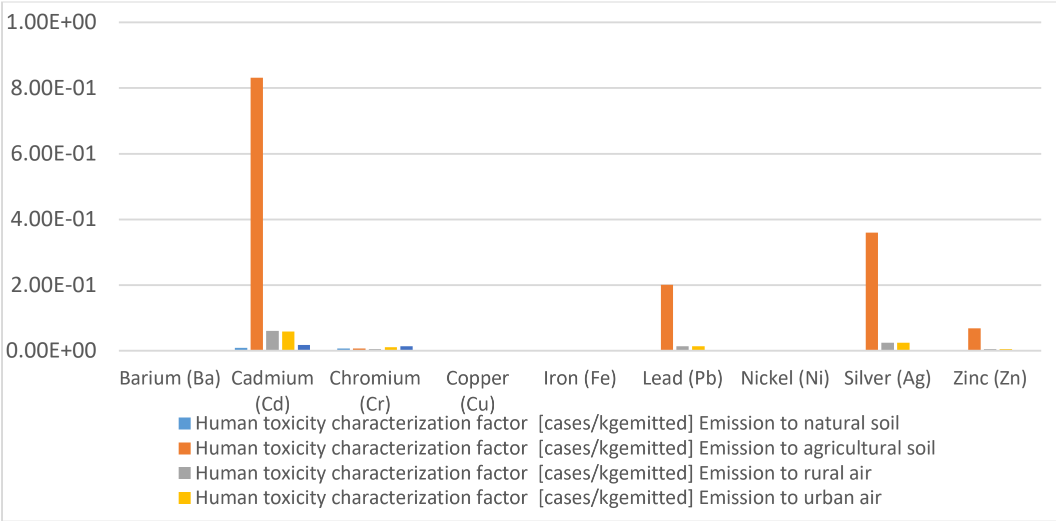

Figure 3.4 : Human-toxicity characterization factors for each metal

Table 3.5 : Calculated Eco toxicity Characterization factor [PAF.m^3.day.kg^{-1}]

Metal name	Eco toxicity Characterization factor [PAF.m^3.day.kg^{-1}]				
	Emission to natural soil	Emission to agricultural soil	Emission to rural air	Emission to urban air	Emission to freshwater
Aluminum (Al)	2.69E+06	2.69E+06	1.83E+06	1.81E+06	4.57E+06
Barium (Ba)	4.48E+04	4.48E+04	3.08E+04	3.07E+04	9.06E+04
Cadmium (Cd)	3.54E+06	3.54E+06	2.42E+06	2.42E+06	7.10E+06
Chromium (Cr)	1.86E+05	1.86E+05	1.28E+05	1.28E+05	3.77E+05
Copper (Cu)	1.83E+05	1.83E+05	1.24E+05	1.24E+05	3.61E+05
Iron (Cesaro *et al.*)	1.15E+06	1.15E+06	7.83E+05	7.80E+05	2.24E+06
Lead (Pb)	2.35E+04	2.35E+04	1.59E+04	1.58E+04	4.35E+04
Nickel (Ni)	3.05E+05	3.05E+05	2.09E+05	2.08E+05	6.08E+05
Silver (Ag)	6.06E+05	6.06E+05	4.12E+05	4.12E+05	1.20E+06
Zinc (Zn)	2.87E+05	2.87E+05	1.96E+05	1.96E+05	5.56E+05

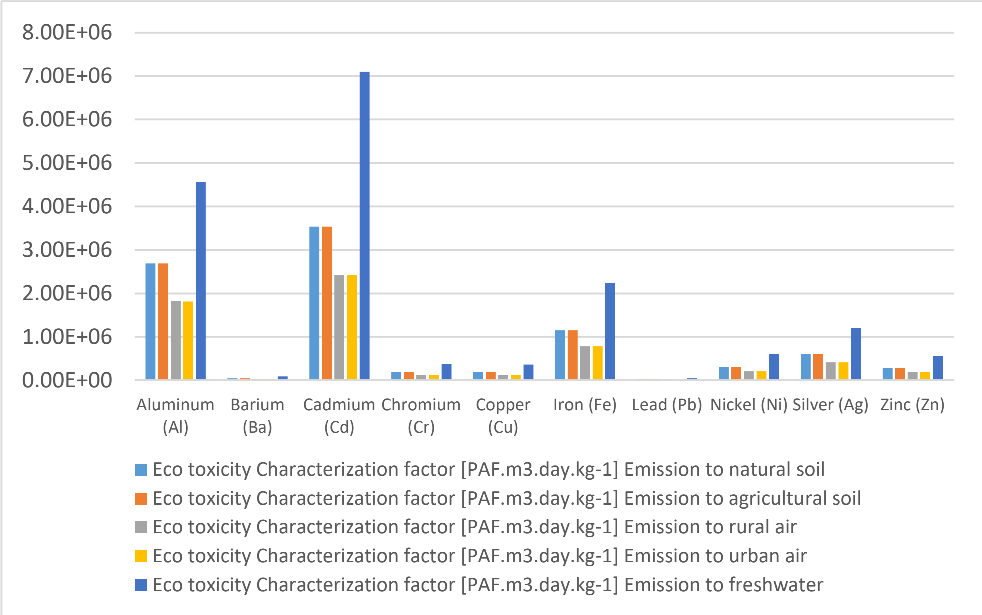

Figure 3.5 : Eco-toxicity characterization factors for each metal

CHAPTER 4

RESULT AND DISCUSSION

4.1 Survey for LED lamps consumers

Results of the survey conducted on LED lamp consumers from electronic and electrical appliances manufacturing facilities in industrial estates in Thailand shows in Figure 4.1, 68% use residential LED lamp models (T8 and E27 LED lamp models) as their light source while only 32% use specifically designed industrial LED lamp model as their lighting application.

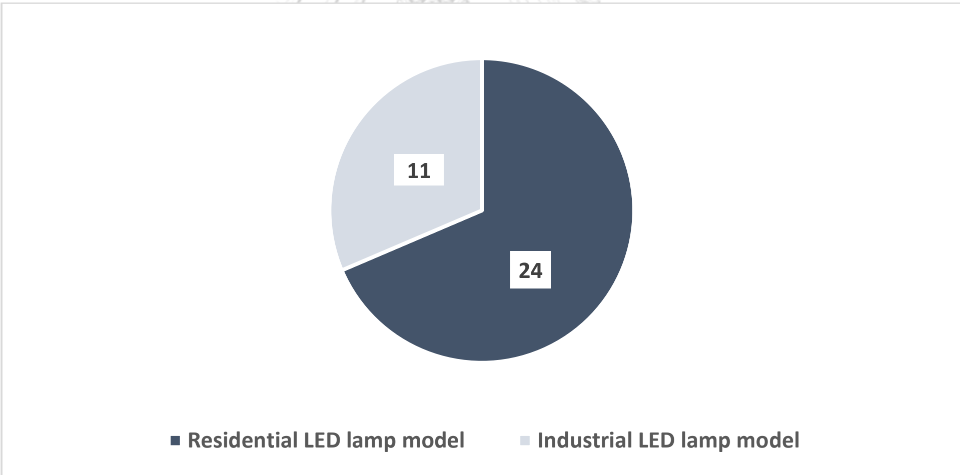

Figure 4.1 : LED lamp model usage among industrial consumers

4.2 Comparative Life Cycle Assessment of LED consumption

In this sector, compare and estimate the environmental impacts of general T8 tube LED model and industrial high bay LED model. ReCiPe V1.03 impact assessment method applied due to following advantages, distribution of midpoint impact categories across wide range, capability to apply different weighing factors during the impact assessment study. Compared to Eco indicator 99 and Impact 2002+ methods, ReCiPe V1.03 does not add possible environmental impacts from future extractions to the final impact assessment results (Golsteijn, 2018).

Results described via two perceptions, Base case scenario which is current practice and sensitivity analysis.

4.2.1 Base case scenario

Results of two selected LED lamp models in base case scenario communicated via 18 midpoint categories as stated in Table 4.1. In all impact indicators, using residential LED model for the industrial lighting purpose originated 25% greater impact compared to industrial LED model as illustrated in Figure 4.2. And also Figure 4.3 indicates general LED model show higher impact in each endpoint environmental indicators. Luminous efficacy acts a crucial role in calculating the electricity energy consumption. Higher efficacy in high bay lamp indicate the production of increased brightness per electricity unit (118 lm/W).

Table 4.1 : Base case scenario – Midpoint environmental impact values of general and industrial LED models

Midpoint indicator	General LED model	Industrial LED model
Global warming	0.451356	0.340118
Stratospheric ozone depletion	0.013202	0.009948
Ionizing radiation	0.001055	0.000795
Ozone formation, Human health	0.267077	0.201255
Fine particulate matter formation	0.115301	0.086884
Ozone formation, Terrestrial ecosystems	0.315391	0.237662
Terrestrial acidification	0.175124	0.131964
Freshwater eutrophication	0.505678	0.381052
Marine eutrophication	0.001317	0.000992
Terrestrial ecotoxicity	1.021285	0.769585
Freshwater ecotoxicity	1.608737	1.212257
Marine ecotoxicity	3.426798	2.582251
Human carcinogenic toxicity	3.694695	2.784123
Human non-carcinogenic toxicity	0.513848	0.387208
Land use	0.001451	0.001093
Mineral resource scarcity	1.19E-05	8.98E-06
Fossil resource scarcity	1.150357	0.866847
Water consumption	0.041615	0.031359

The highest midpoint impact shown in human carcinogenic toxicity category during the base case scenario analysis. Human carcinogenicity defined as formation of cancer cells due to outer substance which disturb cellular metabolism. Electricity energy is the main input for the consumption phase of LED lamps. Emission of pollutants such as particulate hazard matters to the atmosphere from fossil fueled power plants links with human carcinogenicity. Thailand uses natural gas as their main components for the electricity generation process. Natural gas combustion produces Polycyclic aromatic hydrocarbons (PAHs), Polycyclic Organic Compounds (POC), and

$PM_{2.5}$ mix with fly ash and capable of damaging lung tissues and internal fluids increasing the future cancer risk (Natusch, 1978).

Marine eco-toxicity stated as impact of toxic substances emission to marine eco-system. Main actors of marine eco-toxicity are toxic heavy metals emitted into marine water compartment. Combustion of natural gas and lignite for the electricity generation, produce toxic metals such as Ni, Co, Hg and Be. These metals capable of bioaccumulation and reduce the reproduction rate of marine species. Freshwater eco-toxicity correlate with extraction activities for natural gas. Leaching of metals (Cr, Cd, Zn, Mn, and Ni) form phytotoxic reactions within freshwater plants. Metal emission from the combustion process of power plant will increase the water acidity and damage the stability of freshwater eco-system (Vandecasteele *et al.*, 2014).

Currently Thailand generate 57% of electricity using natural gas. Natural gas stated as fossil resource along with crude oil and coal. As in the market, demand for natural gas surpassing the supply hence there is a significant impact visible in the category of fossil fuel scarcity. In terrestrial eco-toxicity, impact on soil eco-system due to toxic material emission from electricity generation process concerned. Natural gas extraction, hydro power importation and lignite combustion contribute to the terrestrial toxicity impact (Oney, 2019).

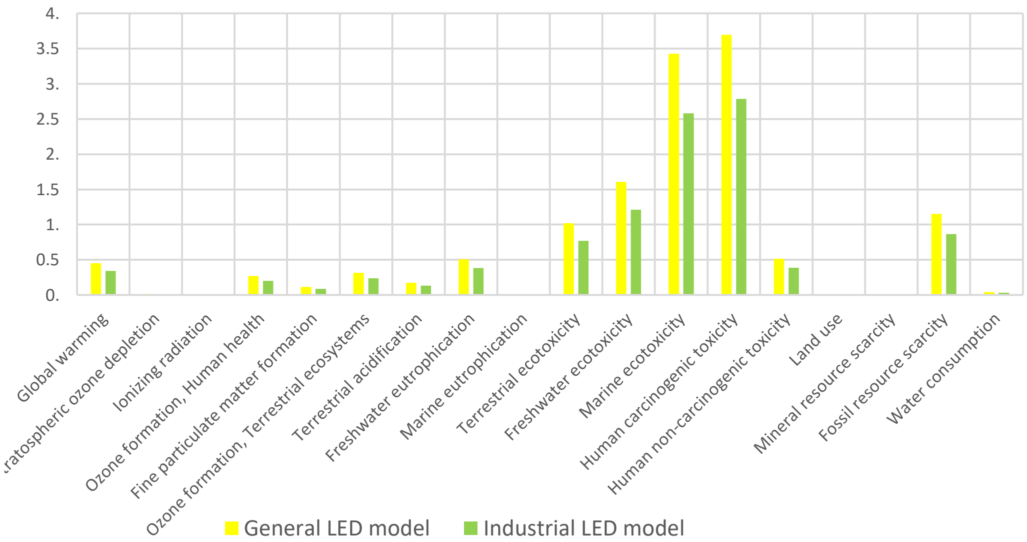

Figure 4.2 : Base case scenario – midpoint environmental impact of general and industrial LED models

Midpoint impact category values aggregated into 3 endpoint impact categories and normalized values stated in Table 4.2.

Table 4.2 : Normalized impact values in endpoint categories

Endpoint Impact Category	General LED model (consumption)	Industrial LED model (Consumption)
Human health	0.2313	0.1743
Ecosystems	0.0179	0.0135
Resources	0.007	0.0053

Summarized values illustrated in Figure 4.3. As detailed in the figure the highest endpoint impact detected on human health (0.2313) due to increased midpoint categories such as, Global warming, Stratospheric ozone depletion, Ionizing radiation, Ozone formation, Human health, Fine particulate matter formation, Human carcinogenic toxicity, Human non-carcinogenic toxicity, and Water consumption.

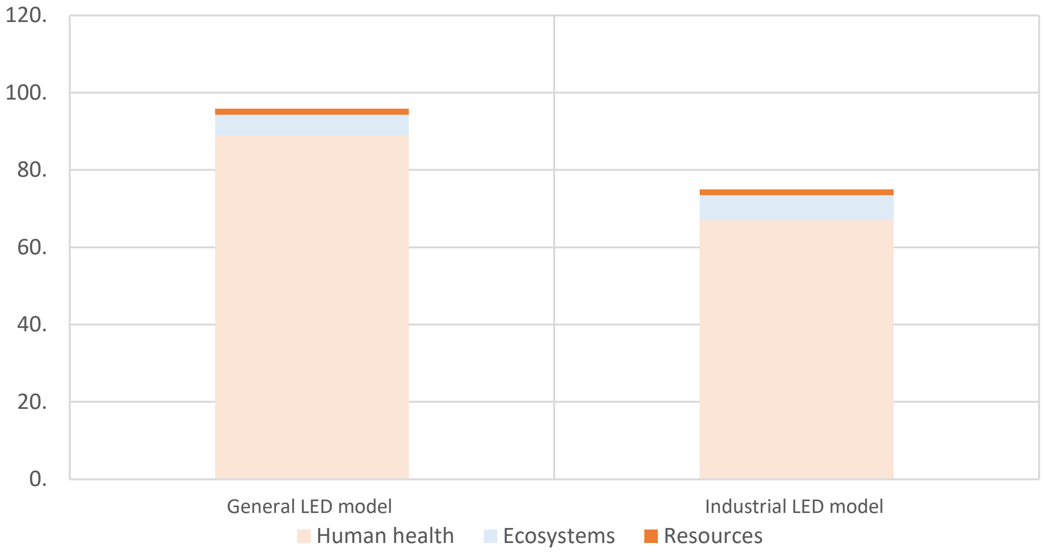

Figure 4.3 : Base case scenario – Single score, endpoint environmental impact of general and industrial LED models

4.2.2 Sensitivity analysis

Results in this section discussed based on the input uncertainty. Comparative environmental impact of LED lamp consumption calculated based on six different scenarios as stated in Table 4.3.

Table 4.3 : Scenario description for the sensitivity analysis

Scenario	Residential LED model			Industrial LED model			Energy mix in 2020	Energy mix in 2036
	Early	*Random*	*Ideal*	*Early*	*Random*	*Ideal*		
S1	☑			☑			☑	
S2	☑			☑				☑
S3		☑			☑		☑	
S4		☑			☑			☑
S5 (Base case scenario)			☑			☑	☑	
S6			☑			☑		☑

In the present study, useful lifespan and energy mix considered as dominant factors for the consumption phase related environmental impact. Figure 4.4 and Figure 4.5 point out the environmental impact of general and industrial LED models in each scenario. The highest impact in both LED models shows during scenario 5 and 6 due to the completion of ideal lifespan. Among scenario 5 and 6 of both models, scenario 6 exhibits the greater impact on categories such as ionizing radiation, freshwater eutrophication, human carcinogenic toxicity and water consumption as a result of energy mix in 2036. In 2036 energy mix, 5% nuclear energy responsible for the increment in ionizing radiation as a consequence of radionuclide emission. 2% boost of electricity generation from lignite escalate human carcinogenic toxicity and freshwater eutrophication on account of toxic chemical emissions (selenium, molybdenum, beryllium and phosphates). The impact on water consumption is mainly because of 15% of domestic hydro power generation.

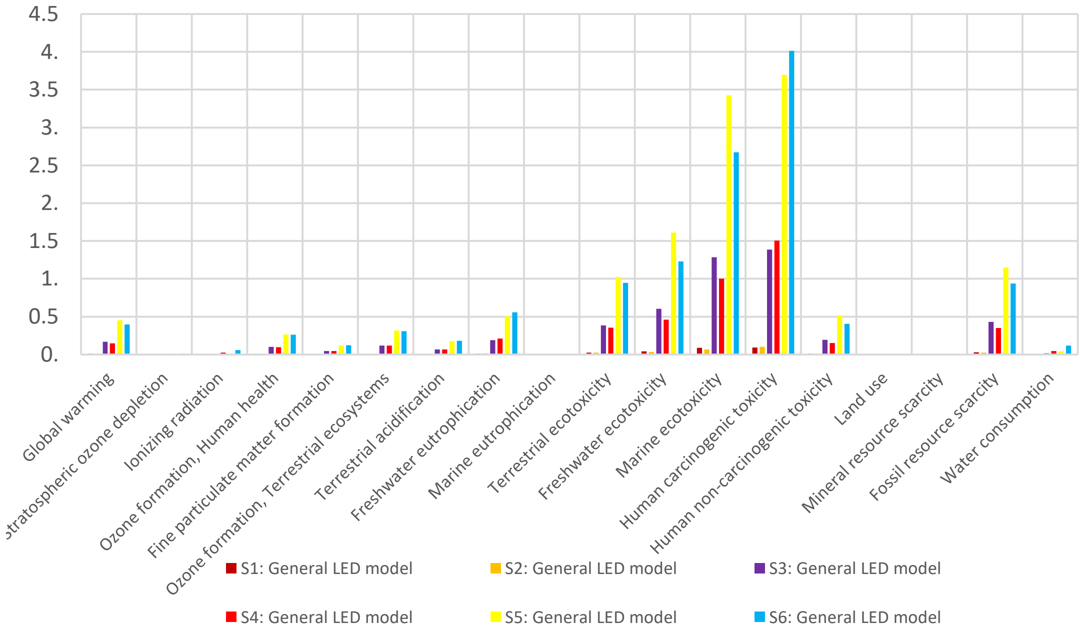

Figure 4.4 : Scenario 1 to 6 – midpoint environmental impact of general LED models

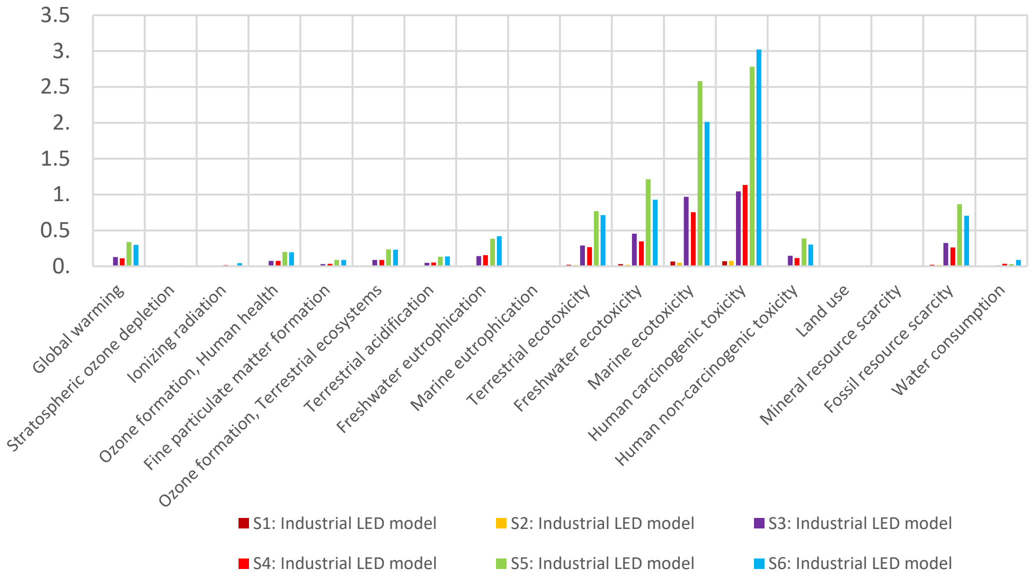

Figure 4.5 : Scenario 1 to 6 – midpoint environmental impact of industrial LED models

As demonstrated in Figure 4.6, human health impact is the main contributor in endpoint indicator of each scenario. Collective impact of human carcinogenic toxicity, human non carcinogenic toxicity, global warming, ozone formation, fine particulate matter formation and water consumption result a greater value in human health category. The scenarios that related with the highest impact are, in decreasing order: scenario 5, scenario 6, scenario 3, scenario 4, scenario 1 and scenario 2. Scenario 5 has the highest total impact because of longer lifespan and energy mix in 2020 while scenario 2 reveal lowest total impact by reason of early failure and energy mix in 2036.

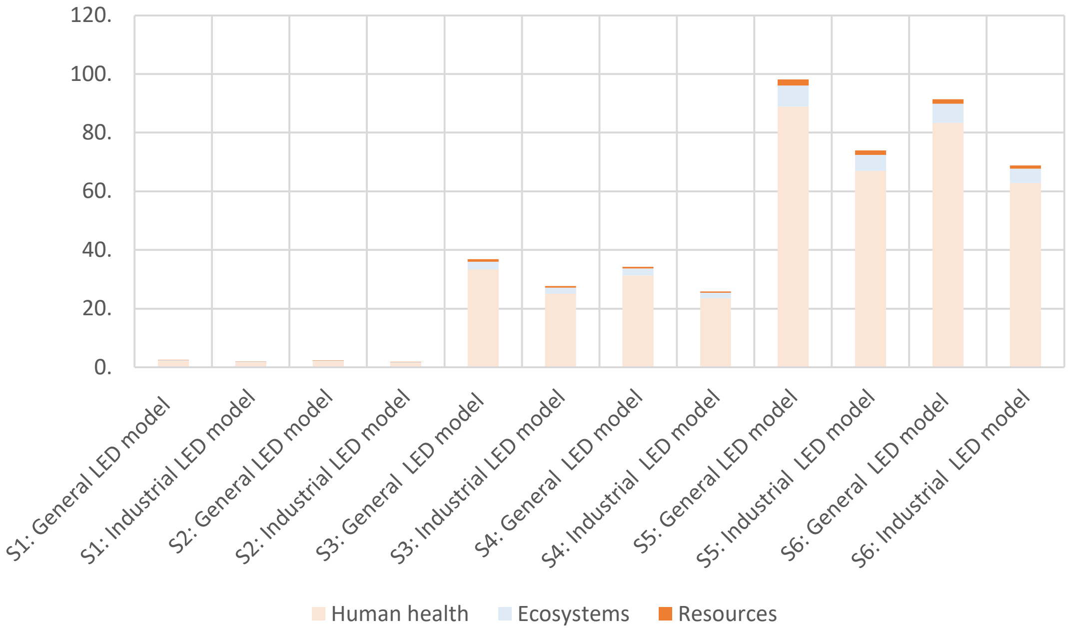

Figure 4.6 : Scenario 1 to 6 – Single score environmental impact of industrial and general LED models

This LCA study estimated that use of general lighting model for the industrial lighting purpose generate 25% excess environmental impact during the use phase. Lower efficacy of general LED model is the main reason for the unnecessary environmental impact during the use phase. Future research could assess from cradle to grave perspective to investigate environmental impact differences between general and industrial LED models.

4.3 Environmental Testing Procedure for waste LED lamp components

Results of environmental testing procedure of selected components from LED waste (LED driver and source) is divided into 3 main sections as illustrated in Figure 4.7.

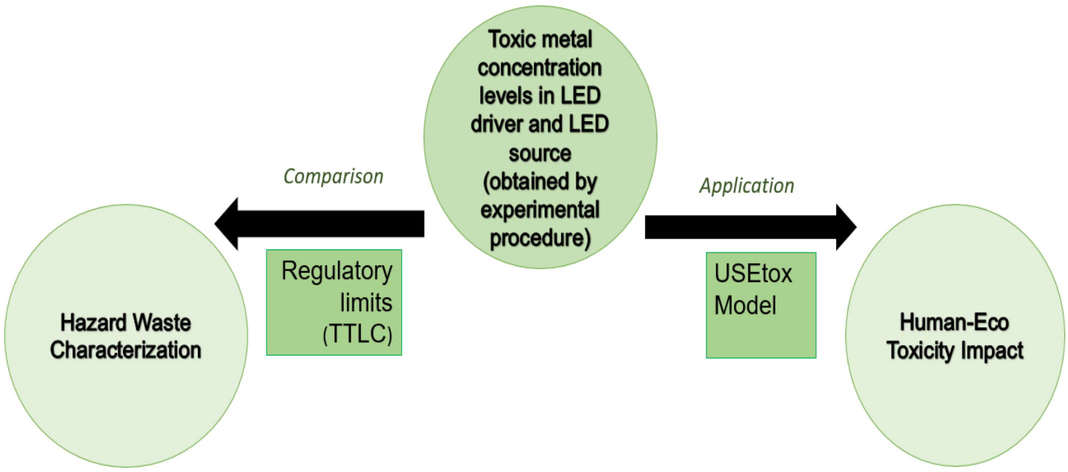

Figure 4.7 : LED environmental testing procedure in this study

In first step, toxic metal (Al, Ba, Cd, Cr, Cu, Fe, Pb, Ni, Ag and Zn) concentration levels in selected LED components evaluated by leaching test. Resulted values then applied to USEtox model to quantify the human – eco toxicity impact from the metal concentration in LED components. On the other hand, resulted values compare with TTLC standards to characterize LED waste based on the toxic metal concentration presented in selected LED components.

4.3.1 Metallic concentrations in LED drivers and sources

LED source and driver functionality depend on the type and quantity of metals exist in LED components. There is no study conducted to estimate metal concentrations and types in LED components (driver and source) in Thailand. Results in this section give insights to the metal content in LED lamps waste, Thailand.

4.3.1.1 Comparison of metal concentration in LED driver with past studies

In this study, TTLC test applied to LED source and driver separately. TTLC results obtained by analyzing 3 LED driver samples. Average concentration values of each metal in 3 LED driver samples stated in Table 4.4 concentration values compared with paste studies. Based on the results in this study, copper is the most abundant metal in LED driver (164,467 mg/kg) whilst aluminum stated as the most abundant metal in literature. Copper is the building material of wire resistors in LED driver. Aluminum (65,766.67 mg/kg), iron (25,933 mg/kg) and zinc (15,433 mg/kg) also present greater amounts in the driver. Polarized capacitor in LED driver built using aluminum and zinc contain in the drive as zinc oxide in varistor (voltage dependent resistor). Zinc oxide layer is in the middle of two electrodes and it provides the quality of changing electrical resistance in accordance with the input voltage. Varistor functions have improved with time to extend the lifespan of the LED driver. As you can see in the Fig. 4.9, Zn concentration increased from 2011 to 2020 in LED drives due to advanced modification (increased thickness) in zinc oxide layer. Printed circuit board in LED driver fabricated in iron–aluminum board. Therefore, aluminum and iron contain greater amounts in LED driver.

There is a significant difference between lead concentration values in the literature (16.7 – 903 mg/kg) and present study (8,767 mg/kg). Lead alloys present in notable amount in printed circuit board (PCB) of LED driver due to creep resistance (ability to resist deformation over long time period or stress) quality. Improvements in LED lifespan is one of the main cause for excess amount of lead in LED driver. Nickel, silver, chromium, barium also present in lower amount in LED driver. Ni commonly used in protective barrier in LED drivers. This protective barrier will prevent Cu diffusion with other precious metals in driver. Ni present in LED drivers within the range of 151 – 2593.8 mg/kg. Lowest concentration of Ni evaluated in US, 2013 by S.R Lim and the team. Ag has great electrical conductivity which makes it as a common building material in PCBs of LED drivers. Ag used as surface plating material in PCB board to protect Cu from oxidation reactions.

The highest concentration of Ag evaluated in the LED driver that tested in 2011, US. Cr on the other hand, used in the electroplating process of LED driver board. Electric wire circuit system also made from Cr and Cu metals. Barium exhibits high electrical conductivity and also provide flexibility in LED driver. Ba metal concentration ranged from 364 – 744 mg/kg in tested LED driver samples. Ba provides heat resistant qualities and prevent spark initiation within the circuit. Cadmium used to bond metal pieces in PCB to the LED driver. Identification of Cd in LED driver occurred only in this study.

Table 4.4 : Metal concentration values in the leachate according to TTLC procedure (LED driver)

Metal	Toxic Metal Concentration in LED driver (mg/kg)				
	Lim et al (2011 US)	Lim et al (2013 US)	Tuenge et al. (2013)	Kumar et al (2019 Canada)	This study (2020 TH)
Aluminum (Al)	118	947,000	-	225,250	65,766.67
Barium (Ba)	-	364	744	500	551.33
Cadmium (Cd)	-	-	-	-	0.73
Chromium (Cr)	56	120	673	60	534.67
Copper (Cu)	2143	31,600	44,197	21,065	164,467
Iron (Cesaro *et al.*)	329,155	12,300	-	33,250	25,933
Lead (Pb)	903	16.7	150	300	8,767
Nickel (Ni)	2593.8	151	761	290	793
Silver (Ag)	406.4	159	34	30	79.4
Zinc (Zn)	50	4,540	8,932	19,325	15,433

Metal content of LED driver varied in different studies. As illustrated in Fig. 4.8, iron was the most abundant metal during the early period of LED technology. In early phase, PCBs in LED driver mainly built using Fe material but due to the high density Fe in PCBs replaced by Al. density of Al is 2.7 g/cm^3. In most small electronic appliances such as LED lamps, Fe replaced by Al to obtain lighter weight. Cu usage in LED drivers selected from Thailand is notably higher than other countries. Increased level of Pb compared to other studies can be seen in LED drivers selected from Thailand.

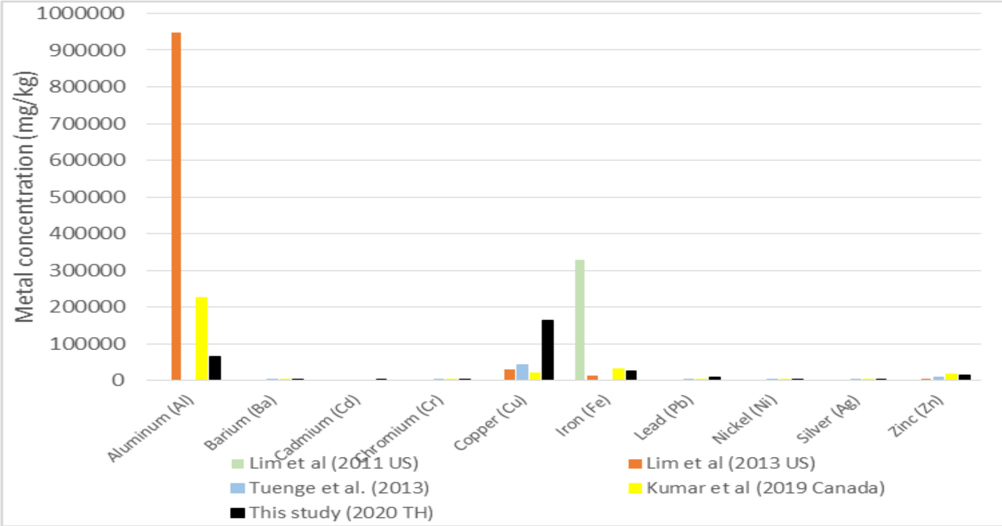

Figure 4.8 : Metal concentration in LED drivers in literature and the current study

4.3.1.2 Comparison of metal concentration in LED source with past studies

TTLC test results from LED source described in this section. In literature, there is only one study has concerned on toxic metal concentration in LED sources. Yong Choi and team has conducted TCLP test separately on LED driver and source. They have selected linear LED lamps in South Korea and proceeded TCLP test on selected components. Comparison of resulted concentration values of LED source from TCLP test in past study and TTLC test in this study stated in Table 4.5. There is a visible gap in metal concentration levels in LED sources in literature. The most abundant metal in LED source is Cu (211,800 mg/kg) due to wiring system in linear LED tubes that conduct current from LED driver to LED source. Fe (64,500 mg/kg) present in greater amount in LED source surface, LED chips attached to the Fe surface. Zn (51,807 mg/kg) is the main material in high brightness LED chips. Zinc oxide (ZnO) layer in LED chip improve Iluminance level per electricity energy unit. Technological advancements in LED chips resulting higher amount of metal usage. Silicon discs in LED chips covered by a Pb frame.

Table 4.5 : Metal concentration values in the leachate according to TTLC procedure (LED sources)

Metal	Toxic Metal Concentration in LED source	
	Choi et al (2019, South Korea) TCLP (mg/l)	*This study (2020, TH) TTLC* (mg/kg)
Aluminum (Al)	n/a	3,931
Barium (Ba)	n/a	32.2
Cadmium (Cd)	0.209	0.53
Chromium (Cr)	n/d	38.23
Copper (Cesaro *et al.*)	0.037	209,200
Iron (Cesaro *et al.*)	n/a	60,000
Lead (Pb)	5.873	16,600
Nickel (Ni)	n/a	1,392
Silver (Ag)	n/a	846
Zinc (Zn)	n/a	39,204

As in the Table 4.2, Ag (846 mg/kg), Ni (1,392 mg/kg), Cr (38.23 mg/kg) and Ba (32.2 mg/kg) also present in LED source. Ag plays a major role in LED chip fabricating process as a vapor deposited coating to protect LED source. Ni used mostly as alloys in chips to conduct electricity from driver to chip. Cr in LED chip gives metallic appearance and high corrosive resistance. Combination of Ba with Ni create an alloy which emit electrons upon the application of heat. Therefor Ba contain in LED chip to support the light generation.

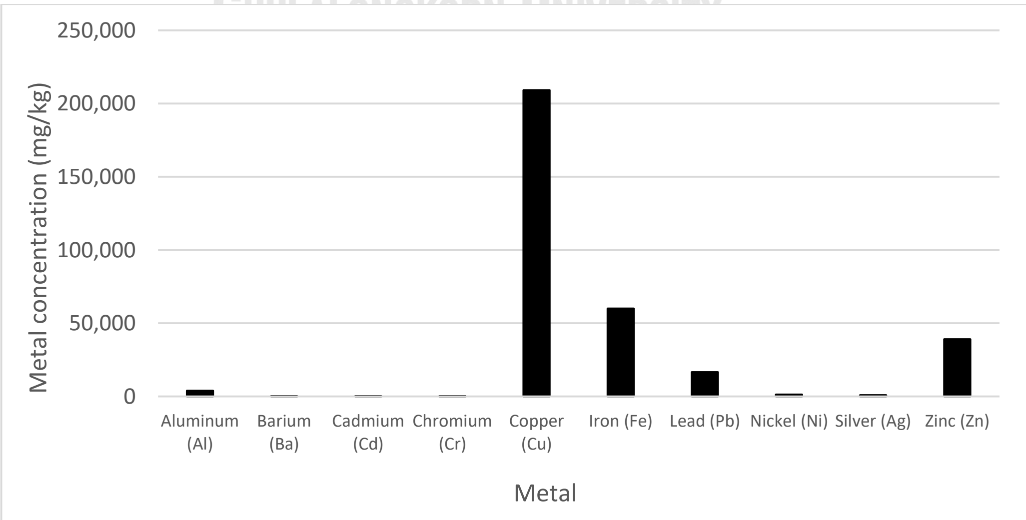

Figure 4.9 : Metal concentration in LED sources of current study

Metal concentration levels detected in LED driver and source are exhibit significant difference compared to past studies in metals such as Cu, Pb, Al, Zn and Ni. Reason behind the difference metal concentration levels between paste studies (Lim *et al.*, 2011, 2013; Tuenge *et al.*, 2013) and this study (2020) is the technological improvements of LED lamps over the time (from 2011 to 2020). On the other hand, different manufacturing countries responsible for the metal concentration levels difference between the study Kumar et al (2019) and this study (2020).

4.3.1.3 Resource depletion of key metals in LED waste

Metal concentration limits in LED driver and source exhibit higher amount of metal concentration compared to LED driver. Cu amount in LED source is 1.29 times higher than LED driver. Fe include in higher amounts in both components but Fe concentration in LED source is almost 2.5 higher times compared to driver. Only Al include in significantly high concentration levels in LED driver compared to the source. Zn content in LED chip is threefold relative to the measure in LED driver. As both LED driver and source contains recyclable metals in higher amount concerns over metal recovery should raise in the perspective of circularity. Under the section 13 of draft WEEE act (Thailand), products which contain valuable materials are encourage to recycle or recover materials. This study shows the composition of metals in LED driver and source which could further extended into the discussion of feasibility of recycling contain metals in LED waste. Results from the gravimetric analysis of selected LED lamps shows in Fig. 4.3. LED driver and source weigh 18% (17.1 g) from the total weight in E12 model while value stated as 21% (105 g) in T8 model. Metal characterization results of LED driver (PCBs) and LED source could raise the attention on material recovery. This section discusses resource depletion of the most abundant metals in LED lamps.

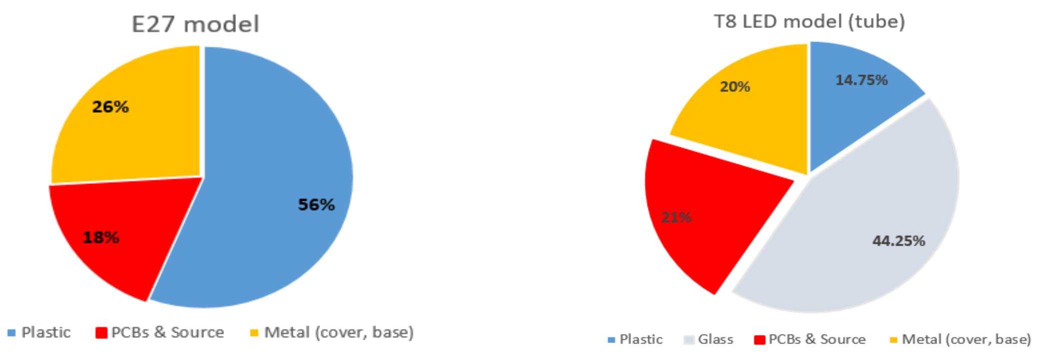

Figure 4.10 : Gravimetric analysis of selected LED model samples

Commodity metal price index explain the normalized average price relative to the demand for metals such as **Al, Cu, Fe, Pb, Ni, Tin (Tuenge *et al.*)**, Uranium (U) and **Zn**. As in the Figure 4.11, commodity metal price index has increased during the year of 2020 due to global Covid-19 situation.

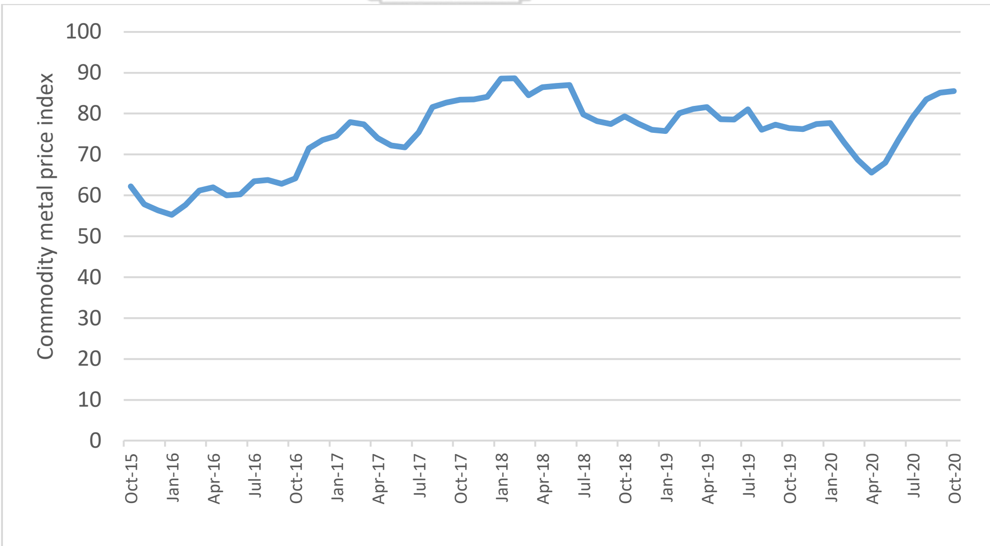

Figure 4.11 : Commodity metal price index from 2015 to 2020

Currently there are active metal mining in Thailand. Table 4.6 describes the local production capacity of key metals of LED waste.

Table 4.6 : Active metal mining in Thailand

Metal	Annual production (tons/year)	Number of plants
Al	200,000	10
Fe	11,000,000	27
Cu	165,000	1(closed in 2020)
Zn	105,000	1(closed in 2020)
Pb	120,000	8

Aluminum

Aluminum exists in ore as bauxite compound, this compound then converts into aluminum for further applications. Al ranks as the second most mined metal in terms of mass. Highest Al production occurred in 2020 (70 million tons/year). Imbalance between demand and production of Al have raised concentrations over urban mining for Al metal. Globally 74% of Al recovery process occurred within the informal recycling sector. Currently 400 million tons of Al in use in several applications. In Thailand, demand for Al grew over 1 million tons during 2018. Economic Intelligence Unit, Siam Commercial Bank evaluated the competition between cheap importers and local manufactures due to 10%-30% reduced price from Chinese Al importers.

Increased tax on import sector in US will increase the Al import rate into Thailand but no significant impact on Al export rate. Al import amount during 2012-2016 illustrated in Figure 4.12. Al recovery from small scale e-waste is distant reality based on the current situation of Al market, Thailand.

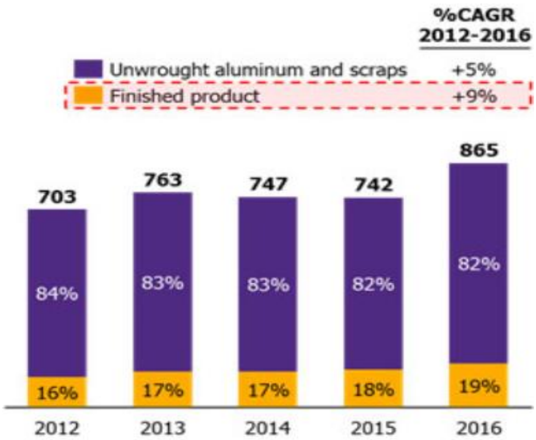

Figure 4.12 : Annual Al import amount from 2012 to 2016, Thailand

Iron

Extraction rate of iron from ores increased suddenly in the year of 2000. Scientists expect global amount of Fe extract and amount of Fe in ores will be equal in 2032 due to the increased levels of extraction. Annual Fe demand expect to increase by 4% in 2021, Thailand which is 19 million tons in amount. But according to domestic Fe production data, local producers will only produce 7.5 million tons and there will be 11.5 million tons Fe shortage in Thailand. Annual Fe import amounts displayed in Figure 4.13.

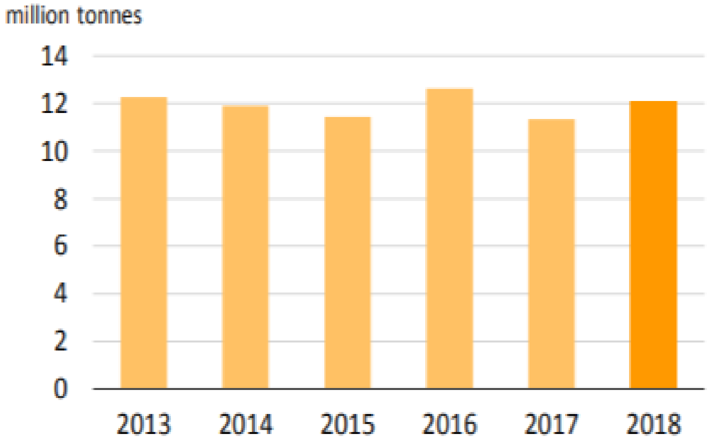

Figure 4.13 : Annual Fe import amount from 2013 to 2018, Thailand (Pollution Control Department, 2019)

Copper

Cu plays a significant role globally in technological applications because of high electrical conductivity. Unsustainable extraction rate generate negative impact on Cu resources. Identification of Cu reserves has increased from 2014 to 2019 due to the high demand (700-870 reserves in million metric tons). Annual Cu export amount has increased from 2010 to 2019 in 950 million tons at the same time import amount increased in lower amount (300 million tons) compared to exporteaiaeaiaea as illustrated in Figure 4.14. Compared to Fe and Al, Cu manufacturing in Thailand shows great improvement. Thailand exhibited the highest market size of end use Cu (332 tons) in ASEAN region (Metal bulletin). Therefor Cu in e-waste (LED lamp waste) has high possibility to recycle within the country.

Figure 4.14 : Annual Cu import amount from 2014 to 2018, Thailand

Zinc

Advance technological improvements in electronic and electrical equipment expect to add more Zn to their products. Expect market growth is high for Zn metal. Global Zn production reached into the amount of 12.9 metric million tons. As detailed in Figure 4.15, Zn production in Thailand has decreased into "0" in 2018. Currently there are no active mines in Thailand for Zn. Therefor end of life electronic and electrical equipment has probability to initiate urban mining process for Zn.

Figure 4.15 : Annual Zn data from 2014 to 2018, Thailand

Lead

Global market for Pb expected to reach for a significantly high value due to increased applications of Pb in several fields such as construction, Pb acid batteries and electronic equipment within the time period of 2018-2027. Fig. 4.16 shows the import amount of Pb. Thailand has the highest demand for Pb in the ASEAN region. There are no active mines for Pb extraction in Thailand. Pb leaching from e-waste would be a practical solution for fulfilling Pb demand to some extent.

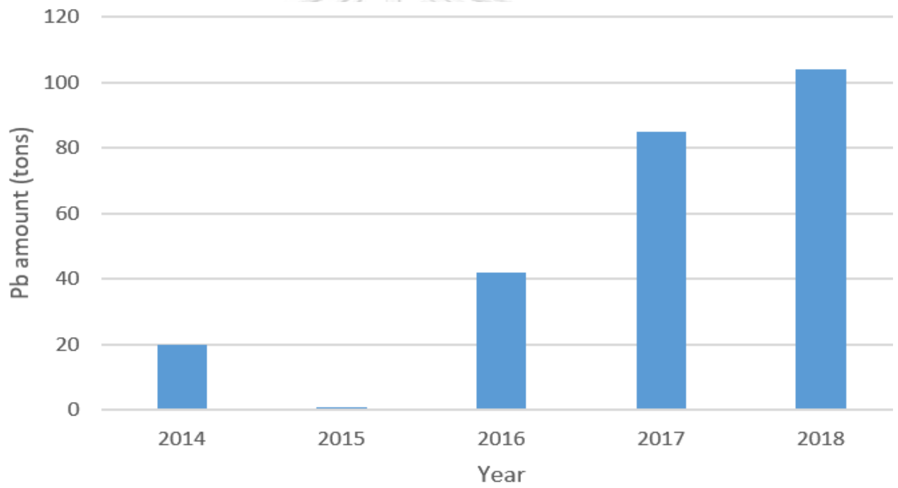

Figure 4.16 : Pb import amount to Thailand

4.3.1.4 Current situation of metal recycling in Thailand

Currently Thailand 4.0 policy structure support local economy in three ways; productive growth, inclusive growth and green growth. Metal recycling plants initiated under the green growth sector. Metal recovery industry in Thailand consider three types of metals such as precious, rare earth and base metals. The main targeted waste type in this policy is e-waste. In 2018, combination project of greening the metal recycling process in Thailand initiated by PCD and United Nations Industrial Development Program (UNIDP). Main components of the project are, policy and regulation generation for toxic emissions from metal recycling facilities, information distributing for the purpose of capacity building and implementing small projects on selecting best available technology for the metal recycling process. Results of this study intend to offer recommendation for 2 main components of the project (toxic emission from metal recycling and information distribution).

Recovery processes for Fe, base metals (Al, Cu, Pb and Zn) from LED lamps waste and possible hazards will be discussed in this section. First of all metal components should physically separate from LED lamp. Metal base, LED driver and LED chip should separate from plastic/ glass cover. After the separation, metal components should go size reduction procedure to increase the metal leaching availability and other material properties.

The most challenging part of metal recovering from LED lamp waste (small scale e-waste) is separation of small amount of metals from the equipment. Researchers from the University of British Colombia have proposed a flow sheet for recovering **Cu, Pb, Zn and Ag** based on their electrical conductivity and density (UBC News). Extraction of Cu from LED lamp via bio-hydrometallurgy technology discussed in the literature. Adapted Acidithiobacillus ferrooxidans bacteria is capable of bioleaching Cu from LED waste (Pourhossein & Mousavi, 2018). In 2019, researchers have designed chemical method for the recovery of Ag from LED lamps waste. Application of 30 $g.l^{-1}$ thiourea with 0.4% of ferric ions results 75% of extraction efficiency (Lee, Molstad & Mishra, 2018). Desilverization process has been applying in China to recover Ag from Pb frame in LED chip (https://patents.google.com/patent/CN102861759A/en). As results show 846 mg/kg Ag and 16,600 mg/kg Pb concentration in selected LED chips, desilverization process could apply to recover Ag and Pb in e-waste facilities, Thailand.

Improper recovery practices on LED lamp waste such as open burning and acid leaching treatments without proper controlled environment could contaminate soil, air and water resources. Open burning of LED sources and driver vaporized heavy metals such as Pb, Cd and Cr and generate pollution via heavy metal toxicity. Comparatively volatile metals in LED lamp waste such as Zn and Cd escape from waste as fly ash during the open burning scenario while Cr mostly stays in soil as metal exhibits comparatively low volatility rate (Cesaro *et al.*, 2019). Even though Pb has relatively mild volatility rate, trace level of emission links with high human toxicological impact (Wang *et al.*, 2017). Improper laptop recycling in Thailand has attributed to generate respiratory diseases among local community (INDEPENDENT, 2019). LED waste exhibits same levels of toxic metal (Cr and Pb) concentration as personal computers therefor improper management of LED waste will also contribute local's respiratory issues in future.

4.3.2 Hazardous waste assessment

Selected components (LED source and LED driver) from LED lamps went through toxicity characterization procedure to testify hazard metal concentration level and categorize LED as hazard or safe waste. Based on the results from TTLC leaching test, both LED driver and source could be classified as hazard waste under the Hazard Substances Act, 1992.

4.3.2.1 Comparison of toxic metal concentration levels in LED driver with regulatory limits

As stated in Table 4.7, LED driver exceeded TTLC standards for three metals, whereas Cu (65,766.67 mg/kg; limit: 2,500 mg/kg), Pb (8,767 mg/kg; limit: 1,000 mg/kg) and Zn (15,433 mg/kg; limit: 5,000 mg/kg). Concentration of Cu in LED driver is 65.79 times higher than the regulatory limit at the same time highly toxic Pb contain in 8 times greater concentration compared to the regulatory level.

Zn content is thrice as much as TTLC level. Ba, Cd, Cr, Ni and Ag show lower concentration measures compared to TTLC values. Therefor those stated metal contents in LED driver are within safe limits.

Table 4.7 : Metal concentration values of LED driver samples

Metal	LED Driver 1 (D1)	LED Driver 2 (D2)	LED Driver 3 (D3)	Average concentration	TTLC level
Aluminum (Al)	62,000	69,100	66,200	65,766.67	n/a
Barium (Ba)	556	566	532	551.33	10,000
Cadmium (Cd)	0.7	0.7	0.8	0.73	100
Chromium (Cr)	738	412	454	534.67	2,500
Copper (Cu)	170,000	189,600	133,800	164,467	2,500
Iron (Cesaro *et al.*)	26,200	33,400	18,200	25,933	n/a
Lead (Pb)	4,354	4,146	17,800	8,767	1,000
Nickel (Ni)	800	966	612	793	2,000
Silver (Ag)	75.3	92.2	70.6	79.4	500
Zinc (Zn)	18,200	15,100	13,000	15,433	5,000

Fig. 4.17 compare regulatory limits with leachate results of LED drivers.

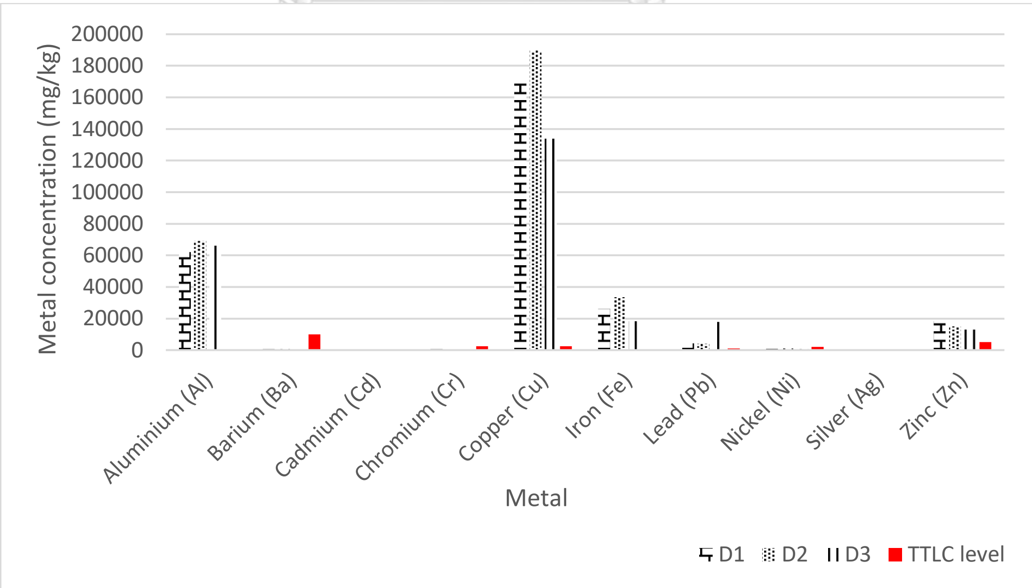

Figure 4.17 : Comparison of regulatory limits with the metal concentrations_in selected 3 samples of LED drivers

Restriction of Hazardous Substances Directive (RoHS) intends to reduce hazard material concentration in electronic and electrical appliances. RoHS directives have standard values for 10 hazard substances which are, lead, cadmium, mercury, hexavalent chromium, poly brominated biphenyl, poly brominated diphenyl, Bis(2-Ethylhexyl) phthalate, Benzyl butyl phthalate, Dibutyl phthalate and Diisobutyl phthalate. Lead, cadmium and chromium present in LED components. Concentration measures of Cd (0.73; limit: 100) and Cr (534.67; limit: 1000) in LED driver are lower than RoHS directives limits but Pb surpassed RoHS limit (8,767; limit: 1000). Therefor under RoHS directives, LED driver could labeled as hazard waste and authority bodies should raise concerns over the hazard concentration levels in LED drivers.

4.3.2.2 Comparison of toxic metal concentration levels in LED sources with regulatory limits

TTLC test conducted on three LED sources from selected lamps to evaluate the average concentration levels. Based on the results shown in table 4.8, Cu (209,200 mg/kg; limit: 2,500 mg/kg), Pb (16,600 mg/kg; limit: 1,000 mg/kg), Ag (846 mg/kg; limit: 500 mg/kg) and Zn (39,204 mg/kg; limit: 5,000 mg/kg) metal concentrations exceed the TTLC level. There is a significant difference between Cu level in LED source and TTLC limit whereas Cu concentration in LED source is 83.68 times higher than the standard. Detected Pb concentration level is 16.6 times higher than the regulatory level while measured Zn level is 7.8 times higher than TTLC level. Figure 4.18 illustrated the comparison of regulatory limits with metal concentrations in LED sources

Table 4.8 : TTLC leachate results comparison with regulatory limit (LED Source)

Metal	**LED source 1 (L1)**	**LED source 2 (L2)**	**LED source 3 (L3)**	**Average concentration**	**TTLC level**
Aluminum (Al)	5,380	3,240	3,173	3,931	0
Barium (Ba)	37	26.6	33	32.2	10,000
Cadmium (Cd)	0.6	0.5	0.5	0.53	100
Chromium (Cr)	43.8	34.7	36.2	38.23	2,500
Copper (Cu)	206,800	216,800	204,000	209,200	2,500
Iron (Cesaro *et al.*)	77,100	51,900	51,000	60,000	0
Lead (Pb)	20,600	14,200	15,000	16,600	1,000
Nickel (Ni)	1,362	1,614	1200	1,392	2,000
Silver (Ag)	484	1,206	847	846	500
Zinc (Zn)	102,800	813	14,000	39,204	5,000

Metal concentrations in LED source compared to RoHS limits as follows, Cd (0.53 mg/kg; limit: 100) and Cr (38.23 mg/kg; limit: 1000) metal concentrations are well below the RoHS limits. But Pb identified in hazard level under the RoHS standards (16,600 mg/kg; limit: 1000). Therefor LED sources could be categorizing as hazard under RoHS regulations.

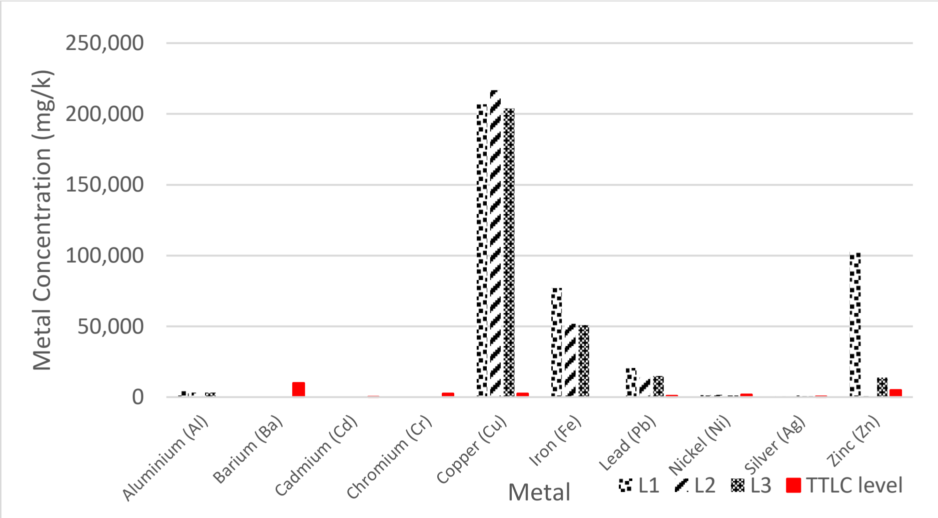

Figure 4.18 : Metal concentrations in 3 selected LED sources

4.3.2.3 Toxic metal concentration differences between LED driver and LED source

As Thailand is in the phase of proposing recommendations to the draft act of waste electrical and electronic equipment management (Manomaivibool & Vassanadumrongdee, 2011), data on hazard characteristics of LED waste intend to generate recommendations for the final version of the draft of WEEE act. Under section 13 of draft of WEEE act, concerns should raise over the situations such as redesigning products to meet environmental friendly output. Figure 4.19 shows that LED driver and source has exceeds the regulatory toxic metal concentration levels (TTLC) therefor authorities should initiate enforcements over LED lamp manufactures to reevaluate metal concentrations in their products and to manage the level of toxic metals under the regulatory limits. Research and developments conducting in the field of LED lamps to improve brightness, effectiveness and lifetime. Amount of metals play a major role in enhancing the LED lamp performances at low cost accordingly toxicity level of LED lamp waste will increase in future (Mittal *et al.*, 2019). Future technological advancements of high efficient and stable LED chips mainly based on adding inorganic materials in high amounts such as Cs, Pb and Ga. (Cao et al, 2019). And also adding metals as Nano-crystals to the LED source is gaining attention from manufactures due to high effectiveness. But toxic metals as nanoparticles have high potential to negatively impact on human health and eco systems (Kabir et al, 2018). These practices could generate more hazard waste in future if not regulated properly by authorities.

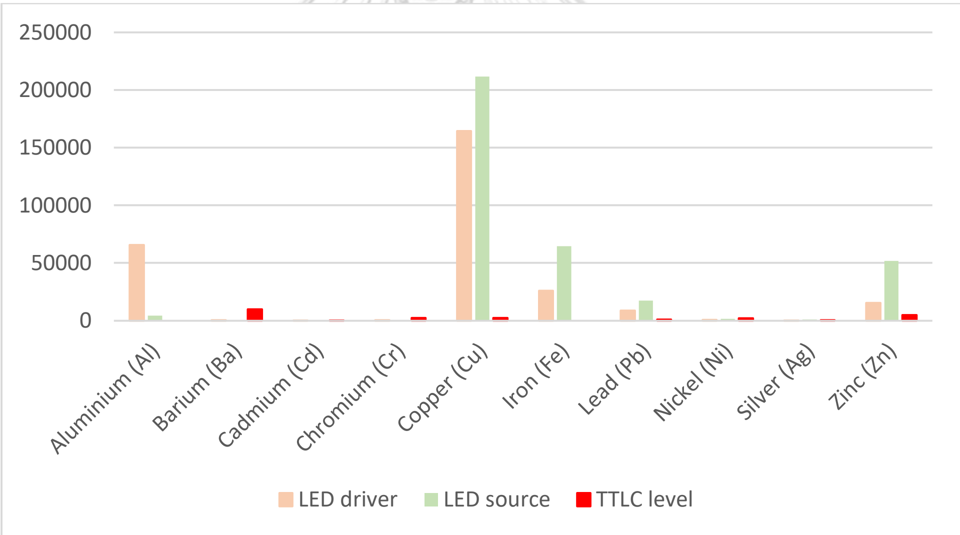

Figure 4.19 : Hazard characterization of LED source and driver.

Thai government proposed plans on increasing sustainable electronic and electrical equipment production and consumption in several ways, encouraging private sector in green supply and eco-designs, regulating environmental impacts during manufacturing and use phase and suggest environmental friendly waste management system. Results of LED drivers and sources from TTLC test suggest redesigning and sustainable waste management procedure for LED lamps waste which aligns with authorities suggestions on proper products manufacturing and consumption.

Open dumping of LED waste capable to discharge air pollutants to atmosphere and generate health impact on the community residents near landfills. LED lamps treated as environmental friendly product due to the positive influence on energy saving, mercury demolishment from daily usage and reduced waste stream. On the other hand LED waste mismanagement pollute environment.

4.3.2.4 Comparison of hazard characteristics with other small electronic and electrical appliances

Small scale electrical and electronic appliances link with high toxicity potential due to the high levels of toxic metal concentrations. According to Thai regulations, electronic and electrical equipment grouped under hazardous waste nevertheless loose enforcements allow to mismanage e-waste within the country. This section weight the difference toxic metal concentrations between LED lamp waste and the most common e-waste types to rank in the list of hazard potential based on the TTLC results.

Technological advancements, rapid changes in people's lifestyle and e-waste importing practices has raised the amount of e-waste in Thailand. Based on the e-waste estimation that conducted in Thailand, end of life mobile phones and computer PCBs play a major role in e-waste stream. Government agencies and commercial sectors concern most on toxicity of CFL lamp waste, disposed mobile phones and computer parts.

As described in the Table 4.9, levels of metals in waste mobile phones for Al, Ba, Cr, Cu, Fe, Pb, Ni, Ag and Zn ranged from 29,942 to 45,281, 1,617 to 15,711, 201 to 43,087, 762 to 25,180, 29,997 to 39,575, 116 to 176, 11,714 to 27,596, 26 to 347 and 2,278 to 6,278 mg/kg, respectively. Cd was not identified as a building material in mobile phones. In selected PCBs from computer Intel series, Al metal concentration levels range from 32,566.7 to 52,400 mg/kg. Similar amount of Ba concentration compared to mobile phones identified in computer parts (645.3-2,720 mg/kg). The highest level of Cd concentration (60.6 mg/kg), Cu concentration (241,000 mg/kg), and Pb concentration (27,966.7 mg/kg) measured in PCBs from Intel 800 series. Maximum Cr concentration (2882.7 mg/kg) detected in Intel series 900.

Table 4.9 : Comparison of leachate from LED lamp waste and other selected e-waste

E-waste type	Metal concentration (mg/kg)									
	Al	Ba	Cd	Cr	Cu	Fe	Pb	Ni	Ag	Zn
LED Lamp waste										
LED driver	65,766.7	551.3	0.73	534.67	164,467	25,933	8,767	793	79.4	15,433
LED source	4,310	31.8	0.55	39.25	211,800	64,500	17,400	1,488	845	51,807
CFL lamp waste										
Total lamp	31,700	17.8	-	1.1	111,000	12,800	3,860	120	12.2	34,500
Mobile phones										
Samsung Galaxy Note 3N 9000	45,281	15,711	n/d	201	762	29,997	116	11,714	347	2,278
iPhone 5C	29,942	1,617	n/d	43,087	25,180	39,575	176	27,596	26	6,278
Computer Intel series (PCB)										
Intel 400	32,566.7	645.3	11.6	288	240,000	31,066.7	26,833.3	2133.3	201	39,933.3
Intel 800	52,400	2020	60.6	379.3	241,000	44,033.3	27,966.7	4213.3	528.7	46,866.7
Intel 900	44,800	2720	8	2882.7	189,000	41,666.7	8956.3	4233.3	459	23,700

Toxic metal concentration variation illustrated in Figure 4.20. The concentration value for Cu in e-waste deviate from regulatory limit (TTLC) in each e-waste type except Samsung Galaxy Note 3N 9000 mobile phones. Cu content in LED source (211,800 mg/kg) stated as the second highest in the list and LED driver ranked above mobile phones (Samsung & iPhone) and fluorescent lamps. Metals such as Fe and Zn contain in LED source high concentrations compared to mobile phones, PCBs in computers and fluorescent lamps. Concentration levels of heavy metals (Cd, Pb and Cr) in selected e-waste compared to LED waste fluctuate in different ranges based on the applications in selected electronic and electrical appliances. Concentration of Cr in LED lamp waste is notably lower than regulatory limit. Neurotoxic Pb amount in LED source and driver is higher than mobile phones and fluorescent lamps. LED source exhibits high Cr concentration compared to PCBs (Intel 900 & iPhone 5C).

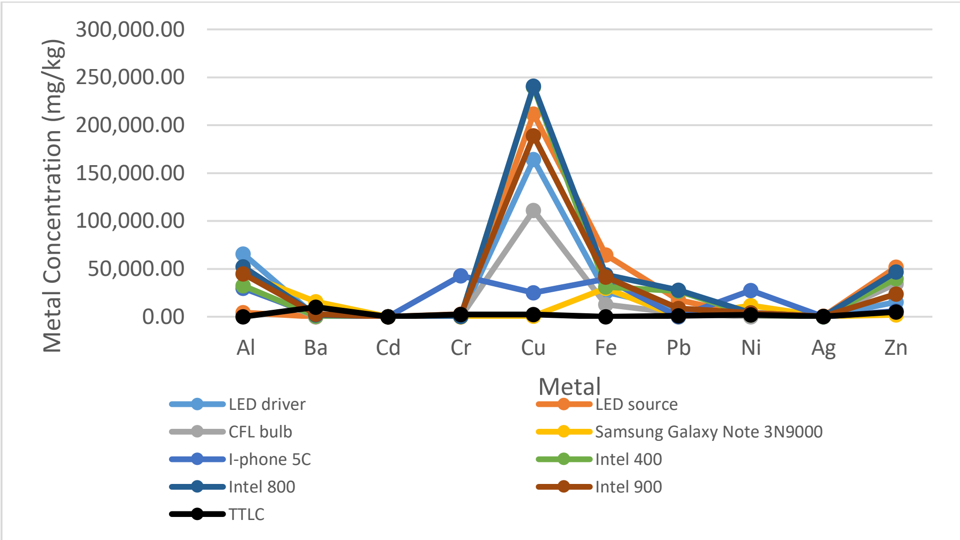

Figure 4.20 : Toxic metal concentrations between LED lamp waste and other major E-waste

CFL-LED lamps waste management

Compact fluorescent lamps phased out from daily usage in 2012, Thailand due to the presence of toxic mercury (Hg) in CFL. LED was introduced by authorities to save energy and reduce the toxic impact from Hg on environment and human health. Figure 4.20 explains that LED driver and source contain high concentration of Ba, Cr, Cu, Fe, Pb, Ni, and Ag. Amount of Al in total CFL is lower than LED driver but higher than LED source. Zn concentration in CFL is lower compared to LED source but higher than LED driver. Overall analysis of toxic metal concentrations in CFL and LED lamp waste shows that LED waste include high level of concentration in each metal compared to CFL waste. Pollution Control Department, Thailand collaborated with Japanese government to tackle the fluorescent lamp waste issue. Waste generators have to register for the collection procedure then Bangkok Metropolitan Authority (BMA) collect and transfer waste fluorescent lamps for proper disposal or pilot recycling procedure as detailed in Figure 4.21. Policy makers should give equal concerns over toxicity and mismanagement of LED and CFL waste.

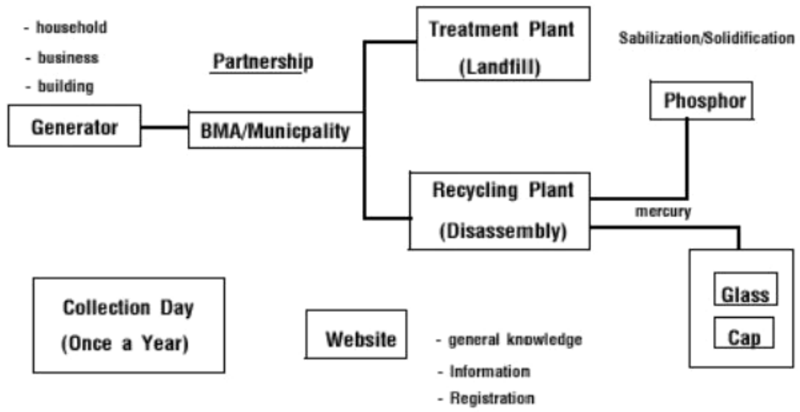

Figure 4.21 : Guidelines for fluorescent lamp management in Thailand

Mobile phones-LED lamps waste management

Public awareness on the management of EoL mobile phones in Thailand described in Fig. 4.22, based on the responses from Thai community, most desirable option for EoL mobile phones is keeping it in home.

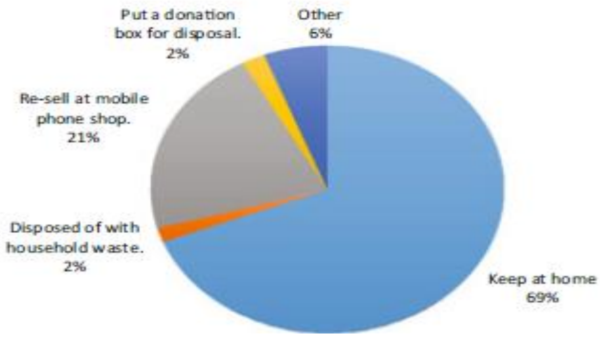

Figure 4.22 : EoL mobile phone management options in Thailand (Sangprasert & Pharino, 2013)

Researchers also evaluate perceptions that will motivate people to participate in sustainable practices on EoL mobile phones management. As shown in Fig. 4.23, 27.35% of people would prefer to get back money or other benefits (discounts or voucher) from the recycling process of mobile phone wastes. 34.85% amount of people (10.19% + 24.66%) believe raising awareness on environmental impact due to toxicity of mobile phone waste will prevent mismanagement of EoL mobile phones. As LED waste contains increased concentrations of Pb and Zn compared to mobile phones (Samsung Galaxy Note 3N 9000 & iPhone 5C), consciousness on LED waste toxicity among the community will help authorities to implement a proper plan for LED lamp waste management in Thailand. Extended producer responsibility principle apply by AIS for mobile phone waste in Thailand. Several collection stations has created from AIS under the campaign of “Throw Away E-waste with AIS”. Since LED lamps exhibit similar level of toxicity as mobile phones, voluntary approaches from manufactures on EoL LED lamps will be helpful to tackle the excess waste problem.

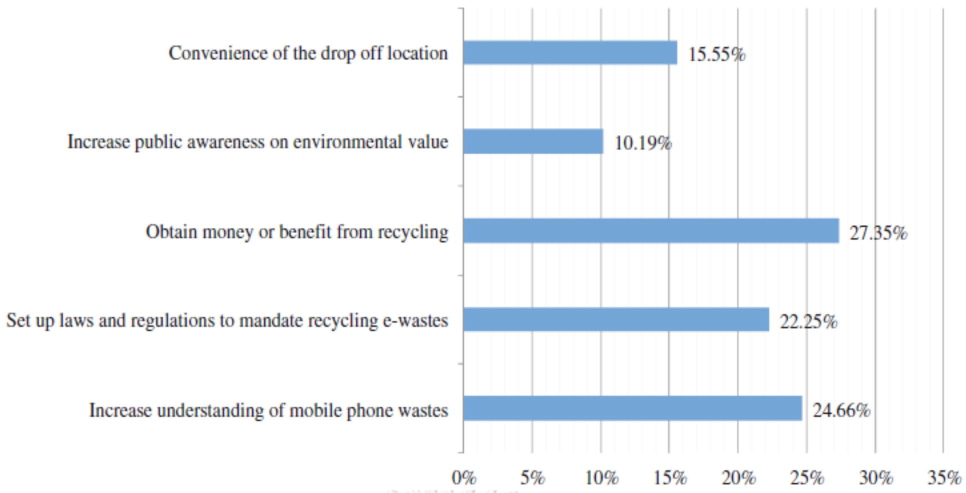

Figure 4.23 : Approaches for sustainable EoL mobile phones management

Computer PCBs – LED waste management

19.1 Million Computers were in use in Thailand during the year of 2010 (Culver, 2005). Authorities have taken considerations over the management of computer waste. Based on the survey that conducted to find out the public perception on computer waste and environmental impact, 78% participants acknowledged about the toxicity of computer waste whereas 64.87% expect proper recycling plan to prevent environmental impacts and recover precious metals from waste. Fig. 4.24 describes PCBs management options in Thailand.

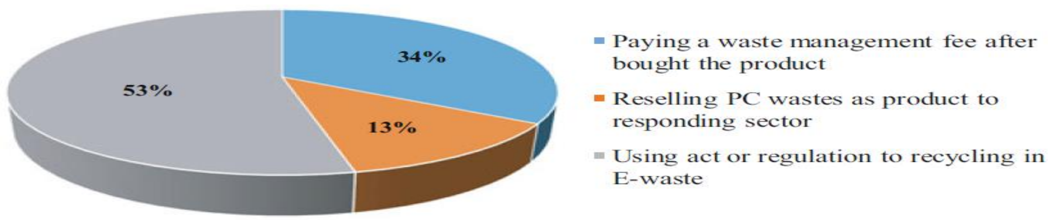

Figure 4.24 : EoL options for computer waste in Thailand (Pharino, 2017)

Since LED components show same level of concentration as computer PCBs in several metals (Al, Cu, Pb, Cr and Fe), management options for computer waste could also suitable for LED waste management except reusing option.

4.3.3 Eco – Human Toxicity Impact via USEtox model

In this sector, toxicological impact modelling results will discussed based on the following assumption explained in Fig. 4.25, emitted metals from LED lamp waste will remain within the emitted compartment without transferring from one media to another media via dispersion and advection. And also modeling conducted based on the assumption that there was no physical, chemical or biological transformation of metals within the compartment.

USEtox model specifically selected for the toxicological impact assessment process due to the highest number of characterization factors availability. And also USEtox is a free modeling tool which readily available for the scientific use.

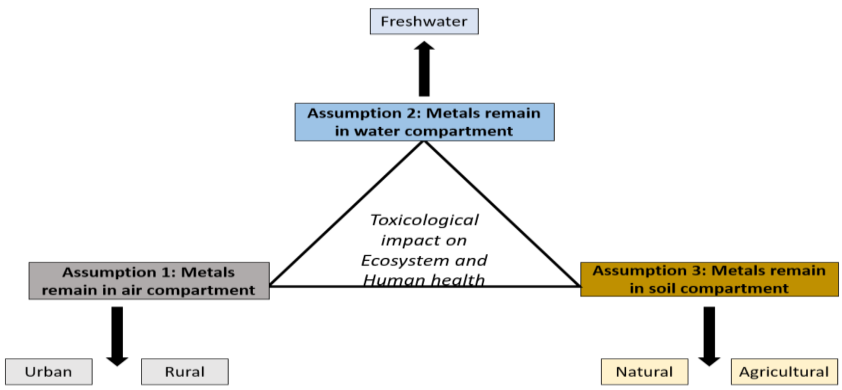

Figure 4.25 : Assumption generated in this study during USEtox model calculation process

Metal concentration measures from the experimental (leaching) procedure apply as input data to model toxic impact on ecosystem and human health. USEtox model. Results were generated with the support of toxicological effect and environmental fate & exposure data library.

4.3.3.1 Leaching of metals from LED lamps waste to soil compartment via open dumping

Thailand is experiencing e-waste management issues as illegally imported e-waste pile up improperly in landfills and contaminate soil ecosystem. Lack of rigid law enforcements on e-waste has initiated dumping hazard waste without prior treatments (Nikkei Asia, 2018). Researchers have evaluated leaching capacity of major metals present in e-waste using landfill columns. According to the results, Al, Pb, Cr, Ni and Zn leach readily from e-waste to soil (Li *et al.*, 2009). But in this study, assumption made that each metal leach in same amount to the soil.

Toxicity impact from metals leaching into soil compartment calculated based on two different scenarios. Emission to natural soil and agricultural soil. Soil qualities and metal concentrations in LED lamp waste components are main two influential factors that change the soil impact quantity. Toxicological impact on ecosystem and human health link with each metal contain in LED driver and source (as stated in literature review, the most toxic metals contain in LED driver and source components therefor toxicity impacts calculated for those components) stated in Table. 4.10.

Table 4.10 : Toxicity impact quantities of metal leaching from LED waste in soil compartment

Metal	LED driver				LED source			
	Eco toxicity impact score for,		Human health toxicity impact score for,		Eco toxicity impact score for,		Human health toxicity impact score for,	
	Natural soil	Agricultural soil	Natural soil	Agricultural soil	Natural soil	Agricultural soil	Natural soil	Agricultural soil
Al	177221.9	177221.9	n/a	n/a	10592.89	10592.89	n/a	n/a
Ba	24.68557	24.68557	3.68E-05	3.7E-05	1.441733	1.441733	2.15E-09	2.16E-09
Cd	2.593555	2.593555	6.28E-06	0.00061	1.874433	1.874433	4.54E-09	4.41E-07
Cr	99.71036	99.71036	0.003552	0.003741	7.129539	7.129539	2.54E-07	2.68E-07
Cu	30062.81	30062.81	0.000138	0.06115	38239.53	38239.53	1.75E-07	7.78E-05
Fe	29887.69	29887.69	n/a	n/a	69149.78	69149.78	n/a	n/a
Pb	205.5908	205.5908	0.003503	1.764963	389.2788	389.2788	6.63E-06	0.003342
Ni	241.5861	241.5861	6.09E-05	0.000668	424.0704	424.0704	1.07E-07	1.17E-06
Ag	48.11282	48.11282	9.88E-05	0.02861	512.6379	512.6379	1.05E-06	0.000305
Zn	4431.53	4431.53	0.009922	1.052325	11257.29	11257.29	2.52E-05	0.002673

The main difference between natural soil and agricultural soil is the management of components in favor of crop cultivation. Increased amount of Nitrogen, Phosphorus and Potassium (NPK) application to agricultural soil simulate the nitrification and denitrification reactions in agricultural soil whereas reactions such as mineralization occurred in natural soil in lower rate. Eco-toxicological impact from inorganic metals in natural and agricultural soil has not studied in details within scientific literature therefor same characterization factor use to calculate eco-toxicological impact score. Whereas in the end same eco-toxicological impact scores could see in natural and agricultural soil as detailed in Table. 4.10.

Eco-toxicological impact in natural & agricultural soil due to the emission of metals from LED driver and source illustrated in Figure 4.26. The highest possible eco-toxicity shown by Al metal leaching from LED driver (177,221.9 PAF.m^3.day.kg^{-1}). Al shows plant toxicity by decreasing the growth rate of roots, phytotoxicity (reduce plant's mineral absorption capability) and slow down elongation of plant cells. Al links with significant level of toxic impact on microbe communities in soil. Whereas, Al capable of breaking the bond between symbiotic bacteria (*Rhizobium* and *Bradyrhizobium*) – plants and Mycorrhiza; linkage between fungus and plants which help plant's nutrition supply (Barabasz *et al.*, 2002). Al toxicity from LED source is insignificant as the concentration is low compared to the driver. Fe (29,887.69 – 69,149.78 PAF.m^3.day.kg^{-1}), Cu (30,062.81–38,239.53 PAF.m^3.day.kg^{-1}) and Zn (4,431.53-11,257.29 PAF.m^3.day.kg^{-1}) also exhibited notable eco-toxic impact. Iron high eco-toxicity on crops like rice by reducing 50% of grain's weight. As the main agricultural crop in Thailand is rice, excess emission of Fe should be concerned by local environmentalists to prevent possible negative impact on rice (Fageria *et al.*, 2008). Cu bind with clay particles in soil and persists in soil due to low solubility compared to other metals. Cu shows toxicity to plants by reducing seed germination rate and plant growth. Zn concentration above 10 mg/kg in soil is stated as potentially harmful for plant health.

And also soil microbes show less tolerance for Zn compared to Cu in soil. LED driver and source exhibit same level of toxicities for Fe, Cu and Zn metals on the other hand LED driver links with high amount of Al eco-toxicity impact.

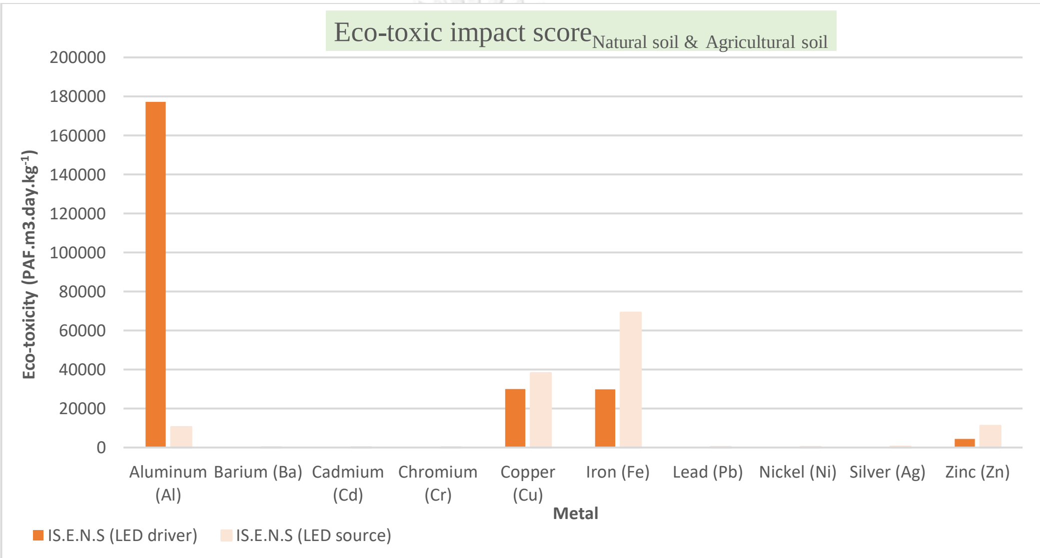

Figure 4.26 : Eco-toxicity impact of metal leaching from LED driver and source into natural & agricultural soil

Human toxicity impact due to different levels of metals in agricultural and natural soil has studied by scientists separately. Therefor different characterization factors exist in literature for calculating human toxicity impact scores for metals in agricultural and natural soil.

Figure 4.27 illustrated human-toxic impact score for the metal emission from LED's to agricultural soil. The highest toxic impact score shown by Pb leaches from LED driver (1.765 cases/kg emitted). Pb accumulation in agricultural soil initiate a threat toward food safety. Pb in food crops could negatively impact on human nervous system and relates with carcinogenic and cardiovascular diseases among the population (Rai *et al.*, 2019). Zn leaches from LED driver shows the second highest human-toxic impact score whereas Zn phytotoxicity in food crops associates with cytotoxicity (being toxic to body cells) in human body.

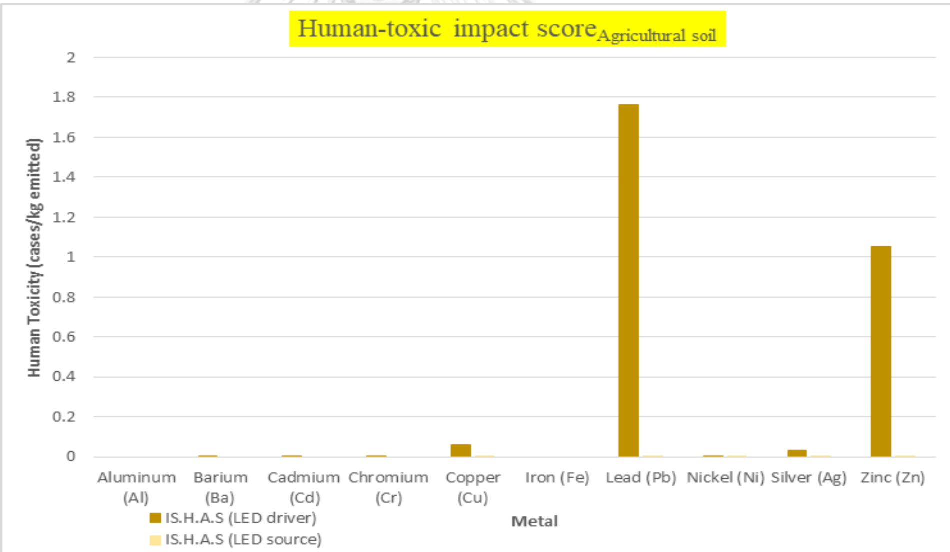

Figure 4.27 : Human-toxicity impact of metal leaching from LED driver and source into agricultural soil

Human health impact due to metal emission to natural soil described in Figure 4.28. Toxicological concentrations of metals in natural soil closely effect on construction labors, farmers or miners due to their direct contact with contaminated soil. Zn exhibits the highest human toxicity in natural soil (0.009922 Cases/kg emitted).

Zn capable of penetrating the skin cells via dermal contact. Pb form a bond with anionic fact cells in skin tissues and long term of exposure to Pb will increase the carcinogenic risk (Wuana & Okieimen, 2011). Cr in the form of hexavalent (VI) is more toxic to absorb via skin. Cr toxicity in skin appear as ulcers or allergy (Shelnutt *et al.*, 2007). Human health toxicity impact due to metals in natural soil directly links with the occupational exposure (Steffan *et al.*, 2017).

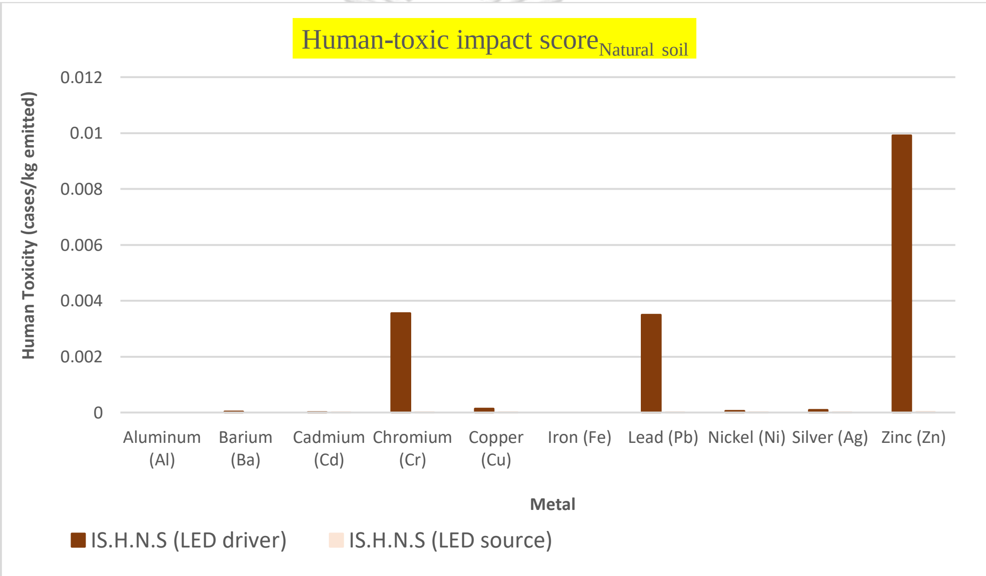

Figure 4.28 : Human toxicity impact from metal emission to natural soil

As detailed in Figure 4.27 and Figure 4.28, metal leaching from LED driver is the main reason for human-toxicity impact via natural and agricultural soil while LED source plays a notable role in eco-toxicity impact in natural and agricultural soil.

4.3.3.2 Emissions of metals from LED lamps waste to air compartment via open burning activities

Open burning of e-waste is the most famous method for separating metals from electrical and electronic equipment in Thailand. Illegal e-waste recycling workers in Buriram Province, Thailand exhibit respiratory problems due to toxic metal particles emitted via open burning activities (Bungadaeng *et al.*, 2019). According to the UN country report on hazardous waste, the most prominent e-waste management activity in the country is open dumping or open burning (Wichienpet, 2019).

In this study assumption made that each metals in LED driver and source emit to air compartment completely. Based on the assumption calculations made in two ways for urban and rural air compartments. Quantitative toxicity impacts displayed in Table. 4.11.

Table 4.11 : Toxicity impact quantities of metal emission from LED waste into air compartment

Metal	LED driver				LED source			
	Eco toxicity impact score for		Human health toxicity impact score for		Eco toxicity impact score for		Human health toxicity impact score for	
	Urban air	Rural air	Urban air	Rural air	Urban air	Rural air	Urban air	Rural air
Al	119,099.6	120,393.9	n/a	n/a	7.12E+03	7.20E+03	n/a	n/a
Ba	16.94872	16.96925	4.89E-08	3.00E-05	9.90E-01	9.91E-01	2.86E-09	1.75E-09
Cd	1.775026	1.777667	4.29E-08	4.46E-05	1.28E+00	1.28E+00	3.1E-08	3.23E-08
Cr	68.23147	68.30773	5.76E-06	2.52E-03	4.88E+00	4.88E+00	4.12E-07	1.8E-07
Cu	20,397.62	20,440.52	4.08E-06	4.16E-03	2.59E+04	2.60E+04	5.19E-06	5.29E-06
Fe	20,236.72	20,297.39	n/a	n/a	4.68E+04	4.70E+04	n/a	n/a
Pb	138.4039	139.1713	0.000121	1.19E-01	2.62E+02	2.64E+02	0.000229	0.000226
Ni	165.2486	165.557	1.26E-07	8.38E-05	2.90E+02	2.91E+02	2.21E-07	1.47E-07
Ag	32.68117	32.73723	1.93E-06	1.97E-03	3.48E+02	3.49E+02	2.06E-05	2.1E-05
Zn	3,017.259	3,027.996	7.2E-05	7.64E-02	7.66E+03	7.69E+03	0.000183	0.000194

Characterization factors for eco-toxicity impacts on rural and urban air are different. Therefor eco-toxic impact for urban and rural air calculated based on different but relatively similar characterization factor values which resulted different but similar range of eco-toxic impact scores for urban and rural air.

Figure 4.29 reveals that Al emission via open burning of LED driver generate the highest eco-toxic impact in urban and rural air compartments (119,099.6 & 120,393.9 PAF.m^3.day.kg^{-1}). Al particulate matters resulting from open burning capable of stimulating wildfires (Herndon & Whiteside, 2018). Al in atmosphere reacts with oxygen and produce insoluble aluminum oxide (Al_2O_3). Fe emission from LED source stated as the second highest eco-toxic impact on urban and rural atmosphere (4.68E+04 & 4.70E+04 PAF.m^3.day.kg^{-1}) while Cu from LED source ranked in 3^{rd} place (2.59E+04-2.6E+04 PAF.m^3.day.kg^{-1}). Burning of Fe and Cu produce inorganic particles capable of absorbing dioxins in atmosphere these complex dioxins have high toxicity to aquatic animals and reproduction rate of birds (White & Birnbaum, 2009). Eco-toxicological impact scores for metal Fe, Cu and Zn mainly related with metal emission due to the open burning of LED source. Therefore, awareness should be shared among the community to avoid burning practices on waste LED sources though the appearance of LED sources look safe.

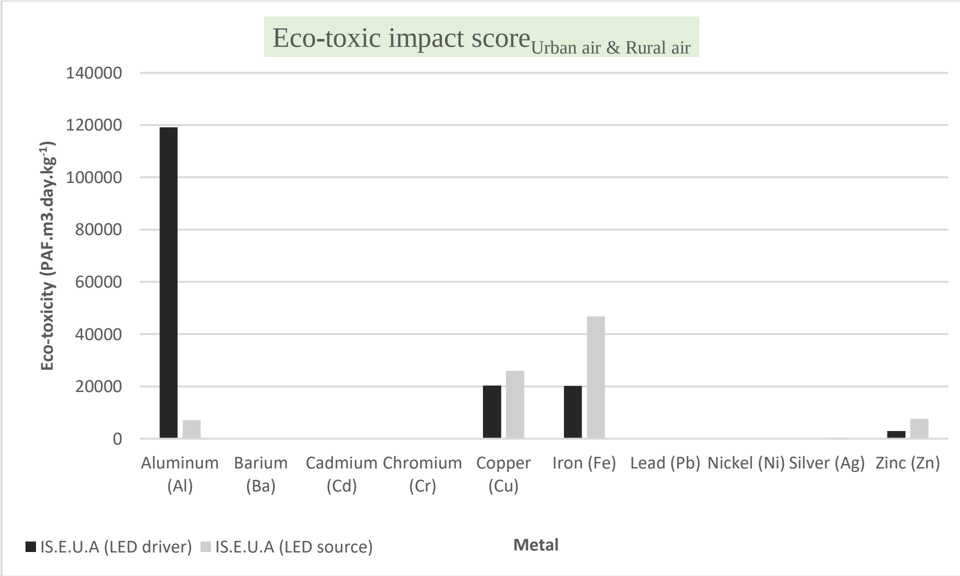

Figure 4.29 : Eco-toxicity impact from metal emission to urban & rural air

There is a significant difference between human-toxic impact score via metal emission to urban and rural air compartments. Fig. 4.30 discussed the human toxic impact score in urban air. In urban environment, number of pollution sources are high and atmosphere is more concentrated due to the limited area in cities (Lee & von Lehmden, 1973). Therefore, even trace emission of pollutant could generate a high toxicological impact in urban atmosphere. Pb emission from LED source contribute to the highest human-toxic impact in urban air section (0.000229 Cases/kg emitted). In Thailand Pb has detected in hazard level in Bangkok atmosphere due to the emission from mobile sources, industries and cremations (ASIA NEWS NETWORK, 2019). Long term inhalation of Pb particles could permanently damage neural network formation of unborn children. Zn emission from LED sources also exhibits second highest human-toxicity in urban air due to the high concentration level of Zn in urban environment from sources such as coal power plants, automobile sources and tire wears. Zn isotope degrade urban air quality and potential for short term reversible disease called metal fever and long term exposure will decrease the rate of immune functions that fight against lower respiratory infections (Cooper, 2008). Open burning of LED sources generates high human-toxicity impact than LED drivers.

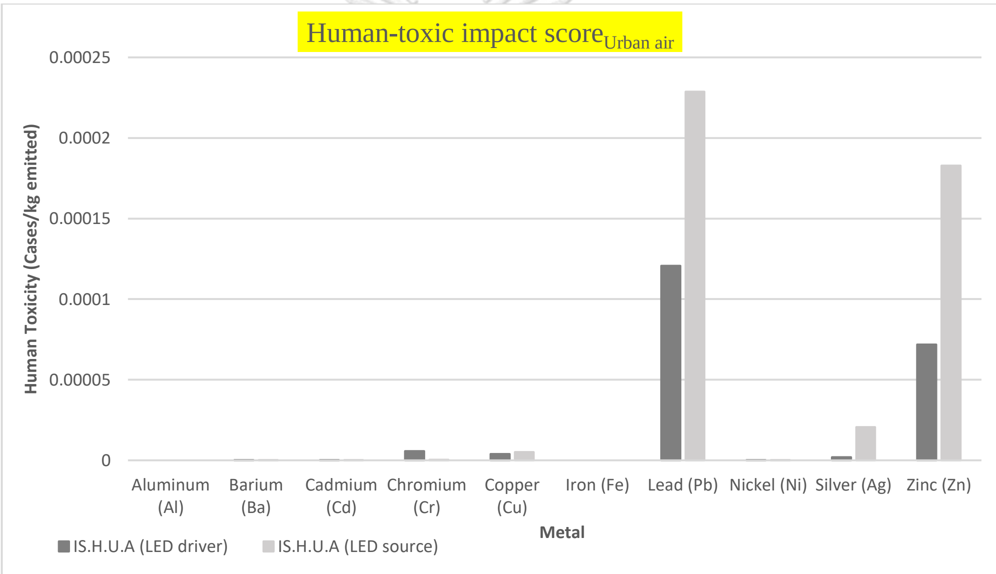

Figure 4.30 : Human-toxicity impact from metal emission to urban air

As detailed in Figure 4.31, Pb emission from LED driver to rural air compartment shows the toxicity level as 0.000121 Cases/kg emitted and also Zn displays 7.2E-05 Cases/kg emitted toxicity level. LED source has not exhibited notable human-toxicity impact in rural air section as LED driver.

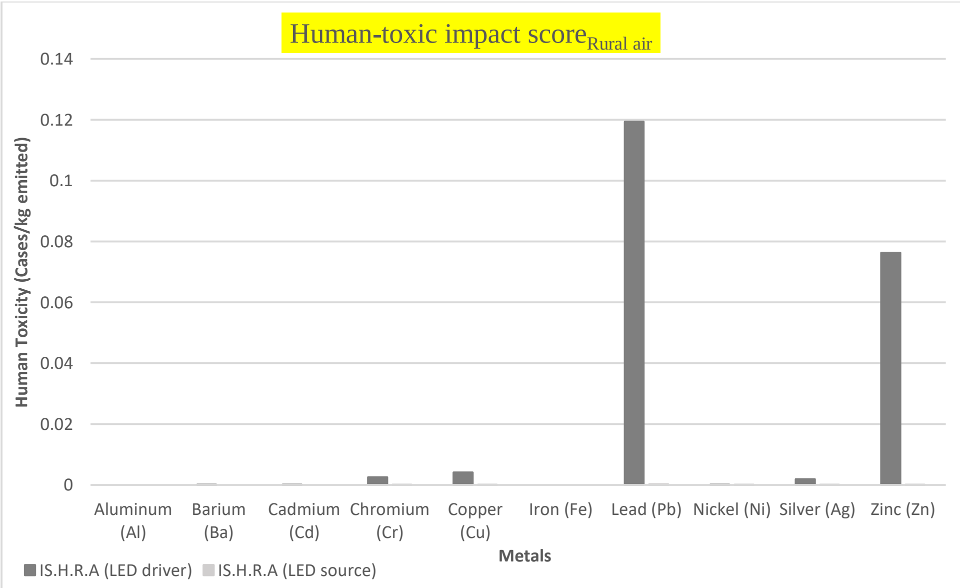

Figure 4.31 : Human toxicity impact from metal emission to rural air

4.3.3.3 Contamination of metals from LED lamps waste to water compartment due to the disposal in freshwater bodies

USEtox model contain inorganic input data for only freshwater toxicity calculation. In this sector assumption made that LED driver and source dumped into freshwater bodies such as rivers, wetlands and lakes. Freshwater bodies provide drinking water for communities and 40% of fish species live in these water bodies. Chao Phraya River stated among the most polluted rivers in world. Dumping e-waste into freshwater bodies could contaminate surface level freshwater bodies due to toxic metals. Eco-toxic and human-toxic impact scores due to metal contamination from LED source and driver stated in table 4.12.

Table 4.12 : Toxicity impact quantities of metal emission from LED waste into freshwater compartment

Metal	LED driver		LED source	
	Eco toxicity impact score for freshwater	Human health toxicity impact score for freshwater	Eco toxicity impact score for freshwater	Human health toxicity impact score for freshwater
Al	300,616.2	n/a	1.80E+04	n/a
Ba	49.94727	7.46E-08	2.92E+00	4.35E-09
Cd	5.209419	1.26E-08	3.76E+00	9.12E-09
Cr	201.3547	7.17E-06	1.44E+01	5.13E-07
Cu	59314.22	2.72E-07	7.54E+04	3.46E-07
Fe	58053.24	n/a	1.34E+05	n/a
Pb	381.6048	6.5E-06	7.23E+02	1.23E-05
Ni	482.2387	1.22E-07	8.47E+02	2.13E-07
Ag	95.58839	1.96E-07	1.02E+03	2.09E-06
Zn	8581.587	1.92E-05	2.18E+04	4.88E-05

Eco-toxicity impact score in freshwater bodies illustrated in Figure 4.32. Al contamination of freshwater from LED driver generate the highest eco-toxic impact (300,616.2 PAF.m^3.day.kg^{-1}). Al responsible for freshwater plant toxicification and also negative impact on digestion process of freshwater invertebrates (Gensemer & Playle, 1999). LED source appeared to be more hazard for metals such as Fe, Cu and Zn 1.34E+05 PAF.m^3.day.kg^{-1}, 7.54E+04 PAF.m^3.day.kg^{-1} and 2.18E+04 PAF.m^3.day.kg^{-1}, respectively. Fe promote growth of algae blocking the pathway of sunlight to freshwater plants, killing aquatic life and increasing the acidity of water (Cadmus *et al.*, 2018). Cu on the other hand acute toxic metal for freshwater fish species by accumulating in cells and forming irreversible changes in cell bodies. Zn toxicity in freshwater appear to specifically target on freshwater fish and insects species.

According to a study conducted in China, Cu, Fe and Zn has identified as high toxic metals for freshwater ecosystem (Su *et al.*, 2017).

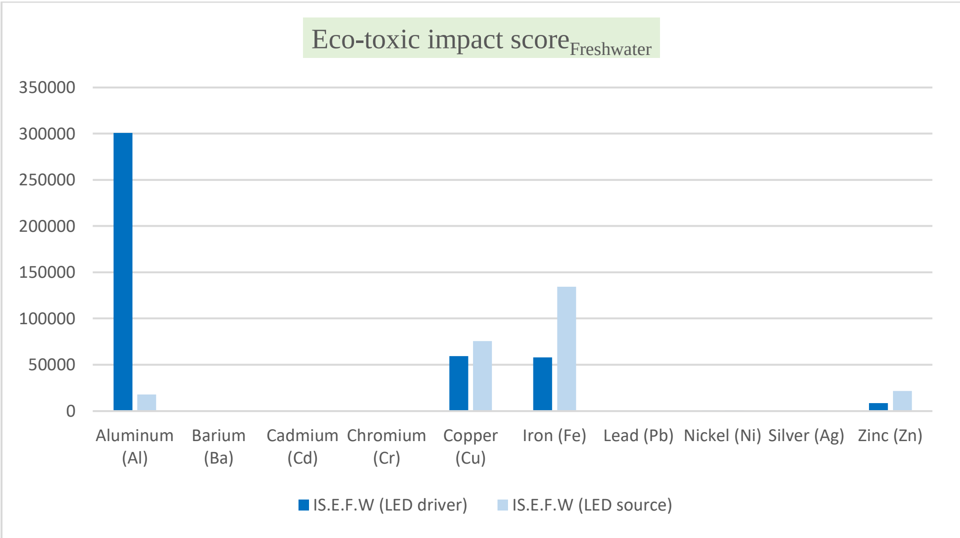

Figure 4.32 : Eco toxicity impact from metal emission to freshwater

Human-toxicity impact scores for metals leaching from LED's to freshwater described in Figure 4.33. Zn leaching from LED source generate the highest human-toxicity level (4.88E-05 Cases/kg emitted) in freshwater bodies as Zn capable of bio magnifying within food webs. Human exposure to Zn in freshwater occur via the route of ingestion. Bio concentration of Zn detected in the fish species called *Daphnia magna* (Memmert, 1987). Pb also has shown bioaccumulation capability in freshwater food chain therefore Pb (7.23E+02 *Cases/kg emitted*) ranked as the second highest while Cr (7.17E-06 *Cases/kg emitted*) is in third place of human-toxic impact scores (Opinion of the Scientific Panel on contaminants in the food chain [CONTAM] related to lead as undesirable substance in animal feed, 2004). LED source shows human-toxicity for metals, Zn and Pb while Zn, Cr and Pb from LED driver responsible for notable human-toxicity.

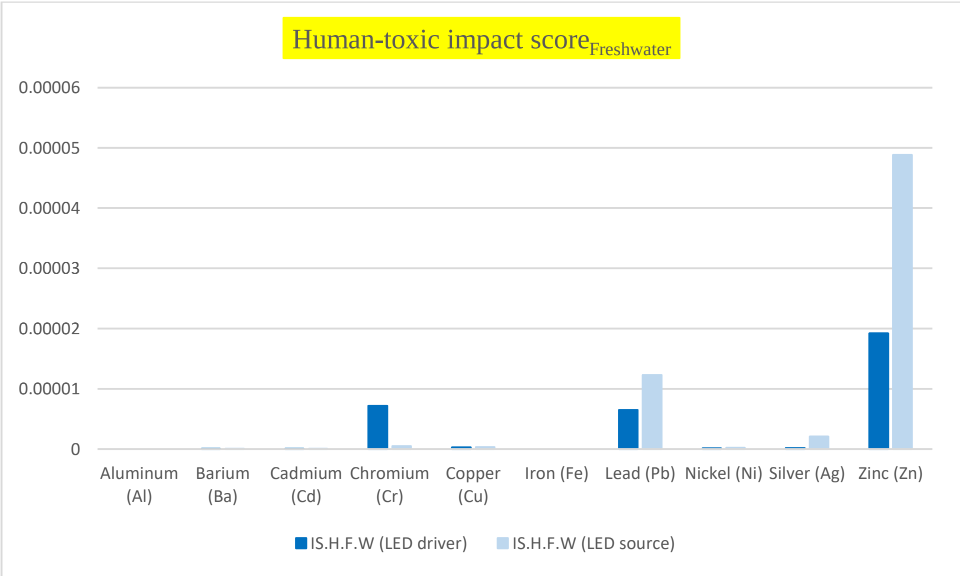

Figure 4.33 : Human toxicity impact from metal emission to freshwater

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study concerned on evaluating the environmental and human health impact due to LED lamps consumption and disposal practices in Thailand industrial sector.

As survey results suggested that industrial consumers apply residential LED models for their lighting applications, focus of the study directed to conduct comparative LCA to identify whether this consumer behavior generate positive or negative impact on environment and human health. Comparative LCA study results divided into two sections: (1) base case scenario (2) sensitivity analysis.

Base case (current situation; energy mix 2020 & ideal lifespan) scenario results detected that using residential LED model for the industrial lighting purpose originated 25% greater impact compared to industrial LED model. This environmental impact initiated due to the unnecessary electricity usage by this practice. The highest midpoint impact shown in human carcinogenic toxicity category during the base case scenario analysis. Thailand uses natural gas as their main components for the electricity generation process. Natural gas combustion produce Polycyclic aromatic hydrocarbons

(PAHs), Polycyclic Organic Compounds (POC), and $PM_{2.5}$ mix with fly ash and capable of damaging lung tissues and internal fluids increasing the future cancer risk.

Sensitivity analysis results discussed based on different values among input parameters (useful lifespan and energy mix). Among useful lifespans, completion of ideal lifespans generated the highest impact in both LED models that used 2020 and 2036 energy mix. Among energy mixes, 2020 energy mix generate greater impact compared to 2036 energy mix in following impact categories, terrestrial, marine and freshwater ecotoxicity, global warming and fossil fuel scarcity while 2036 energy mix exhibits the greater impact on categories such as ionizing radiation, freshwater eutrophication, human carcinogenic toxicity and water consumption.

Disposal activities (landfilling or recycling) of LED lamps mainly depend on contained metal concentrations.

Leaching test results showed that concentration measures of metals such as Cu, Zn, Pb and Ag, exceed TTLC limits in LED lamps waste (driver and source). Therefor landfilling of LED waste components generate negative impact on environment and human health. In LED driver, Cu (65,766.67 mg/kg; limit: 2,500 mg/kg), Pb (8,767 mg/kg; limit: 1,000 mg/kg) and Zn (15,433 mg/kg; limit: 5,000 mg/kg) metals exceed TTLC limits. Whereas in LED source, Cu (209,200 mg/kg; limit: 2,500 mg/kg), Pb (16,600 mg/kg; limit:

1,000 mg/kg), Ag (846 mg/kg; limit: 500 mg/kg) and Zn (39,204 mg/kg; limit: 5,000 mg/kg) metal concentrations exceed the TTLC level.

Quantities of contained metal content in LED lamps waste components decide the potential for recycling process. Results from this study shown that in LED driver, Cu is the most abundant metal (164,467 mg/kg), Al (65,766.67 mg/kg), Fe (25,933 mg/kg) and Zn (15,433 mg/kg) also present greater amounts in the LED driver. The most abundant metal in LED source is also Cu (211,800 mg/kg), Fe (64,500 mg/kg), and Zn (51,807 mg/kg). Among these metals in LED driver and source, Cu, Zn, and Pb has possibility to recycle within Thailand due to the high market demand.

USEtox results from this study indicated that Al metal from LED driver showed the highest eco-toxicity level in all three compartments, soil compartment (natural and agricultural): 177,221.9 PAF.m^3.day.kg^{-1}, air compartment (rural: 119,099.6 PAF.m^3.day.kg^{-1} and urban: 120,393.9 PAF.m^3.day.kg^{-1}), and water (freshwater): 300,616.2 PAF.m^3.day.kg^{-1}. On the other hand, the highest human toxicity impact from LED driver occurred due to Pb leaching to agricultural soil (1.765 cases/kg $_{emitted}$), air (rural (0.000121 cases/kg $_{emitted}$) and urban (0.000229 cases/kg $_{emitted}$)) compartments. Zn leaching from LED source responsible for the highest human toxicity impact on freshwater compartment ($4.88x10^{-5}$ cases/kg $_{emitted}$).

5.2 Recommendation

1. Selection of LED lamp models for lighting applications should intended to save electricity and reduce environmental impact. As study results suggested, residential LED lamp models should not use for industrial lighting applications.

2. Avoid improper landfilling of LED lamp waste and should treat as hazard waste.

3. Recycling of abundant metals (Al, Ag, Cu, Pb, and Zn) from LED driver and source should be concerned by authorities.

5.3 Limitations of the study

1. Technology characterization limitation

Results of this study should not take as points to represent LED lighting technology. As models within LED lighting technology are extremely diverse and rapidly transformative.

2. LED lamp model selection limitation

Selected T8 & High bay models should not represent entire model characteristics since design and building materials could change due to different manufactures, manufactured time period and the manufacturing country. Therefor no single test result can be published with absolute confidence.

3. LCA study limitations

3.1 LCA study was covered only consumption phase because of lack of data support from manufactures and LED lamp assembling factories during Covid-19 period.

3.2 Data input for the LCA phase strongly depends on Simapro libraries (raw materials, emission to air, water, and soil compartments due to the generation of 1 MJ of electric energy).

4. Limitations on the contaminants investigated

4.1 In this study, we considered only on toxic metals and did not focus on persistent organic compounds preset in the LED lamp models.

4.2 Toxic metals concentration testifies only in LED driver and source components.

5. Limitations in USEtox model application

- Assumptions made that emitted metal remain in the emitted compartment and neglected the fate and transformation of metals in ecosystem.
- USEtox characterization factors calculated mainly based on the USEtox inorganic substances library data.
- Assumption made that improper disposal activities (open dumping in landfills & freshwater and open burning) capable to release toxic metals completely from LED lamps waste.

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APPENDIX A

Survey for LED consumers

Sampling process for the research part 1 – LED lamp consumers in industrial estates

Type of sampling: Probability sampling → stratified sampling

Population specification: Type of origin (100% Thai / Thai- Foreign) 10

Size of illumination area → 10

Types of manufacturing products (Large scale, small scale) → 10

Location of the factory (Industrial park, zone and estate) → 9

Sample Frame: Selection details will get from following databases, List of Electronic and electrical equipment manufacturing factories Office of industrial estate, zone and park.

Respond collection methods: Direct interviews was the first priority.

Phone calls was the second priority.

Emails/ registered mails was the last priority due to the low responding rate of responders.

Population size: 39

Confidence level: 90%

Margin of error: 5%

Ideal sample size: 35

Source: https://www.qualtrics.com/blog/calculating-sample-size/

Survey for LED lamp consumers in Electronic/ Electrical industry

Life Cycle Assessment LED lamps used from 2012 to 2019 in industrial lighting.

Center of Excellence on Hazardous Substance management,

Chulalongkorn University (HSM) has been conducting the project of Life cycle Assessment of

LED light bulbs in Electronic/Electrical industrial lighting: comparison between LED lamp models from 2012 to 2019 in electronic/electrical industries Thailand, HSM would like you to complete the LED lamps related-questions as a primary information for the project.

“N/A” is recommended for the not available data.

Thank you for your corporation for the project. All information in the questionnaire is confidential. Please contact Miss Lakshani Gunawardhana, master student, Call 0882136010,E-mail:lakshi1217@gmail.com for more information.

1. General information section

Date	
Company Name	
Industrial estate	
Manufacturing product	
Total working hours (Total number of hours lights keep on)	
Name of the person filling this	
Position	
Telephone Number / email	

Operating temperature in the working space	28°C	25°C	Other

2. Information about LED lamp.

Add the data according to the year you have installed LED lamp, if you have not install LED lamp in each year you can only fill years that you installed LED lamp.

** Please check following table for the LED lamp brand and fill according to your LED brand

LED Lamp Brand	
Siam LED	A
LeKise	B
Toshiba	C
Panasonic	D
Philips	E
Other (Please specify)	F

Year	Number of LED lamps installed	LED Lamp Brand	LED Lamp Model
2012			
2013			
2014			
2015			
2016			
2017			
2018			

2019			

3. LED lamp waste generation

** Please check following table for reason for LED lamp waste generation.

A	End of lifetime
B	Manufacturing defects
C	Reduced light output
D	Replaced by more energy efficient new LED lamp

Year	2012	2013	2014	2015	2016	2017	2018	2019
Reason for the LED lamp waste generation								
Amount of LED lamp waste generated								

4. LED lamp waste handling in your factory

	Yes	No
Do you separate LED waste from other solid waste?		
Do you treat LED as hazardous industrial waste?		

Year	LED Lamp waste collector	LED waste transporter	LED lamp waste processor
2012			
2013			
2014			
2015			
2016			
2017			
2018			
2019			

แบบสำรวจการใช้หลอดไฟฟ้าแอลอีดี (LED) ในอุตสาหกรรมอิเล็กทรอนิกส์ในประเทศไทย

ด้วยนางสาวลักชนี คุณะวัฒนา (Miss Lakshani Gunawardhana) นิสิตระดับปริญญาโท จากหลักสูตรสหสาขาวิชาการจัดการสารอันตรายและสิ่งแวดล้อม (นานาชาติ) จุฬาลงกรณ์มหาวิทยาลัย โดยมีอาจารย์ที่ปรึกษาคือ ดร.วัชราภรณ์ สุนสิน นิสิตกำลังทำวิทยานิพนธ์เกี่ยวกับการประเมินวัฏจักรชีวิตของหลอดไฟฟ้า LED ในอุตสาหกรรมอิเล็กทรอนิกส์ที่ถูกใช้ในช่วงระหว่างปี พ.ศ. 2555 ถึง พ.ศ. 2562 เพื่อศึกษาผลกระทบทางด้านสิ่งแวดล้อมของหลอดไฟฟ้า LED ที่ใช้งานในช่วงดังกล่าวภายในอุตสาหกรรมอิเล็กทรอนิกส์ในประเทศไทย จึงขออนุญาตให้ทางหน่วยงานของท่านช่วยกรุณากรอกข้อมูลในแบบสอบถามที่เกี่ยวข้องกับหลอดไฟฟ้า LED เพื่อใช้เป็นข้อมูลในการทำวิจัยต่อไป

ทางทีมวิจัยขอขอบพระคุณที่ท่านช่วยกรุณาให้ข้อมูลที่เป็นประโยชน์สำหรับการทำดำเนินการวิจัยในครั้งนี้ โดยข้อมูลในแบบสอบถามนี้จะถูกเก็บเป็นความลับและใช้ในการศึกษาเท่านั้น หากท่านต้องการสอบถามข้อมูลเพิ่มเติมเกี่ยวกับโครงการวิจัย กรุณาติดต่อ นางสาวลักชนี คุณะวัฒนา ได้ที่เบอร์โทรศัพท์ 088-213-6010 หรือ อีเมลล์ lakshi1217@gmail.com หรือ ติดต่อ ดร.วัชราภรณ์ สุนสิน ได้ที่อีเมลล์ vacharaporn.so@chula.ac.th

หมายเหตุ หากท่านไม่มีข้อมูล กรุณากรอก **"ไม่มีข้อมูล"**

1. **ข้อมูลทั่วไป**

วัน เดือน ปี ที่ให้ข้อมูล			
ชื่อบริษัท			
นิคมอุตสาหกรรม			
ประเภทผลิตภัณฑ์ที่ผลิต			
จำนวนชั่วโมงที่เปิดใช้หลอด LED			
ชื่อ-สกุล ผู้กรอกข้อมูล			
ตำแหน่ง			
เบอร์โทรศัพท์/อีเมลล์			
โปรดเลือกอุณหภูมิในสถานประกอบการ	28 องศาเซลเซียส	25 องศาเซลเซียส	อื่นๆ โปรดระบุ

2. ข้อมูลเกี่ยวกับหลอดไฟฟ้า LED

กรุณากรอกข้อมูลในปีที่ท่านได้มีการติดตั้งหลอดไฟฟ้า LED

*** สำหรับการระบุยี่ห้อหลอดไฟฟ้า LED กรุณาระบุเป็นตัวอักษร A-F ดังแสดงในตารางด้านล่าง*

ยี่ห้อหลอดไฟฟ้า LED ที่ใช้	ตัวอักษร
Siam LED	A
LeKise	B
Toshiba	C
Panasonic	D
Philips	E
อื่นๆ (โปรดระบุยี่ห้อหลอดไฟฟ้า LED ที่ใช้)	F

ปี พ.ศ.	จำนวนหลอดไฟฟ้า LED ที่มีการติดตั้ง	ยี่ห้อหลอดไฟฟ้า LED ที่ใช้ (ระบุเป็นตัวอักษร)	รุ่นของหลอดไฟฟ้า LED (Model)
2555			
2556			
2557			
2558			
2559			
2560			
2561			
2562			

3. การเลิกใช้หรือทิ้งหลอดไฟฟ้า LED หลังการใช้งาน

กรุณากรอกตัวอักษร A-D เพื่อระบุเหตุผลของการเลิกใช้หรือทิ้งหลอดไฟฟ้า LED

เหตุผลของการเลิกใช้หรือทิ้งหลอดไฟฟ้า LED	
A	หลอดหมดอายุ
B	หลอดชำรุด หรือ ทำงานบกพร่อง
C	ต้องการลดการใช้หลอดไฟ
D	เปลี่ยนไปใช้หลอดไฟฟ้าชนิดอื่นที่ประหยัดพลังงานมากกว่า

ปี พ.ศ.	2555	2556	2557	2558	2559	2560	2561	2562
เหตุผลของการเลิกใช้หรือทิ้งหลอดไฟฟ้า LED								
ปริมาณหลอดไฟฟ้า LED ที่เลิกใช้/ทิ้ง (ระบุหน่วย – หลอด)								

4. การจัดการหลอดไฟฟ้า LED ในโรงงาน

วิธีการจัดการหลอดไฟฟ้า LED ในโรงงาน	ใช่	ไม่ใช่
ทิ้งหลอดLED แยกกับขยะมูลฝอย		
จัดการหลอดLEDที่ถูกทิ้ง เช่นเดียวกับการจัดการกากของเสียอุตสาหกรรมที่เป็นอันตราย		

ปี พ.ศ.	รายชื่อผู้ดำเนินการ		
	ชื่อผู้รวบรวมขยะหลอดไฟฟ้า LED	ชื่อผู้ขนส่งขยะหลอดไฟฟ้า LED	ชื่อผู้บำบัดและกำจัดของเสีย
2555			
2556			
2557			
2558			
2559			
2560			
2561			
2562			

****ทางทีมวิจัยขอขอบพระคุณที่ท่านสละเวลาในการตอบแบบสอบถามในครั้งนี้****

APPENDIX B

Factory list for the survey distribution

Industrial estate	Factory name	Address
Amata	SEI Thai Electric Conductor Co., Ltd.	7/414 Moo 6, Tambol Mabyangporn, Amphur Pluakdaeng, Rayong 21140 Thailand
	Hi-P Thailand	Hi-P Thailand Company Limited 7/132 Moo 4, Amata City Industrial Estate, T.Mabyangporn, A.Pluakdeang, Rayong
	Chubu techno	WHA Eastern Seaboard IE 1 500/108 Moo3 T.Tasit, A.Pluakdaeng Rayong 21140 Thailand
	Sahacharoen metal plastic product Co., ltd	111/1 M.12, Kingkaew Rd., Bangpleeyai, Bangplee, Samutprakarn 10540
	Marunix (Thailand) Co., ltd	7/153 Moo 4, T.Mabyangporn , A. Pluakdaeng, Rayong 21140 Thailand Rayong Amata City Special Industrial Zone
	Dts draeslmaier automotive systems (Thailand) Co., ltd	7/418 Village No. 6, Amata City Industrial Estate, Mapyangporn Sub-district, Pluak Daeng District, Rayong Province 21140
	Sumitomo electric wiring systems (Thailand) Co., ltd	Siam Eastern Industrial Park, 60/2 Moo 3, Mabyangporn Pluakdaeng Rayong, 21140 Thailand
Bangpa in	N & E (Thailand) Co., ltd	552 Soi Mu Ban Kt Green Ville, Tambon Sam Ruan, Bang Pa-in District, Phra Nakhon Si Ayutthaya 13160
	Yamaichi manufacturing (Thailand) Co., ltd	No.718, Moo 2, Bangpa-in Industrial Estate, Udomsorayuth Road, Tambol Klongjig, Amphur Bangpa-in, Ayutthaya 13160, THAILAND
	Kashiwa industrial (Thailand) Co., Ltd.	Bangpa-In Industrial Estate 145 Moo 16, Bangkasan, Amphur Bangpa-In, Ayutthaya 13160 Thailand
	Tse Lup Technology (Thailand) Ltd	39/5 Moo 9, Soi 14, Kabinburi Industrial Zone, Thambol Nongki, Amphur Kabinburi, Prachinburi 25110
	Mitsui (Thailand) Co., ltd https://www.mitsui.com/jp/en/company/outline/worldwide/asia/index.html#1206862	15th - 17th Floor, Sathorn City Tower 175 South Sathorn Road, Tungmahamek Sathorn Bangkok 10120, Thailand (P. O. Box 865, Bangkok 10120)

	189,198,296 Moo 16, Bangpa-in Industrial Estate, Udomsorayuth Rd., T.Bangdrasan, A.Bangpa-in Ayutthaya, Thailand 13160	Mektec precision component (Thailand) Co., ltd
Bang phli	Cheval electronic enclosure co., ltd	145 Bangplee Industrial Estate Soi 4 Moo 17 Bangsaotong Samutprakarn 10570 Thailand
	Thai asahi and goh co., ltd	Bangplee Industrial Estate at No.362 , Thai Daiho Bangplee Factory 2nd F 1., No.208, Moo 17, Tambol Bangsaothong, King-Amphur Bangsaothong, Samutprakarn 10540 Thailand
	New era international ltd.	8 Bangna Complex, Soi Bangna-Trad 25,Bangna, Bangna, Bangkok 10260, Thailand.
	Nisshinbo mechatronics (Thailand) ltd	419 Samut Prakan Bang Sao Thong, Bang Sao Thong District, Samut Prakan 10570
	Yamaha motor electronics (Thailand) Co., ltd	366 Moo 17 Bangplee Industrial Estate, Bangna-Trad Rd., Km. 23, Tambol Bangsaothong, Amphur Bangsaothong, Samutprakarn 10570
	Johoku (Thailand) Co., ltd	406 Moo 17, Bangsaothong District, Bangplee, Samutprakarn 10540 THAILAND
Bang poo	Jinpao precision industry Co., ltd	631 Moo Soi 12 Pharaksa, Amphur Muang, Samutprakarn 10280 Thailand. +66-2-7093367 EXT. 111
	Thaifirst precision industry Co., ltd	852 Moo4, Bangpoo Industrial Estate, Soi 12, Phrakasa District Amphur Muang Samutprakarn, Samutprakarn 10280, Thailand
	PAIBUL E.C.P. CO., LTD	281 Bangpoo Industrial Estate, Moo4, Sukhumvit Rd., Prakkasa, Amphur Muang Samutprakarn, Samutprakarn 10280
	YAMAGATA (Thailand) Co.,ltd	324 Moo 4, Bangpoo Industrial Estate Soi 6, Sukhumvit Rd., T. Phraeksa A. Muang Samutprakarn, Samutprakarn Thailand 10280
	Tirathai Public Company Limited	516/1 Moo 4, Bangpoo Industrial Estate, Sukhumvit Road, T. Praksa, A. Muang, Samutprakarn, 10280
	Pattonaero Co., ltd Has changed to SCMREFTHAI	998/12-13 Moo 21, Soi TeedinThai, Thepharak Road, Bangphi Yai Sub-district Bangphli District, Samutprakarn 10540 Thailand

Nava nakhon	BETSUKAWA (THAILAND) CO.,LTD.	60/112 Moo 19, Phaholyothin Rd. Tamol Klongnueng Amphur Klongluang Pathumthani 12120
	BELTON INDUSTRIAL (THAILAND) LTD.	101/110 หมู่ที่ 20, ถนนพหลโยธิน, ตำบลคลองหนึ่ง อำเภอคลองหลวง จังหวัดปทุมธานี, 13180
	C.E.S systems Company Ltd.	64/104 Navanakorn Industrial Estate Zone3 Klongluang Distric Pathumthani 12120 Thailand
	DDK (THAILAND) Ltd. https://ddk.co.th/page-2651-location.html	55/25 Moo 13 Navanakorn Industrial Estate, Paholyothin Road, Klong Nueng, Klong Luang, Pathumthani 12120 THAILAND
	Focuz Manufacturing Co., Ltd.	60/97 Moo 19, Paholyothin Rd., Navanakorn Industrial Estate Klongluang, Patumthanee 12120 Thailand
	FUJIKURA ELECTRONICS (THAILAND) LTD. (Factory 1)	Navanakorn Factory 1 101/2 Moo 20 Navanakorn Industrial Zone, Phaholyothin Road, Tambol Klongnueng, Amphur Klongluang, Pathumthani 12120

APPENDIX C

Life cycle Inventory Data for 1 MJ of electricity generation

Table C1: inventory data for generation of 1 MJ of Electricity in 2020 and 2036 (Raw material)

Substance	Compartm -ent	Unit	Electricity TH 2020 medium voltage	Electricity TH 2036 medium voltage
Aluminium	Raw	mg	21.23704	18.8453
Anhydrite	Raw	ng	147.5166	120.2713
Argon-40	Raw	mg	3.51167	3.273974
Barite	Raw	mg	68.68415	57.43654
Basalt	Raw	mg	12.4506	9.452773
Borax	Raw	µg	361.7257	362.9884
Bromine	Raw	µg	2.033897	1.920612
Cadmium	Raw	µg	-12.1159	-9.1371
Calcite	Raw	g	8.656409	9.277113
Carbon dioxide, in air	Raw	g	5.128046	5.116622
Carbon, organic, in soil or biomass stock	Raw	mg	25.19241	24.29805
Carnallite	Raw	ng	345.0834	357.5235
Cerium	Raw	pg	3.226149	3.182331
Chromium	Raw	mg	14.91287	15.3094
Cinnabar	Raw	pg	161.8411	170.9078
Clay, bentonite	Raw	mg	17.17775	16.69179
Clay, unspecified	Raw	mg	916.2946	905.9402
Coal, brown	Raw	g	128.3184	135.3895
Coal, hard	Raw	g	1.661104	1.627858
Cobalt	Raw	µg	2.444928	2.445228
Cobalt, Co 5.0E-2%, in mixed ore	Raw	ng	36.91808	39.37154
Colemanite	Raw	µg	412.0838	413.7459
Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	Raw	mg	2.188934	1.69593
Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore	Raw	mg	1.219321	0.945647
Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore	Raw	mg	2.118047	2.297063
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	Raw	mg	3.127267	2.510629

Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore	Raw	µg	23.63769	25.20857
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore	Raw	mg	1.738084	1.349966
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore	Raw	µg	280.0572	215.0404
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore	Raw	µg	869.4204	671.0638
Copper, Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore	Raw	mg	3.227524	2.70211
Copper, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore	Raw	µg	-0.10353	-1.38132
Copper, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	Raw	ng	233.8353	256.1245
Copper, Cu 6.8E-1%, in mixed ore	Raw	ng	502.0327	535.3962
Diatomite	Raw	ng	18.5976	21.80568
Dolomite	Raw	mg	4.149667	3.620836
Energy, geothermal, converted	Raw	kJ	34.11657	34.16905
Energy, gross calorific value, in biomass	Raw	kJ	57.61926	57.45137
Energy, gross calorific value, in biomass, primary forest	Raw	J	422.9594	407.9338
Energy, kinetic (in wind), converted	Raw	kJ	1.076467	1.530085
Energy, potential (in hydropower reservoir), converted	Raw	kJ	435.1911	540.5349
Energy, solar, converted	Raw	J	12.58232	13.68788
Europium	Raw	pg	0.008083	0.007973
Feldspar	Raw	ng	1.097834	1.123164
Fluorine	Raw	µg	86.13763	75.8149
Fluorine, 4.5% in apatite, 3% in crude ore	Raw	µg	30.99248	28.94061
Fluorspar	Raw	mg	1.736483	1.941674
Gadolinium	Raw	pg	0.020172	0.019898
Gallium	Raw	µg	6.592163	5.849724
Gangue, bauxite	Raw	mg	225.5635	200.1595
Gas, mine, off-gas, process, coal mining/m3	Raw	cm3	14.96052	14.6226
Gas, natural/m3	Raw	dm3	80.09674	65.9652
Gold	Raw	ng	11.02527	10.81811
Gold, Au 1.0E-7%, in mixed ore	Raw	pg	7.61579	8.12191
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore	Raw	ng	-116.094	-100.359
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	Raw	ng	3.692344	3.622964
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	Raw	pg	799.035	784.0209
Gold, Au 4.3E-4%, in ore	Raw	ng	2.151878	2.111443
Gold, Au 4.9E-5%, in ore	Raw	ng	10.79317	10.59036
Gold, Au 5.4E-4%, Ag 1.5E-5%, in ore	Raw	pg	60.73292	59.59173
Gold, Au 6.7E-4%, in ore	Raw	ng	11.51256	11.29624
Gold, Au 6.8E-4%, Ag 1.5E-4%, in ore	Raw	pg	82.53043	80.97966
Gold, Au 7.1E-4%, in ore	Raw	ng	5.330354	5.230195
Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	Raw	ng	78.63929	65.83747
Gold, Au 9.7E-5%, Ag 7.6E-5%, in ore	Raw	pg	298.5706	292.9604

Granite	Raw	pg	2.140887	4.026191
Gravel	Raw	g	7.027032	8.162194
Gypsum	Raw	mg	-3.33829	2.976648
Indium	Raw	ng	-201.928	-152.283
Iodine	Raw	ng	261.1017	244.2296
Iron	Raw	mg	906.9847	847.5978
Kaolinite	Raw	µg	208.9137	249.6494
Kieserite	Raw	µg	2.756046	3.06182
Lanthanum	Raw	pg	0.967154	0.954018
Lead	Raw	µg	-201.915	-152.272
Lead, Pb 0.014%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, in ore	Raw	µg	390.0815	326.5795
Lithium	Raw	ng	10.77942	10.16461
Magnesite	Raw	mg	-3.01526	-2.71776
Manganese	Raw	mg	8.288456	7.87306
Metamorphous rock, graphite containing	Raw	µg	20.02939	17.73162
Molybdenum	Raw	µg	241.5526	261.9684
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore	Raw	µg	25.24539	19.4857
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore	Raw	µg	5.747771	4.413395
Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore	Raw	µg	52.48086	40.66083
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore	Raw	µg	27.23497	21.12214
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore	Raw	µg	42.03068	32.81963
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore	Raw	µg	34.67323	26.93063
Neodymium	Raw	pg	0.531935	0.52471
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore	Raw	µg	45.96217	49.01666
Nickel, 1.98% in silicates, 1.04% in crude ore	Raw	mg	10.32447	10.39433
Nickel, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore	Raw	ng	-74.7416	-997.185
Nickel, Ni 2.5E+0%, in mixed ore	Raw	µg	1.808546	1.928736
Nickel, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore	Raw	ng	333.4695	365.2558
Nitrogen, atmospheric	Raw	mg	189.3794	176.5608
Occupation, annual crop	Raw	mm 2a	86.78802	83.6987
Occupation, annual crop, irrigated	Raw	mm 2a	6.615728	6.38023
Occupation, annual crop, irrigated, intensive	Raw	mm 2a	2.40E-07	2.51E-07
Occupation, annual crop, non-irrigated	Raw	mm 2a	0.000423	0.000463
Occupation, annual crop, non-irrigated, extensive	Raw	mm 2a	-3.33E-10	-3.22E-10

Occupation, annual crop, non-irrigated, intensive	Raw	mm2a	34.39318	33.18162
Occupation, construction site	Raw	mm2a	3.85315	3.983495
Occupation, dump site	Raw	mm2a	47.42965	47.96714
Occupation, forest, extensive	Raw	mm2a	12.55946	12.5649
Occupation, forest, intensive	Raw	cm2a	76.23266	76.06936
Occupation, grassland, natural (non-use)	Raw	mm2a	48.88924	48.89149
Occupation, industrial area	Raw	mm2a	111.7542	88.16494
Occupation, inland waterbody, unspecified	Raw	mm2a	-0.00104	-0.0008
Occupation, mineral extraction site	Raw	mm2a	157.799	165.4714
Occupation, pasture, man made, extensive	Raw	mm2a	5.16E-07	5.41E-07
Occupation, pasture, man made, intensive	Raw	mm2a	-0.00214	-0.00225
Occupation, permanent crop	Raw	mm2a	-14.4948	-13.9566
Occupation, permanent crop, irrigated	Raw	mm2a	-0.7275	-0.70675
Occupation, seabed, drilling and mining	Raw	mm2a	4.818741	3.983038
Occupation, seabed, infrastructure	Raw	mm2a	0.039635	0.032907
Occupation, shrub land, sclerophyllous	Raw	mm2a	5.142608	5.482017
Occupation, traffic area, rail network	Raw	mm2a	8.025222	8.349441
Occupation, traffic area, rail/road embankment	Raw	mm2a	46.62107	46.95114
Occupation, traffic area, road network	Raw	mm2a	34.81383	36.76884
Occupation, unknown	Raw	mm2a	0.033637	0.029721
Occupation, urban, discontinuously built	Raw	mm2a	0.030948	0.029958
Occupation, urban/industrial fallow (non-use)	Raw	mm2a	0.000548	0.000514
Occupation, water bodies, artificial	Raw	cm2a	7.665877	18.91773
Oil, crude	Raw	mg	706.8398	691.6125
Olivine	Raw	ng	58.18421	48.17256
Oxygen	Raw	mg	253.3926	249.6564
Palladium, Pd 1.6E-6%, in mixed ore	Raw	pg	120.8538	128.8854
Palladium, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	Raw	pg	650.6721	712.6943

Palladium, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	Raw	pg	-23.5858	-314.676
Peat	Raw	μg	57.21568	47.02641
Perlite	Raw	μg	2.322511	2.02766
Phosphorus	Raw	μg	126.9504	119.3971
Phosphorus, 18% in apatite, 4% in crude ore	Raw	μg	344.5505	303.2596
Platinum, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	Raw	pg	-8.08488	-107.867
Platinum, Pt 4.7E-7%, in mixed ore	Raw	pg	34.95772	37.2809
Platinum, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	Raw	ng	1.531113	1.677059
Potassium chloride	Raw	mg	2.02612	2.032204
Praseodymium	Raw	pg	0.05644	0.055674
Rhenium	Raw	pg	76.48755	75.74938
Rhodium, Rh 1.6E-7%, in mixed ore	Raw	pg	11.86066	12.64888
Rhodium, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore	Raw	pg	-0.64563	-8.61382
Rhodium, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore	Raw	pg	76.65731	83.9643
Samarium	Raw	pg	0.040275	0.039728
Sand	Raw	μg	21.01596	26.69388
Shale	Raw	mg	347.0246	334.6003
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	Raw	ng	-294.511	-222.104
Silver, Ag 1.5E-4%, Au 6.8E-4%, in ore	Raw	pg	18.52393	18.17587
Silver, Ag 1.5E-5%, Au 5.4E-4%, in ore	Raw	pg	1.695625	1.663764
Silver, Ag 1.8E-6%, in mixed ore	Raw	pg	134.8369	143.7978
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore	Raw	pg	813.6189	798.3308
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore	Raw	μg	-4.34856	-3.75919
Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore	Raw	ng	1.318756	1.293976
Silver, Ag 7.6E-5%, Au 9.7E-5%, in ore	Raw	pg	233.9284	229.5328
Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	Raw	μg	3.977079	3.329644
Sodium chloride	Raw	mg	13.82376	13.72106
Sodium nitrate	Raw	pg	174.1082	133.843
Sodium sulfate	Raw	mg	-3.61006	-3.41889
Spodumene	Raw	ng	3.391367	3.197937
Stibnite	Raw	ng	1.932692	2.26608
Strontium	Raw	ng	-182.259	-139.798
Sulfur	Raw	μg	5.709912	5.641587
Talc	Raw	ng	-222.335	143.2929
Tantalum	Raw	ng	56.09605	60.73127
Tin	Raw	μg	4.503467	4.665822
TiO2, 54% in ilmenite, 18% in crude ore	Raw	μg	943.7153	840.2173
TiO2, 54% in ilmenite, 2.6% in crude ore	Raw	ng	102.0484	110.2382
TiO2, 95% in rutile, 0.40% in crude ore	Raw	ng	16.33467	17.59739

Transformation, from annual crop	Raw	mm 2	107.3674	103.547
Transformation, from annual crop, non-irrigated	Raw	mm 2	0.001275	0.001394
Transformation, from annual crop, non-irrigated, extensive	Raw	mm 2	-2.64E-10	-2.55E-10
Transformation, from annual crop, non-irrigated, intensive	Raw	mm 2	10.76372	10.40617
Transformation, from cropland fallow (non-use)	Raw	mm 2	0.004255	0.003776
Transformation, from dump site, inert material landfill	Raw	mm 2	0.681129	0.733113
Transformation, from dump site, residual material landfill	Raw	mm 2	0.039857	0.038597
Transformation, from dump site, sanitary landfill	Raw	mm 2	0.287467	0.304355
Transformation, from dump site, slag compartment	Raw	mm 2	0.020004	0.020276
Transformation, from forest, extensive	Raw	mm 2	0.167638	0.167894
Transformation, from forest, intensive	Raw	mm 2	105.2046	105.0005
Transformation, from forest, primary (non-use)	Raw	mm 2	1.433087	1.405448
Transformation, from forest, secondary (non-use)	Raw	mm 2	0.99113	0.955968
Transformation, from forest, unspecified	Raw	mm 2	17.43271	22.50338
Transformation, from grassland, natural (non-use)	Raw	mm 2	0.000444	0.000174
Transformation, from grassland, natural, for livestock grazing	Raw	mm 2	0.007208	0.006958
Transformation, from heterogeneous, agricultural	Raw	mm 2	-5.88E-07	-5.66E-07
Transformation, from industrial area	Raw	mm 2	0.292485	0.273014
Transformation, from mineral extraction site	Raw	mm 2	4.960411	5.222828
Transformation, from pasture, man made	Raw	mm 2	4.572656	4.479845
Transformation, from pasture, man made, extensive	Raw	mm 2	1.03E-08	1.08E-08
Transformation, from pasture, man made, intensive	Raw	mm 2	-8.72E-05	-9.15E-05
Transformation, from permanent crop	Raw	mm 2	-0.73226	-0.70494
Transformation, from permanent crop, irrigated	Raw	mm 2	-0.03807	-0.03676
Transformation, from seabed, infrastructure	Raw	mm 2	0.000493	0.000406
Transformation, from seabed, unspecified	Raw	mm 2	4.821652	3.985496
Transformation, from shrub land, sclerophyllous	Raw	mm 2	3.833429	3.745514

Transformation, from traffic area, rail/road embankment	Raw	mm2	0.455753	0.454339
Transformation, from unknown	Raw	mm2	8.134199	7.873545
Transformation, from unspecified, natural (non-use)	Raw	mm2	0.075053	0.075168
Transformation, from wetland, inland (non-use)	Raw	mm2	-7.02E-05	-6.76E-05
Transformation, to annual crop	Raw	mm2	45.19797	43.99912
Transformation, to annual crop, fallow	Raw	mm2	0.007608	0.007092
Transformation, to annual crop, irrigated, intensive	Raw	mm2	4.12E-07	4.31E-07
Transformation, to annual crop, non-irrigated	Raw	mm2	0.001198	0.001314
Transformation, to annual crop, non-irrigated, extensive	Raw	mm2	-3.70E-10	-3.57E-10
Transformation, to annual crop, non-irrigated, intensive	Raw	mm2	79.77465	76.96056
Transformation, to dump site	Raw	mm2	0.246762	0.244325
Transformation, to dump site, inert material landfill	Raw	mm2	0.681129	0.733113
Transformation, to dump site, residual material landfill	Raw	mm2	0.039858	0.038597
Transformation, to dump site, sanitary landfill	Raw	mm2	0.287467	0.304355
Transformation, to dump site, slag compartment	Raw	mm2	0.020004	0.020276
Transformation, to forest, extensive	Raw	mm2	0.096611	0.096653
Transformation, to forest, intensive	Raw	mm2	105.2562	105.0531
Transformation, to forest, unspecified	Raw	mm2	1.145065	1.225601
Transformation, to grassland, natural (non-use)	Raw	mm2	0.651857	0.651886
Transformation, to heterogeneous, agricultural	Raw	mm2	0.269571	0.225569
Transformation, to industrial area	Raw	mm2	2.96101	2.430727
Transformation, to inland waterbody, unspecified	Raw	mm2	-1.04E-05	-8.01E-06
Transformation, to mineral extraction site	Raw	mm2	20.1766	17.94077
Transformation, to pasture, man made	Raw	mm2	0.231899	0.191203
Transformation, to pasture, man made, extensive	Raw	mm2	1.03E-08	1.08E-08
Transformation, to pasture, man made, intensive	Raw	mm2	-0.00011	-0.00011
Transformation, to permanent crop	Raw	mm2	-0.95834	-0.92279

Transformation, to permanent crop, irrigated	Raw	mm 2	-0.03807	-0.03676
Transformation, to seabed, drilling and mining	Raw	mm 2	4.818741	3.983038
Transformation, to seabed, infrastructure	Raw	mm 2	0.002911	0.002458
Transformation, to seabed, unspecified	Raw	mm 2	0.000493	0.000406
Transformation, to shrub land, sclerophyllous	Raw	mm 2	1.028458	1.096342
Transformation, to traffic area, rail network	Raw	mm 2	0.018563	0.019313
Transformation, to traffic area, rail/road embankment	Raw	mm 2	0.482372	0.482102
Transformation, to traffic area, road network	Raw	mm 2	0.579162	0.616674
Transformation, to unknown	Raw	mm 2	0.114699	0.125898
Transformation, to urban, discontinuously built	Raw	mm 2	0.000695	0.000675
Transformation, to urban/industrial fallow	Raw	mm 2	7.31E-06	6.86E-06
Transformation, to water bodies, artificial	Raw	mm 2	7.691597	14.99049
Ulexite	Raw	µg	1.851344	2.461443
Uranium	Raw	µg	514.3664	872.2272
Volume occupied, final repository for low-active radioactive waste	Raw	mm 3	1.28871	2.417764
Volume occupied, final repository for radioactive waste	Raw	mm 3	0.148852	0.251445
Volume occupied, reservoir	Raw	m3d ay	0.822134	2.647503
Volume occupied, underground deposit	Raw	mm 3	1.780296	1.500528
Water, cooling, unspecified natural origin, AT	Raw	mm 3	741.7211	801.0184
Water, cooling, unspecified natural origin, AU	Raw	mm 3	876.4015	816.7999
Water, cooling, unspecified natural origin, BA	Raw	mm 3	70.26453	65.48494
Water, cooling, unspecified natural origin, BE	Raw	mm 3	593.2064	607.2412
Water, cooling, unspecified natural origin, BG	Raw	mm 3	47.89801	49.32462
Water, cooling, unspecified natural origin, BR	Raw	cm3	1.809808	1.740578
Water, cooling, unspecified natural origin, CA	Raw	cm3	-12.5793	-11.6961
Water, cooling, unspecified natural origin, CH	Raw	cm3	1.170557	1.659391
Water, cooling, unspecified natural origin, CL	Raw	mm 3	250.2371	240.7722
Water, cooling, unspecified natural origin, CN	Raw	cm3	72.0218	68.98103
Water, cooling, unspecified natural origin, CY	Raw	mm 3	58.38102	56.13826

Water, cooling, unspecified natural origin, CZ	Raw	cm3	17.2393	15.97151
Water, cooling, unspecified natural origin, DE	Raw	cm3	6.800073	6.335295
Water, cooling, unspecified natural origin, DK	Raw	mm3	474.5789	446.5038
Water, cooling, unspecified natural origin, EE	Raw	mm3	6.258986	5.829764
Water, cooling, unspecified natural origin, ES	Raw	cm3	1.730098	1.873829
Water, cooling, unspecified natural origin, Europe without Switzerland	Raw	mm3	658.8631	643.1421
Water, cooling, unspecified natural origin, FI	Raw	mm3	190.8998	190.1653
Water, cooling, unspecified natural origin, FR	Raw	mm3	258.4508	239.9092
Water, cooling, unspecified natural origin, GB	Raw	cm3	2.427613	2.448944
Water, cooling, unspecified natural origin, GLO	Raw	mm3	977.3643	922.4622
Water, cooling, unspecified natural origin, GR	Raw	cm3	5.777179	5.367958
Water, cooling, unspecified natural origin, HR	Raw	mm3	209.6464	217.8587
Water, cooling, unspecified natural origin, HU	Raw	mm3	610.1363	571.2981
Water, cooling, unspecified natural origin, IAI Area, Africa	Raw	mm3	0.420203	0.371314
Water, cooling, unspecified natural origin, IAI Area, Asia, without China and GCC	Raw	mm3	0.00032	0.000283
Water, cooling, unspecified natural origin, IAI Area, EU27 & EFTA	Raw	mm3	1.995578	1.763399
Water, cooling, unspecified natural origin, IAI Area, Gulf Cooperation Council	Raw	mm3	0.000546	0.000482
Water, cooling, unspecified natural origin, IAI Area, Russia & RER w/o EU27 & EFTA	Raw	mm3	2.226092	1.967106
Water, cooling, unspecified natural origin, IAI Area, South America	Raw	mm3	0.311699	0.275436
Water, cooling, unspecified natural origin, ID	Raw	cm3	2.385717	2.285591
Water, cooling, unspecified natural origin, IE	Raw	mm3	45.25548	42.26835
Water, cooling, unspecified natural origin, IN	Raw	cm3	38.587	37.04886
Water, cooling, unspecified natural origin, IR	Raw	cm3	3.002384	2.885525
Water, cooling, unspecified natural origin, IS	Raw	mm3	0.037507	0.033153
Water, cooling, unspecified natural origin, IT	Raw	cm3	6.393556	6.98084
Water, cooling, unspecified natural origin, JP	Raw	mm3	-582.519	-631.449
Water, cooling, unspecified natural origin, KR	Raw	cm3	5.949792	5.722774
Water, cooling, unspecified natural origin, LT	Raw	mm3	293.1026	274.1632
Water, cooling, unspecified natural origin, LU	Raw	mm3	200.2708	216.1042
Water, cooling, unspecified natural origin, LV	Raw	mm3	180.5301	195.6974

Water, cooling, unspecified natural origin, MA	Raw	mm3	2.776864	2.433658
Water, cooling, unspecified natural origin, MK	Raw	mm3	84.1609	85.71649
Water, cooling, unspecified natural origin, MT	Raw	mm3	42.68559	39.86876
Water, cooling, unspecified natural origin, MX	Raw	cm3	2.80841	2.692199
Water, cooling, unspecified natural origin, MY	Raw	cm3	1.41487	1.360065
Water, cooling, unspecified natural origin, NL	Raw	cm3	3.577211	3.865835
Water, cooling, unspecified natural origin, NO	Raw	mm3	10.16452	9.216564
Water, cooling, unspecified natural origin, OCE	Raw	mm3	0.030811	0.027226
Water, cooling, unspecified natural origin, PE	Raw	mm3	353.5758	339.7402
Water, cooling, unspecified natural origin, PH	Raw	mm3	0.101545	0.086001
Water, cooling, unspecified natural origin, PL	Raw	cm3	31.53428	29.31401
Water, cooling, unspecified natural origin, PT	Raw	mm3	115.767	125.1846
Water, cooling, unspecified natural origin, RER	Raw	cm3	8.959424	8.745176
Water, cooling, unspecified natural origin, RNA	Raw	mm3	2.592348	2.290803
Water, cooling, unspecified natural origin, RO	Raw	mm3	511.7671	481.4264
Water, cooling, unspecified natural origin, RoW	Raw	cu.in	100.9217	154.5055
Water, cooling, unspecified natural origin, RS	Raw	mm3	195.3948	182.7154
Water, cooling, unspecified natural origin, RU	Raw	cm3	70.7208	68.79619
Water, cooling, unspecified natural origin, SA	Raw	cm3	2.691381	2.586328
Water, cooling, unspecified natural origin, SE	Raw	mm3	109.7625	101.7683
Water, cooling, unspecified natural origin, SI	Raw	cm3	2.84335	2.633837
Water, cooling, unspecified natural origin, SK	Raw	cm3	2.72822	2.525922
Water, cooling, unspecified natural origin, TH	Raw	dm3	22.4432	19.69613
Water, cooling, unspecified natural origin, TR	Raw	cm3	3.354964	3.21611
Water, cooling, unspecified natural origin, TW	Raw	cm3	2.705248	2.596681
Water, cooling, unspecified natural origin, UA	Raw	cm3	2.265813	2.113491
Water, cooling, unspecified natural origin, US	Raw	cm3	13.41823	15.44641
Water, cooling, unspecified natural origin, WEU	Raw	mm3	-0.04436	-0.04266
Water, cooling, unspecified natural origin, ZA	Raw	mm3	524.891	504.9804
Water, lake, CA	Raw	cm3	1.409034	1.340498
Water, lake, CH	Raw	mm3	33.39424	33.30954
Water, lake, CN	Raw	mm3	8.00E-05	0.000138
Water, lake, DE	Raw	mm3	5.092332	4.851659

Water, lake, Europe without Switzerland	Raw	mm3	967.3073	981.7153
Water, lake, RER	Raw	mm3	0.111086	0.101627
Water, lake, RNA	Raw	mm3	2.72E-05	4.69E-05
Water, lake, RoW	Raw	mm3	91.56324	157.7225
Water, lake, US	Raw	mm3	0.000428	0.000448
Water, river, AU	Raw	mm3	30.91638	23.93571
Water, river, BR	Raw	mm3	-18.3891	-17.737
Water, river, CA	Raw	mm3	-0.58613	-0.14791
Water, river, CH	Raw	mm3	195.5967	195.7675
Water, river, CN	Raw	mm3	-177.832	-171.525
Water, river, DE	Raw	mm3	-28.5249	-27.5566
Water, river, ES	Raw	mm3	-125.667	-121.222
Water, river, Europe without Switzerland	Raw	mm3	115.301	112.5499
Water, river, FR	Raw	mm3	-42.139	-40.6482
Water, river, GLO	Raw	mm3	646.4045	647.3737
Water, river, IN	Raw	mm3	-174.8	-168.514
Water, river, MY	Raw	mm3	-277.809	-267.499
Water, river, NL	Raw	mm3	0.079889	0.070698
Water, river, PE	Raw	mm3	0.004692	0.004604
Water, river, PH	Raw	mm3	-20.4448	-20.7691
Water, river, RAS	Raw	mm3	574.042	445.4884
Water, river, RER	Raw	cm3	281.5089	268.7992
Water, river, RLA	Raw	mm3	130.2209	101.6096
Water, river, RNA	Raw	mm3	217.2809	168.8878
Water, river, RO	Raw	mm3	5.788922	5.117
Water, river, RoW	Raw	cm3	708.3257	676.3176
Water, river, RU	Raw	mm3	-0.02881	-0.36504

Water, river, SE	Raw	mm3	0.674289	0.564522
Water, river, TN	Raw	mm3	-0.72317	-0.69752
Water, river, TZ	Raw	mm3	0.071908	0.070557
Water, river, US	Raw	mm3	261.1021	251.815
Water, river, WEU	Raw	mm3	-8.63E-07	-9.83E-07
Water, river, ZA	Raw	mm3	6.725723	6.524628
Water, salt, ocean	Raw	cm3	42.8637	35.35732
Water, salt, sole	Raw	mm3	511.1812	493.5767
Water, turbine use, unspecified natural origin, AT	Raw	cm3	-96.831	-107.186
Water, turbine use, unspecified natural origin, AU	Raw	cm3	48.78402	41.56446
Water, turbine use, unspecified natural origin, BA	Raw	cm3	88.48587	80.68138
Water, turbine use, unspecified natural origin, BE	Raw	mm3	-518.067	-987.306
Water, turbine use, unspecified natural origin, BG	Raw	cm3	3.263485	2.995637
Water, turbine use, unspecified natural origin, BR	Raw	cm3	255.5501	240.4912
Water, turbine use, unspecified natural origin, CA	Raw	cu.in	-69.7162	-64.556
Water, turbine use, unspecified natural origin, CH	Raw	cm3	578.0708	835.2889
Water, turbine use, unspecified natural origin, CL	Raw	cm3	93.42678	89.89302
Water, turbine use, unspecified natural origin, CN	Raw	cu.in	377.833	361.5807
Water, turbine use, unspecified natural origin, CZ	Raw	cm3	-11.6086	-10.84
Water, turbine use, unspecified natural origin, DE	Raw	cm3	3.123169	3.432117
Water, turbine use, unspecified natural origin, DK	Raw	mm3	-54.7285	-50.846
Water, turbine use, unspecified natural origin, ES	Raw	cm3	10.98165	9.311372
Water, turbine use, unspecified natural origin, FR	Raw	m3	2.750067	2.500089
Water, turbine use, unspecified natural origin, GB	Raw	mm3	554.2332	489.9032
Water, turbine use, unspecified natural origin, GR	Raw	cm3	7.037036	6.220245
Water, turbine use, unspecified natural origin, HR	Raw	mm3	-473.653	-545.725
Water, turbine use, unspecified natural origin, ID	Raw	mm3	539.9963	477.5652
Water, turbine use, unspecified natural origin, IE	Raw	cm3	3.900393	3.642943
Water, turbine use, unspecified natural origin, IN	Raw	cm3	332.0192	319.173
Water, turbine use, unspecified natural origin, IR	Raw	cm3	552.5095	530.6197
Water, turbine use, unspecified natural origin, IS	Raw	cm3	70.48719	62.30573
Water, turbine use, unspecified natural origin, IT	Raw	cm3	-100.159	-110.898
Water, turbine use, unspecified natural origin, JP	Raw	cm3	-31.0312	-34.8051
Water, turbine use, unspecified natural origin, KR	Raw	cm3	703.6488	676.3153
Water, turbine use, unspecified natural origin, LU	Raw	cm3	-4.43643	-4.99401

Water, turbine use, unspecified natural origin, LV	Raw	mm3	-234.133	-274.949
Water, turbine use, unspecified natural origin, MK	Raw	cm3	16.04127	14.23631
Water, turbine use, unspecified natural origin, MX	Raw	cm3	513.4917	492.2382
Water, turbine use, unspecified natural origin, MY	Raw	mm3	480.9929	425.3834
Water, turbine use, unspecified natural origin, NL	Raw	mm3	51.02379	45.10144
Water, turbine use, unspecified natural origin, NO	Raw	cm3	15.87511	14.13581
Water, turbine use, unspecified natural origin, NP	Raw	cm3	10.42211	10.01401
Water, turbine use, unspecified natural origin, PE	Raw	mm3	277.752	266.8835
Water, turbine use, unspecified natural origin, PL	Raw	cm3	-46.9179	-44.4657
Water, turbine use, unspecified natural origin, PT	Raw	cm3	54.14598	45.39819
Water, turbine use, unspecified natural origin, RER	Raw	mm3	-4.29115	-4.23469
Water, turbine use, unspecified natural origin, RNA	Raw	mm3	0.001269	0.00219
Water, turbine use, unspecified natural origin, RO	Raw	cm3	36.39784	32.51231
Water, turbine use, unspecified natural origin, RoW	Raw	m3	1.741281	1.741301
Water, turbine use, unspecified natural origin, RS	Raw	cm3	101.9819	95.36416
Water, turbine use, unspecified natural origin, RU	Raw	cm3	-222.462	-238.647
Water, turbine use, unspecified natural origin, SE	Raw	cm3	29.58887	26.15448
Water, turbine use, unspecified natural origin, SI	Raw	cm3	-4.23431	-4.27146
Water, turbine use, unspecified natural origin, SK	Raw	cm3	9.494474	7.954014
Water, turbine use, unspecified natural origin, TH	Raw	dm3	67.5	337.5
Water, turbine use, unspecified natural origin, TR	Raw	cm3	463.6578	443.9352
Water, turbine use, unspecified natural origin, TW	Raw	cm3	391.9374	375.952
Water, turbine use, unspecified natural origin, UA	Raw	cm3	413.9117	385.838
Water, turbine use, unspecified natural origin, US	Raw	cu.in	37.52413	64.16933
Water, turbine use, unspecified natural origin, ZA	Raw	cm3	12.65261	12.10133
Water, unspecified natural origin, AU	Raw	mm3	1.09E-09	1.12E-09
Water, unspecified natural origin, CA	Raw	mm3	-730.956	-682.957
Water, unspecified natural origin, CH	Raw	cm3	1.25652	1.700329
Water, unspecified natural origin, CL	Raw	mm3	-0.02579	-0.0223
Water, unspecified natural origin, CN	Raw	mm3	91.26214	80.64112
Water, unspecified natural origin, DE	Raw	mm3	-0.2108	-0.20045
Water, unspecified natural origin, Europe without Switzerland	Raw	cm3	1.076302	1.379354
Water, unspecified natural origin, GLO	Raw	cm3	2.718412	2.530783
Water, unspecified natural origin, IAI Area, Africa	Raw	mm3	4.60124	4.065929
Water, unspecified natural origin, IAI Area, Asia, without China and GCC	Raw	mm3	9.264454	8.186301

Water, unspecified natural origin, IAI Area, EU27 & EFTA	Raw	mm3	23.35868	20.64068
Water, unspecified natural origin, IAI Area, Gulf Cooperation Council	Raw	mm3	0.412375	0.364397
Water, unspecified natural origin, IAI Area, Russia & RER w/o EU27 & EFTA	Raw	mm3	33.92009	29.97358
Water, unspecified natural origin, IAI Area, South America	Raw	mm3	11.60613	10.25514
Water, unspecified natural origin, IN	Raw	mm3	28.46101	27.46691
Water, unspecified natural origin, OCE	Raw	mm3	12.75548	11.27047
Water, unspecified natural origin, PG	Raw	mm3	0.056893	0.055824
Water, unspecified natural origin, PH	Raw	mm3	0.025386	0.0215
Water, unspecified natural origin, RAF	Raw	mm3	82.17887	80.92834
Water, unspecified natural origin, RER	Raw	cm3	1.366752	1.259694
Water, unspecified natural origin, RLA	Raw	mm3	6.878862	7.496986
Water, unspecified natural origin, RME	Raw	mm3	808.0922	795.7953
Water, unspecified natural origin, RNA	Raw	mm3	296.8638	485.5417
Water, unspecified natural origin, RoW	Raw	cm3	54.64777	55.26396
Water, unspecified natural origin, RU	Raw	mm3	114.9912	113.2414
Water, unspecified natural origin, TH	Raw	mm3	9.35E-05	0.000115
Water, unspecified natural origin, US	Raw	mm3	123.069	137.7903
Water, unspecified natural origin, WEU	Raw	mm3	-0.00267	-0.00268
Water, unspecified natural origin, ZA	Raw	mm3	2.748814	2.651753
Water, well, AT	Raw	mm3	1.01E-05	1.01E-05
Water, well, AU	Raw	mm3	141.8789	137.956
Water, well, BR	Raw	mm3	-4.25201	-4.10121
Water, well, CA	Raw	mm3	0.961676	0.946577
Water, well, CH	Raw	mm3	96.11792	94.55868
Water, well, CN	Raw	cm3	2.003219	1.93913
Water, well, DE	Raw	mm3	-103.917	-100.231
Water, well, ES	Raw	mm3	-74.1535	-71.5302
Water, well, Europe, without Russia and Turkey	Raw	mm3	31.1525	29.0336

Water, well, FR	Raw	mm3	-33.9242	-32.724
Water, well, GLO	Raw	mm3	547.2572	457.4898
Water, well, ID	Raw	mm3	289.797	282.0817
Water, well, IN	Raw	cm3	2.455723	2.37451
Water, well, IS	Raw	mm3	0.052635	0.052716
Water, well, IT	Raw	mm3	0.056474	0.056561
Water, well, JP	Raw	mm3	0.026368	0.026409
Water, well, MA	Raw	mm3	0.212281	0.191485
Water, well, MX	Raw	mm3	0.058767	0.058858
Water, well, MY	Raw	mm3	-24.1573	-23.2608
Water, well, NORDEL	Raw	mm3	1.11E-05	9.68E-06
Water, well, PE	Raw	mm3	0.007609	0.007466
Water, well, PG	Raw	mm3	0.491351	0.482117
Water, well, PH	Raw	mm3	-3.19627	-3.24697
Water, well, PT	Raw	mm3	0.001475	0.001477
Water, well, RER	Raw	mm3	441.284	409.991
Water, well, RLA	Raw	mm3	25.83023	24.85315
Water, well, RNA	Raw	mm3	-109.074	-98.8193
Water, well, RoW	Raw	cm3	448.7029	473.6424
Water, well, RU	Raw	mm3	159.1071	154.2504
Water, well, SE	Raw	mm3	0.117271	0.098181
Water, well, TH	Raw	mm3	1.01E-05	1.01E-05
Water, well, TN	Raw	mm3	-1.11228	-1.07284
Water, well, TR	Raw	mm3	0.006676	0.006703
Water, well, US	Raw	mm3	605.0034	583.314
Water, well, WEU	Raw	mm3	5.02E-05	3.90E-05
Water, well, ZA	Raw	mm3	9.270198	8.972409
Wood, hard, standing	Raw	cm3	2.579277	2.574272

Wood, soft, standing	Raw	cm3	2.656708	2.65045
Wood, unspecified, standing/m3	Raw	mm3	0.000259	0.000277
Zinc	Raw	µg	-357.384	-269.43
Zinc, Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore	Raw	µg	505.6636	423.3458
Zirconium	Raw	ng	15.25119	16.47516

Table C2: Inventory data for generation of 1 MJ of electricity in 2020 and 2036 (Airborne emission)

Substance	Compartment	Unit	Electricity TH 2020 medium voltage	Electricity TH 2036 medium voltage
1-Butanol	Air	pg	926.5724	855.3685
1-Pentanol	Air	pg	77.55615	73.12576
1-Pentene	Air	pg	106.8504	102.9114
1-Propanol	Air	ng	2.901803	2.793521
1,4-Butanediol	Air	pg	987.9136	950.1468
2-Aminopropanol	Air	pg	99.10526	93.64489
2-Butene, 2-methyl-	Air	pg	0.035202	0.033194
2-Methyl-1-propanol	Air	pg	298.3164	282.0225
2-Methyl-4-chlorophenoxyacetic acid	Air	pg	-8.86809	-8.55444
2-Nitrobenzoic acid	Air	pg	236.619	223.5105
2-Propanol	Air	µg	-2.79725	-2.06088
2,4-D	Air	ng	94.47698	91.11392
4-Methyl-2-pentanone	Air	pg	-5.32479	-5.06539
Acenaphthene	Air	ng	2.58198	2.139707
Acenaphthylene	Air	ng	-60.1758	-55.9403
Acephate	Air	ng	10.04232	9.684849
Acetaldehyde	Air	µg	15.07781	14.50795
Acetamide	Air	ng	2.472076	2.384079
Acetic acid	Air	µg	377.7244	314.4347
Acetone	Air	µg	24.90799	24.77031
Acetonitrile	Air	µg	1.734755	1.673186
Acifluorfen	Air	ng	1.378553	1.329481
Acrolein	Air	ng	187.0546	189.1287
Acrylic acid	Air	pg	558.6833	605.6478
Actinides, radioactive, unspecified	Air	µBq	276.4019	264.3971
Aerosols, radioactive, unspecified	Air	nBq	308.3951	535.3746
Alachlor	Air	ng	9.755733	9.408461
Aldehydes, unspecified	Air	ng	443.3028	601.9601
Aluminium	Air	µg	656.178	617.5401

Ammonia	Air	mg	1.279834	1.261084
Ammonium carbonate	Air	pg	731.6931	668.815
Aniline	Air	pg	226.2878	207.3384
Anthracene	Air	pg	4.54E-05	4.38E-05
Anthranilic acid	Air	pg	184.2992	174.087
Antimony	Air	µg	6.055322	6.236078
Antimony-124	Air	nBq	10.44417	40.46742
Antimony-125	Air	nBq	512.7701	512.8393
Argon-40	Air	mg	2.904649	2.333616
Argon-41	Air	mBq	0.03409	14.9041
Arsenic	Air	µg	10.43784	9.620779
Arsine	Air	pg	0.006513	0.00706
Atrazine	Air	ng	7.716465	7.441785
Azoxystrobin	Air	ng	4.562033	4.39964
Barium	Air	µg	21.6566	22.72983
Barium-140	Air	µBq	0.037406	25.88956
Bentazone	Air	ng	4.228194	4.077685
Benzal chloride	Air	pg	1.155163	0.983269
Benzaldehyde	Air	ng	363.4037	366.1794
Benzene	Air	µg	885.0122	890.7343
Benzene, 1-methyl-2-nitro-	Air	pg	204.3246	193.0052
Benzene, 1,2-dichloro-	Air	ng	1.570187	1.500095
Benzene, ethyl-	Air	µg	7.418712	6.936868
Benzene, hexachloro-	Air	ng	-2.70645	-2.48329
Benzene, pentachloro-	Air	pg	166.2197	172.9672
Benzo(a)anthracene	Air	ng	-1.16222	-1.08042
Benzo(a)pyrene	Air	µg	3.494074	3.497615
Benzo(b)fluoranthene	Air	ng	-1.3746	-1.27785
Benzo(g,h,i)perylene	Air	pg	-84.6591	-78.7004
Benzo(k)fluoranthene	Air	pg	-994.081	-924.112
Beryllium	Air	ng	14.20329	12.91098
Boric acid	Air	pg	0.00029	0.000297
Boron	Air	mg	2.26034	2.384217
Boron trifluoride	Air	pg	1.946228	1.988921
Bromine	Air	µg	88.40988	92.50601
Bromoxynil	Air	pg	-8.65809	-8.35187
Butadiene	Air	pg	63.77423	60.40083
Butane	Air	mg	2.868123	2.374375
Butene	Air	ng	867.1986	855.7634
Butyric acid, 4-(2,4-dichlorophenoxy)-	Air	pg	-3.261	-3.14566
Cadmium	Air	µg	3.704248	3.285485

Calcium	Air	µg	379.6957	382.7005
Carbaryl	Air	ng	1.151621	1.110627
Carbon	Air	ng	4.32807	4.258569
Carbon-14	Air	Bq	0.439537	1.291866
Carbon dioxide, biogenic	Air	g	5.097947	5.086154
Carbon dioxide, fossil	Air	g	300.3621	278.5024
Carbon dioxide, land transformation	Air	g	0.339842	1.286447
Carbon disulfide	Air	µg	124.438	103.4037
Carbon monoxide, biogenic	Air	mg	5.938979	5.898361
Carbon monoxide, fossil	Air	mg	112.2552	99.40266
Carbon monoxide, land transformation	Air	mg	1.002303	0.96673
Carbonyl sulfide	Air	µg	1.122899	0.998033
Carfentrazone-ethyl	Air	pg	126.5477	122.043
Cerium-141	Air	µBq	0.007386	6.275837
Cesium-134	Air	nBq	0.353727	300.5722
Cesium-137	Air	µBq	0.165653	5.363902
Chloramine	Air	pg	517.9674	488.856
Chlorimuron-ethyl	Air	ng	2.302462	2.220502
Chlorinated solvents, unspecified	Air	µg	-8.30624	-8.319
Chlorine	Air	µg	14.80257	14.45529
Chloroacetic acid	Air	ng	6.748159	6.528769
Chloroform	Air	ng	19.73045	53.68442
Chlorosilane, trimethyl-	Air	ng	10.21718	7.762517
Chlorosulfonic acid	Air	pg	480.0757	460.8289
Chlorpyrifos	Air	ng	45.93227	44.29723
Chromium	Air	µg	56.00704	57.26342
Chromium-51	Air	nBq	0.473274	402.1545
Chromium IV	Air	pg	0.007576	0.007456
Chromium VI	Air	µg	1.697511	1.749014
Chrysene	Air	pg	-126.841	-117.913
Clethodim	Air	ng	6.811857	6.569377
Cloransulam-methyl	Air	ng	1.199191	1.156504
Cobalt	Air	µg	1.609673	1.637184
Cobalt-58	Air	nBq	359.7081	640.5165
Cobalt-60	Air	µBq	1.66314	5.318802
Copper	Air	µg	32.78378	30.6245
Cumene	Air	µg	1.25279	1.076138
Cyanide	Air	µg	35.22919	34.05297
Cyanoacetic acid	Air	pg	393.0823	377.2622
Cyclohexane	Air	pg	275.4792	271.1668

Cyfluthrin	Air	pg	240.3841	231.8272
Cyhalothrin, gamma-	Air	ng	2.758665	2.660466
Dibenz(a,h)anthracene	Air	pg	-646.005	-600.536
Dicamba	Air	pg	772.0366	744.5548
Diethyl ether	Air	pg	0.024238	0.024769
Diethylamine	Air	pg	122.1063	112.5285
Diethylene glycol	Air	pg	0.020537	0.020987
Diflubenzuron	Air	pg	126.5477	122.043
Dimethenamid	Air	pg	1.53E-05	1.62E-05
Dimethyl malonate	Air	pg	492.9265	473.0879
Dimethylamine	Air	pg	1.329814	2.293177
Dinitrogen monoxide	Air	mg	6.381217	5.970764
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	pg	22.89247	22.41222
Dipropylamine	Air	pg	21.54286	18.53378
Esfenvalerate	Air	ng	1.437625	1.386451
Ethane	Air	mg	9.798227	8.121028
Ethane, 1,1-difluoro-, HFC-152a	Air	ng	16.42864	16.77434
Ethane, 1,1,1-trichloro-, HCFC-140	Air	ng	2.667166	2.5513
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	ng	80.434	129.5386
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	ng	2.674403	2.574681
Ethane, 1,2-dichloro-	Air	ng	102.7196	109.1124
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	µg	2.381715	3.981976
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	ng	2.647886	2.545935
Ethane, hexafluoro-, HFC-116	Air	ng	79.5586	70.68751
Ethanol	Air	µg	1.09364	1.329959
Ethene	Air	µg	29.39676	27.8938
Ethene, chloro-	Air	ng	36.21017	37.37764
Ethene, tetrachloro-	Air	ng	6.3834	6.105796
Ethene, trichloro-	Air	ng	7.450561	7.171506
Ethyl acetate	Air	ng	320.1371	347.0891
Ethyl cellulose	Air	pg	626.1459	678.8373
Ethylamine	Air	pg	404.5419	383.2111
Ethylene diamine	Air	pg	131.8136	134.0234
Ethylene oxide	Air	ng	28.41611	27.60903
Ethyne	Air	ng	632.1898	598.118
Fenoxaprop	Air	ng	1.881741	1.814758
Fluazifop-p-butyl	Air	ng	2.700178	2.604061
Flufenacet	Air	ng	1.012421	0.976382
Flumetsulam	Air	pg	236.8748	228.4429
Flumiclorac-pentyl	Air	pg	405.3191	390.8911
Flumioxazin	Air	ng	4.099981	3.954036
Fluoranthene	Air	ng	-10.5898	-9.8444
Fluorene	Air	ng	-9.61632	-8.93948
Fluorine	Air	µg	3.403234	3.307903

Fluosilicic acid	Air	ng	509.2418	449.9932
Fomesafen	Air	ng	15.24382	14.70119
Formaldehyde	Air	µg	214.1238	200.5608
Formamide	Air	pg	141.8423	133.7396
Formic acid	Air	µg	10.60171	10.22548
Furan	Air	µg	46.26013	44.6183
Glyphosate	Air	µg	3.047531	2.939049
Heat, waste	Air	J	677.8252	682.6372
Helium	Air	µg	56.26049	46.45611
Heptane	Air	µg	9.580642	9.426128
Hexane	Air	mg	2.370459	1.966251
Hydrocarbons, aliphatic, alkanes, cyclic	Air	µg	2.835146	2.735024
Hydrocarbons, aliphatic, alkanes, unspecified	Air	µg	423.4718	430.2004
Hydrocarbons, aliphatic, unsaturated	Air	µg	424.8503	438.6386
Hydrocarbons, aromatic	Air	mg	5.380447	4.423171
Hydrocarbons, chlorinated	Air	ng	34.97849	48.72971
Hydrocarbons, unspecified	Air	µg	3.78701	3.647533
Hydrogen	Air	µg	37.86903	44.22604
Hydrogen-3, Tritium	Air	Bq	0.64765	1.976072
Hydrogen chloride	Air	mg	7.282019	7.637042
Hydrogen fluoride	Air	mg	2.749081	2.893832
Hydrogen peroxide	Air	pg	470.8618	510.498
Hydrogen sulfide	Air	mg	1.486758	1.225842
Imazamox	Air	pg	606.3215	584.7385
Imazaquin	Air	ng	1.933015	1.864207
Imazethapyr	Air	ng	4.000552	3.858146
Indeno(1,2,3-cd)pyrene	Air	pg	-253.977	-236.101
Iodine	Air	µg	60.59673	63.63414
Iodine-129	Air	µBq	178.1179	300.8823
Iodine-131	Air	µBq	79.50402	974.1012
Iodine-133	Air	µBq	39.88212	39.8875
Iron	Air	µg	16.66109	16.77226
Isocyanic acid	Air	µg	2.113377	2.313871
Isoprene	Air	ng	154.2006	148.7278
Isopropylamine	Air	pg	184.482	174.5739
Krypton-85	Air	mBq	0.127643	65.16906
Krypton-85m	Air	mBq	216.5252	420.8696
Krypton-87	Air	mBq	0.097724	82.65776
Krypton-88	Air	mBq	0.129126	109.3753

Krypton-89	Air	mBq	0.054895	46.61656
Lactic acid	Air	pg	16.87949	14.52213
Lactofen	Air	ng	1.946663	1.877368
Lanthanum-140	Air	µBq	0.002604	2.212546
Lead	Air	µg	26.18741	23.59748
Lead-210	Air	mBq	11.83934	12.72859
Lithium	Air	pg	0.73924	0.727368
m-Xylene	Air	µg	6.36598	6.35495
Magnesium	Air	µg	22.25855	21.97309
Manganese	Air	µg	23.37261	23.41379
Manganese-54	Air	nBq	0.242369	205.9476
Mercury	Air	µg	6.934177	7.221637
Methane	Air	ng	14.78454	14.57791
Methane, biogenic	Air	mg	11.97903	57.25178
Methane, bromo-, Halon 1001	Air	pg	0.264241	0.224921
Methane, bromochlorodifluoro-, Halon 1211	Air	ng	58.08993	50.01633
Methane, bromotrifluoro-, Halon 1301	Air	µg	1.018981	0.843526
Methane, chlorodifluoro-, HCFC-22	Air	µg	1.608425	1.588343
Methane, dichloro-, HCC-30	Air	µg	-11.5825	-10.7651
Methane, dichlorodifluoro-, CFC-12	Air	ng	-1.08454	-1.0343
Methane, dichlorofluoro-, HCFC-21	Air	pg	0.229807	0.24925
Methane, fossil	Air	mg	388.1363	329.2242
Methane, land transformation	Air	µg	65.53519	63.20925
Methane, monochloro-, R-40	Air	ng	70.63472	67.56672
Methane, tetrachloro-, CFC-10	Air	ng	7.479214	10.36464
Methane, tetrafluoro-, CFC-14	Air	µg	1.309992	1.157617
Methane, trichlorofluoro-, CFC-11	Air	pg	0.253529	0.274981
Methane, trifluoro-, HFC-23	Air	pg	73.12035	79.30684
Methanesulfonic acid	Air	pg	397.2212	381.2345
Methanol	Air	µg	24.73162	23.78677
Methyl acetate	Air	pg	54.78865	51.7534
Methyl acrylate	Air	pg	633.9279	687.2176
Methyl borate	Air	pg	102.8249	97.03899
Methyl ethyl ketone	Air	ng	320.2476	347.204
Methyl formate	Air	ng	-10.2412	-9.56075
Methyl lactate	Air	pg	18.52499	15.93731
Methylamine	Air	pg	252.1734	242.191
Metolachlor	Air	ng	31.88621	30.75117
Metribuzin	Air	ng	12.62552	12.1761
Molybdenum	Air	µg	2.447615	2.579295
Monoethanolamine	Air	µg	6.144613	6.140118

Naphthalene	Air	pg	123.9352	104.9698
Nickel	Air	µg	28.07793	26.55713
Niobium-95	Air	µBq	9.001822	7.979785
Nitrate	Air	µg	1.0463	1.579349
Nitrobenzene	Air	ng	1.435665	1.407962
Nitrogen fluoride	Air	pg	0.005682	0.005807
Nitrogen oxides	Air	mg	484.7271	481.3159
Nitrogen, atmospheric	Air	mg	186.7341	173.2206
NMVOC, non-methane volatile organic compounds, unspecified origin	Air	mg	65.41787	55.20501
Noble gases, radioactive, unspecified	Air	kBq	1.714786	2.892757
o-Xylene	Air	ng	21.89337	23.06146
Organic carbon	Air	ng	10.76461	10.59175
Ozone	Air	mg	1.221449	1.221742
PAH, polycyclic aromatic hydrocarbons	Air	µg	30.55149	26.26647
Paraquat	Air	ng	8.121979	7.832864
Parathion, methyl	Air	ng	1.558695	1.50321
Particulates, < 2.5 um	Air	mg	81.29482	84.26797
Particulates, > 10 um	Air	mg	71.6518	74.71246
Particulates, > 2.5 um, and < 10um	Air	mg	14.57235	14.93211
Pendimethalin	Air	ng	85.56737	82.52146
Pentane	Air	mg	3.60797	3.024259
Pentane, 2-methyl-	Air	ng	4.479998	4.418138
Pentane, 2,2,4-trimethyl-	Air	pg	0.112412	0.10841
Permethrin	Air	ng	1.271521	1.226259
Phenanthrene	Air	ng	-148.08	-137.657
Phenol	Air	µg	2.136612	1.683019
Phenol, 2,4-dichloro-	Air	ng	1.695596	1.630728
Phenol, pentachloro-	Air	µg	1.51265	1.515686
Phosgene	Air	pg	194.8583	196.0806
Phosphine	Air	pg	13.75046	14.08184
Phosphoric acid	Air	pg	0.010279	0.010504
Phosphorus	Air	µg	15.90905	15.8833
Phosphorus trichloride	Air	pg	5.193992	4.861221
Platinum	Air	ng	6.443784	6.85987
Plutonium-238	Air	nBq	0.024298	0.041045
Plutonium-alpha	Air	nBq	0.0557	0.094091
Polonium-210	Air	mBq	21.3972	22.89747
Polychlorinated biphenyls	Air	ng	2.681414	2.553791
Potassium	Air	mg	1.231551	1.228769
Potassium-40	Air	mBq	3.880494	4.054544

Propanal	Air	ng	72.16462	71.76111
Propane	Air	mg	4.027737	3.335382
Propene	Air	µg	27.88485	28.55893
Propiconazole	Air	ng	1.492614	1.439482
Propionic acid	Air	µg	46.72013	38.47597
Propylamine	Air	pg	54.11792	51.22823
Propylene oxide	Air	ng	23.7864	24.64071
Protactinium-234	Air	µBq	133.9461	214.8946
Pyraclostrobin (prop)	Air	ng	3.517143	3.391944
Pyrene	Air	ng	-7.72846	-7.18449
Quizalofop ethyl ester	Air	pg	471.995	455.1935
Radioactive species, other beta emitters	Air	mBq	29.83099	34.97815
Radium-226	Air	mBq	6.087625	8.420027
Radium-228	Air	mBq	1.678211	1.755927
Radon-220	Air	mBq	161.3334	169.3315
Radon-222	Air	Bq	274.6074	464.9195
Ruthenium-103	Air	nBq	0.006321	5.371337
Scandium	Air	ng	2.269482	3.389365
Selenium	Air	µg	15.72971	16.42513
Sethoxydim	Air	ng	1.01593	0.979766
Silicon	Air	µg	12.632	11.9308
Silicon tetrafluoride	Air	ng	2.297817	2.01382
Silver	Air	pg	726.4502	778.5809
Silver-110	Air	nBq	68.58848	68.59773
Sodium	Air	µg	71.25953	71.08713
Sodium chlorate	Air	ng	35.38215	39.37662
Sodium dichromate	Air	pg	247.377	248.4666
Sodium formate	Air	ng	-1.09743	-1.06737
Sodium hydroxide	Air	ng	1.742305	1.888836
Sodium tetrahydroborate	Air	pg	3.772586	3.855269
Strontium	Air	µg	17.59841	18.45081
Styrene	Air	µg	3.236739	3.125975
Sulfate	Air	µg	109.6681	149.4058
Sulfentrazone	Air	ng	9.714791	9.368977
Sulfur dioxide	Air	mg	499.4113	511.8556
Sulfur hexafluoride	Air	ng	642.3034	587.5363
Sulfur oxides	Air	ng	18.60382	15.87778
Sulfur trioxide	Air	ng	2.85311	2.661628
Sulfuric acid	Air	ng	-55.4968	-42.4646

t-Butyl methyl ether	Air	ng	21.61252	25.2776
t-Butylamine	Air	pg	389.331	372.2056
Tefluthrin	Air	pg	3.92E-06	4.16E-06
Terpenes	Air	μg	1.445629	1.394322
Tetramethyl ammonium hydroxide	Air	pg	136.2804	139.2672
Thallium	Air	ng	6.435265	7.513753
Thifensulfuron	Air	pg	138.4597	133.531
Thiodicarb	Air	pg	493.4404	475.8756
Thorium	Air	pg	818.1375	727.996
Thorium-228	Air	μBq	896.0183	939.3468
Thorium-230	Air	μBq	301.4695	495.462
Thorium-232	Air	mBq	1.405822	1.474708
Thorium-234	Air	μBq	134.026	215.0295
Tin	Air	μg	1.480211	1.379464
Titanium	Air	ng	478.8877	466.686
Toluene	Air	μg	276.8039	269.9285
Toluene, 2-chloro-	Air	ng	1.125953	1.004739
Trifloxystrobin	Air	pg	88.58923	85.43575
Trifluralin	Air	ng	139.9219	134.9411
Trimethylamine	Air	pg	115.1669	108.7835
Tungsten	Air	pg	226.9898	385.0378
Uranium	Air	ng	1.077249	0.957338
Uranium-234	Air	mBq	0.958429	1.598012
Uranium-235	Air	μBq	44.88046	76.12974
Uranium-238	Air	mBq	3.375716	4.129427
Uranium alpha	Air	mBq	5.163997	8.758313
Vanadium	Air	μg	6.616276	6.769012
Water/m3	Air	cu.in	67.15438	126.7453
Xenon-131m	Air	mBq	0.513546	434.1622
Xenon-133	Air	Bq	13.24234	18.90101
Xenon-133m	Air	mBq	0.018042	14.88992
Xenon-135	Air	Bq	3.641799	7.186533
Xenon-135m	Air	Bq	0.004744	4.021555
Xenon-137	Air	mBq	0.150247	127.6041
Xenon-138	Air	mBq	1.119699	950.4216

Xylene	Air	mg	1.175061	1.227987
Zeta-cypermethrin	Air	pg	583.3164	562.5523
Zinc	Air	µg	46.72739	47.4796
Zinc-65	Air	µBq	0.00121	1.028347
Zirconium	Air	pg	200.7089	201.0406
Zirconium-95	Air	µBq	1.266612	1.288882

Table C3: Inventory data for generation of 1 MJ of electricity in 2020 and 2036 (Soil emission)

Substance	**Compartment**	**Unit**	**Electricity TH 2020 medium voltage**	**Electricity TH 2036 medium voltage**
2-Methyl-4-chlorophenoxyacetic acid	Soil	ng	-110.975	-107.05
2,4-D	Soil	µg	4.955282	4.779192
Acephate	Soil	pg	430.2757	414.9594
Acetamide	Soil	pg	64.10427	61.83594
Acetochlor	Soil	pg	8.118864	8.627105
Acifluorfen	Soil	pg	59.09198	56.9885
Aclonifen	Soil	pg	7.248812	6.990778
Alachlor	Soil	pg	418.5682	403.725
Aldicarb	Soil	pg	0.006387	0.006305
Aldrin	Soil	pg	18.09411	18.94496
Aluminium	Soil	mg	1.028022	0.956535
Amidosulfuron	Soil	pg	0.006545	0.006853
Anthraquinone	Soil	ng	-31.9056	-30.7772
Antimony	Soil	ng	26.72672	24.59852
Arsenic	Soil	ng	351.5248	324.554
Asulam	Soil	pg	-2.63E-05	-0.00094
Atrazine	Soil	pg	-95.199	-25.0199
Azoxystrobin	Soil	ng	-35.179	-33.9334
Barium	Soil	µg	319.3593	286.4881
Benomyl	Soil	ng	-1.34799	-1.29793
Bentazone	Soil	ng	2.319689	2.237132
Beryllium	Soil	ng	8.920125	8.641937
Bifenox	Soil	ng	-8.1716	-7.88258
Bifenthrin	Soil	pg	0.029583	0.031435
Bitertanol	Soil	ng	-3.44569	-3.32382
Boron	Soil	µg	6.677806	6.007334
Bromine	Soil	ng	20.86501	20.34713
Bromoxynil	Soil	ng	-21.0243	-20.2807
Butyric acid, 4-(2,4-dichlorophenoxy)-	Soil	pg	-740.88	-714.676

Cadmium	Soil	ng	180.5815	179.3059
Calcium	Soil	mg	5.706683	5.437169
Carbaryl	Soil	pg	52.63655	50.76677
Carbendazim	Soil	ng	-4.61227	-4.4396
Carbetamide	Soil	pg	0.749838	0.723147
Carbofuran	Soil	ng	-739.025	-711.582
Carbon	Soil	mg	2.392097	2.20255
Carbon dioxide, to soil or biomass stock	Soil	µg	-246.819	-237.685
Carfentrazone-ethyl	Soil	pg	-313.633	-302.541
Chloride	Soil	mg	2.277728	2.047942
Chlorimuron-ethyl	Soil	ng	2.095299	2.020713
Chlorine	Soil	ng	138.3243	146.3921
Chlormequat	Soil	pg	-562.312	-541.872
Chlorothalonil	Soil	ng	32.37661	35.6742
Chlorpyrifos	Soil	ng	8.389823	8.091238
Chlorpyrifos methyl	Soil	µg	1.794182	1.730315
Chlortoluron	Soil	ng	-49.2248	-47.4837
Chromium	Soil	µg	5.678522	5.317155
Chromium VI	Soil	ng	452.4588	419.0165
Cinidon-ethyl	Soil	pg	0.007933	0.008306
Clethodim	Soil	ng	3.184778	3.071457
Clomazone	Soil	pg	305.6349	295.1171
Clopyralid	Soil	pg	-722.164	-696.615
Cloransulam-methyl	Soil	pg	908.5219	876.1815
Cobalt	Soil	ng	243.9429	242.8469
Copper	Soil	µg	2.612534	2.56222
Cyfluthrin	Soil	pg	10.31244	9.946025
Cyhalothrin, gamma-	Soil	pg	118.2619	114.0522
Cypermethrin	Soil	ng	65.39038	62.84203
Cyproconazole	Soil	ng	-1.24695	-1.20284
Cyprodinil	Soil	ng	-97.7134	-94.2615
Deltamethrin	Soil	pg	-499.654	-481.969
Desmedipham	Soil	pg	0.011299	0.013759
Dicamba	Soil	pg	33.32397	32.16125
Dichlorprop-P	Soil	pg	0.29749	0.311479
Diclofop	Soil	ng	-50.8115	-49.0143
Diclofop-methyl	Soil	ng	-51.163	-49.3534
Dicrotophos	Soil	pg	0.000349	0.000344
Difenoconazole	Soil	ng	21.00307	20.22741
Diflubenzuron	Soil	µg	3.033666	2.925678
Diflufenican	Soil	ng	-39.4655	-38.0696
Diflufenzopyr-sodium	Soil	pg	0.026295	0.027941
Dimethachlor	Soil	pg	746.411	720.7249

Dimethenamid	Soil	pg	0.691893	0.735154
Dimethoate	Soil	pg	0.680665	0.712673
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Soil	pg	0.238103	0.242718
Diquat	Soil	pg	-233.947	-225.26
Dithianone	Soil	pg	0.065448	0.068526
Diuron	Soil	pg	0.000536	0.000529
Endosulfan	Soil	ng	919.4242	886.6958
Endothall	Soil	pg	7.656976	7.393478
Epoxiconazole	Soil	ng	-7.04195	-6.79287
Esfenvalerate	Soil	pg	61.60818	59.41524
Ethalfluralin	Soil	pg	248.8469	240.2834
Ethephon	Soil	ng	-87.8198	-84.7135
Ethofumesate	Soil	pg	-10.2768	-10.7706
Fenbuconazole	Soil	pg	0.017105	0.01791
Fenoxaprop	Soil	ng	1.791555	1.727781
Fenoxaprop-P ethyl ester	Soil	ng	-2.37013	-2.2863
Fenoxaprop ethyl ester	Soil	ng	-4.23422	-4.08446
Fenpiclonil	Soil	ng	1.274568	1.40435
Fenpropidin	Soil	ng	-104.09	-100.409
Fenpropimorph	Soil	ng	-16.3359	-15.758
Fipronil	Soil	pg	0.041527	0.04397
Florasulam	Soil	pg	-867.422	-836.742
Fluazifop-P-butyl	Soil	pg	870.9625	840.1767
Fludioxonil	Soil	ng	-2.04564	-1.9736
Flufenacet	Soil	ng	-34.6535	-33.4278
Flumetsulam	Soil	pg	10.19947	9.840919
Flumiclorac-pentyl	Soil	pg	17.36692	16.74872
Flumioxazin	Soil	ng	1.174041	1.132249
Fluoride	Soil	µg	32.21005	28.89923
Fluquinconazole	Soil	pg	0.014874	0.015574
Fluroxypyr	Soil	ng	-1.45852	-1.40693
Flurtamone	Soil	ng	-36.1436	-34.8652
Flusilazole	Soil	ng	-3.94817	-3.80852
Fomesafen	Soil	ng	7.207836	6.951261
Foramsulfuron	Soil	pg	0.00493	0.005239
Fungicides, unspecified	Soil	pg	4.946827	4.771144
Glufosinate	Soil	ng	2.93978	2.837909
Glyphosate	Soil	ng	390.4508	413.4841
Heat, waste	Soil	J	10.15589	8.959936
Herbicides, unspecified	Soil	ng	5.748798	5.544161
Hydrocarbons, unspecified	Soil	ng	-18.175	-16.7056
Imazamox	Soil	pg	883.1188	851.6827
Imazapyr	Soil	pg	0.000657	0.000699
Imazaquin	Soil	pg	82.83795	79.88919

Imazethapyr	Soil	ng	2.312615	2.230294
Imidacloprid	Soil	ng	-16.0804	-15.5116
Insecticides, unspecified	Soil	pg	8.29E-07	8.80E-07
Iodide	Soil	pg	3.710966	3.256118
Iodosulfuron	Soil	pg	0.000992	0.001038
Ioxynil	Soil	ng	-12.3062	-11.8709
Iprodione	Soil	pg	333.8493	322.3606
Iron	Soil	mg	2.009688	1.895225
Isoproturon	Soil	ng	-214.09	-206.517
Isoxaflutole	Soil	pg	0.150233	0.159565
Kresoxim-methyl	Soil	pg	-312.908	-301.831
Lactofen	Soil	pg	83.42282	80.45325
Lambda-cyhalothrin	Soil	ng	-3.66621	-3.53657
Lead	Soil	µg	1.36951	1.322529
Lenacil	Soil	pg	0.006137	0.007473
Linuron	Soil	ng	412.998	398.2969
Lithium	Soil	pg	346.6352	366.8529
Magnesium	Soil	µg	871.9578	818.3338
Malathion	Soil	ng	-24.938	-24.0119
Mancozeb	Soil	ng	42.05054	46.33343
Manganese	Soil	µg	243.3549	240.2273
MCPB	Soil	pg	0.095808	0.096224
Mecoprop-P	Soil	pg	0.1547	0.161974
Mefenpyr	Soil	ng	-8.46857	-8.16905
Mefenpyr-diethyl	Soil	ng	-4.7404	-4.57274
Mepiquat chloride	Soil	ng	-33.4339	-32.2514
Mercury	Soil	ng	3.639452	3.598223
Mesotrione	Soil	pg	0.213659	0.227034
Metalaxil	Soil	ng	-2.99452	-2.88332
Metaldehyde (tetramer)	Soil	ng	-108.851	-105
Metam-sodium dihydrate	Soil	ng	-7.90741	-7.61377
Metamitron	Soil	pg	0.320549	0.389978
Metazachlor	Soil	ng	1.76121	1.700601
Metconazole	Soil	pg	72.07215	69.59413
Metolachlor	Soil	µg	3.014358	2.907115
Metribuzin	Soil	ng	68.54268	66.30629
Metsulfuron-methyl	Soil	ng	5.945477	5.743513
Molybdenum	Soil	ng	54.7403	54.40793
Monocrotophos	Soil	ng	370.6218	357.4289
Monosodium acid methanearsonate	Soil	pg	0.000178	0.000176
Napropamide	Soil	pg	855.4279	825.9903
Nickel	Soil	ng	649.1755	641.6342
Nicosulfuron	Soil	pg	0.036157	0.03842
Nitrate	Soil	ng	399.4566	422.7551

Nitrogen, atmospheric	Soil	µg	1.329637	1.295159
Oils, biogenic	Soil	µg	55.0216	55.05672
Oils, unspecified	Soil	mg	2.270538	2.235642
Orbencarb	Soil	ng	7.99553	8.809883
Organic carbon	Soil	ng	35.02768	34.4652
Oxydemeton methyl	Soil	pg	0.069375	0.072637
PAH, polycyclic aromatic hydrocarbons	Soil	ng	1.039907	1.10056
Paraquat	Soil	ng	-2.92698	-2.81774
Parathion	Soil	pg	4.423115	4.275058
Parathion, methyl	Soil	pg	66.81234	64.43405
Pendimethalin	Soil	ng	53.41529	51.51396
Permethrin	Soil	pg	54.50574	52.56697
Pesticides, unspecified	Soil	pg	0.009019	0.008903
Phenmedipham	Soil	pg	0.038461	0.046768
Phenol, pentachloro-	Soil	pg	-19.473	-17.8987
Phosphorus	Soil	µg	140.0607	136.4286
Picoxystrobin	Soil	ng	-11.3492	-10.9478
Pirimicarb	Soil	pg	-37.2373	-39.0878
Potassium	Soil	µg	827.2532	802.4252
Primisulfuron	Soil	pg	0.016435	0.017464
Prochloraz	Soil	pg	0.160645	0.168199
Procymidone	Soil	pg	119.2337	115.1306
Profenofos	Soil	pg	0.000277	0.000273
Prometryn	Soil	pg	0.000149	0.000147
Propiconazole	Soil	ng	-39.0484	-37.6673
Prosulfuron	Soil	pg	0.003014	0.003201
Prothioconazol	Soil	pg	355.7014	343.4607
Pyraclostrobin (prop)	Soil	ng	-3.81164	-3.67686
Pyrithiobac sodium salt	Soil	pg	9.94E-06	9.81E-06
Quizalofop-P	Soil	pg	17.15192	16.56167
Quizalofop ethyl ester	Soil	pg	35.47895	34.23409
Rimsulfuron	Soil	pg	0.016435	0.017464
Scandium	Soil	ng	24.6238	23.8329
Selenium	Soil	ng	26.67145	26.29815
Sethoxydim	Soil	pg	120.8691	116.6581
Silicon	Soil	mg	1.247525	1.228954
Silver	Soil	ng	4.107097	3.92591
Simazine	Soil	pg	0.331983	0.352765
Sodium	Soil	mg	1.283986	1.152295
Spiroxamine	Soil	pg	130.9737	126.5065
Strontium	Soil	µg	7.300115	6.615105
Sulfate	Soil	ng	666.8615	705.7564
Sulfentrazone	Soil	ng	10.702	10.32105
Sulfosate	Soil	ng	42.35234	40.84474

Sulfur	Soil	µg	543.5062	502.8474
Sulfuric acid	Soil	pg	0.724435	0.785332
Tebuconazole	Soil	ng	-6.63974	-6.40433
Tebupirimphos	Soil	pg	0.13806	0.146702
Tebutam	Soil	pg	-0.00015	-0.00015
Teflubenzuron	Soil	pg	98.70843	108.762
Tefluthrin	Soil	pg	0.108482	0.115273
Terbufos	Soil	pg	0.369004	0.39209
Thallium	Soil	ng	1.688812	1.642812
Thiamethoxam	Soil	pg	1.71E-05	1.68E-05
Thidiazuron	Soil	pg	1.74E-05	1.72E-05
Thifensulfuron-methyl	Soil	pg	5.936042	5.724863
Thiodicarb	Soil	pg	21.15302	20.40004
Thiram	Soil	ng	-16.827	-16.2021
Tin	Soil	ng	100.0372	93.61999
Titanium	Soil	µg	23.60259	23.31548
Tralkoxydim	Soil	ng	-80.9487	-78.0856
Triadimenol	Soil	pg	0.035947	0.037638
Tribenuron	Soil	pg	0.003738	0.003914
Tribenuron-methyl	Soil	ng	-1.86464	-1.79869
Tribufos	Soil	pg	0.000163	0.000161
Triclopyr	Soil	ng	-24.0138	-22.3789
Trifloxystrobin	Soil	ng	-4.6796	-4.51409
Trifluralin	Soil	ng	65.57611	63.24434
Trinexapac-ethyl	Soil	ng	-65.3742	-63.0619
Vanadium	Soil	ng	870.7219	870.0896
Vinclozolin	Soil	pg	39.74414	38.37644
Zeta-cypermethrin	Soil	pg	24.9937	24.10401
Zinc	Soil	µg	30.50018	29.52505

Table C4: Inventory data for generation of 1 MJ of electricity in 2020 and 2036 (Water emission)

Substance	Compartme-nt	Unit	Electricity TH 2020 medium voltage	Electricity TH 2036 medium voltage
1-Butanol	Water	ng	99.69905	93.0572
1-Pentanol	Water	pg	186.1374	175.5043
1-Pentene	Water	pg	140.6611	132.6259
1-Propanol	Water	pg	777.1458	741.9276
1,4-Butanediol	Water	ng	2.272198	2.185334
2-Aminopropanol	Water	pg	237.9916	224.8818
2-Butene, 2-methyl-	Water	pg	0.084485	0.079667
2-Methyl-1-propanol	Water	pg	715.9466	676.8421
2-Methyl-4-chlorophenoxyacetic acid	Water	pg	-25.9479	-25.0301
2-Propanol	Water	ng	-47.4378	-35.1269
4-Methyl-2-pentanol	Water	pg	-0.00074	-0.00071
4-Methyl-2-pentanone	Water	ng	293.7895	241.7727
Acenaphthene	Water	pg	387.0442	356.5773
Acenaphthylene	Water	pg	14.70007	14.24973
Acetaldehyde	Water	ng	176.1026	165.6496
Acetic acid	Water	ng	236.771	227.2633
Acetone	Water	ng	837.6052	722.589
Acetonitrile	Water	pg	329.1517	315.9046
Acetyl chloride	Water	pg	146.224	137.871
Acidity, unspecified	Water	µg	14.96608	12.32412
Acrylate	Water	ng	1.322265	1.433418
Actinides, radioactive, unspecified	Water	µBq	289.313	488.7163
Allyl chloride	Water	ng	-6.26679	-6.69222
Aluminium	Water	mg	2.105005	1.945684
Aluminium hydroxide	Water	pg	79.74075	67.16954
Ammonium, ion	Water	mg	1.041293	0.920025
Aniline	Water	ng	1.461202	1.421448
Anthracene	Water	pg	33.84533	28.66452
Antimony	Water	µg	54.82127	57.71498
Antimony-122	Water	µBq	19.80958	19.81225
Antimony-124	Water	µBq	913.1241	926.2069
Antimony-125	Water	µBq	913.8251	932.1542
AOX, Adsorbable Organic Halogen as Cl	Water	ng	918.0387	851.1674
Arsenic	Water	µg	268.2171	279.6698
Atrazine	Water	pg	0.00053	0.000562
Barite	Water	mg	3.279684	2.719398
Barium	Water	mg	19.71141	16.21909
Barium-140	Water	µBq	0.079261	67.35044

Bentazone	Water	pg	79.04868	76.23482
Benzene	Water	µg	125.6572	104.0899
Benzene, 1,2-dichloro-	Water	ng	147.6382	138.5918
Benzene, chloro-	Water	ng	224.0024	210.2924
Benzene, ethyl-	Water	µg	7.484714	6.291673
Benzo(a)anthracene	Water	pg	0.127718	0.108168
Benzo(a)pyrene	Water	pg	0.015518	0.013142
Benzo(b)fluoranthene	Water	pg	0.015135	0.012818
Benzo(g,h,i)perylene	Water	pg	0.00213	0.001804
Benzo(k)fluoranthene	Water	pg	0.00712	0.00603
Beryllium	Water	µg	1.323886	1.232226
Bisphenol A	Water	ng	120.9085	129.1166
BOD5, Biological Oxygen Demand	Water	mg	22.96479	20.04118
Borate	Water	ng	41.28117	38.75785
Boron	Water	µg	514.3967	470.8112
Bromate	Water	ng	824.5078	756.6392
Bromide	Water	µg	1.770618	1.671865
Bromine	Water	mg	15.15533	12.50008
Bromoxynil	Water	pg	-2.44011	-2.3538
Butene	Water	ng	-103.069	-96.2663
Butyl acetate	Water	ng	126.7582	118.3445
Butyric acid, 4-(2,4-dichlorophenoxy)-	Water	pg	-23.114	-22.2964
Butyrolactone	Water	pg	3.746783	3.765517
Cadmium	Water	µg	2.719133	2.335933
Calcium	Water	mg	447.9923	420.063
Carbaryl	Water	pg	6.21E-08	6.59E-08
Carbon	Water	ng	14.81036	14.57253
Carbon-14	Water	nBq	899.9341	795.4787
Carbon disulfide	Water	pg	576.2253	564.7532
Carbonate	Water	µg	12.64793	19.38399
Carboxylic acids, unspecified	Water	µg	197.3983	185.8512
Cerium-141	Water	µBq	3.8849	27.79171
Cerium-144	Water	µBq	10.56219	10.56361
Cesium	Water	ng	36.66158	35.67655
Cesium-134	Water	µBq	82.78056	169.0974
Cesium-136	Water	µBq	6.157624	6.158454
Cesium-137	Water	mBq	35.35141	64.49772
Chloramine	Water	ng	4.623343	4.363523
Chlorate	Water	µg	7.596839	7.239806
Chloride	Water	g	2.603866	2.154526
Chlorides, unspecified	Water	µg	77.04564	68.47972
Chlorinated solvents, unspecified	Water	ng	7.394589	22.24241
Chlorine	Water	ng	154.7749	175.6096
Chloroacetic acid	Water	ng	631.3308	608.403

Chloroacetyl chloride	Water	pg	317.3974	299.9135
Chloroform	Water	pg	287.5267	280.8631
Chlorosulfonic acid	Water	ng	1.196936	1.148764
Chromium	Water	µg	36.60544	30.44027
Chromium-51	Water	mBq	0.171321	4.9665
Chromium VI	Water	µg	124.7119	130.5352
Chrysene	Water	pg	0.082378	0.069768
Cobalt	Water	µg	11.02228	11.21744
Cobalt-57	Water	µBq	195.4662	195.4926
Cobalt-58	Water	mBq	24.98254	26.07558
Cobalt-60	Water	mBq	8.669756	20.40166
COD, Chemical Oxygen Demand	Water	mg	31.86051	27.45842
Copper	Water	µg	14.80289	13.36704
Cu-HDO	Water	pg	0.92995	0.935657
Cumene	Water	µg	4.466915	3.836796
Cyanide	Water	µg	3.621011	3.018037
Dibenz(a,h)anthracene	Water	pg	0.001491	0.001263
Dicamba	Water	pg	5.61E-05	5.96E-05
Dichromate	Water	ng	13.39719	12.46259
Diethylamine	Water	pg	293.0523	270.0655
Dimethenamid	Water	pg	5.47E-06	5.80E-06
Dimethylamine	Water	ng	4.934226	4.696796
Dipropylamine	Water	pg	51.71026	44.48802
DOC, Dissolved Organic Carbon	Water	mg	10.81825	9.273076
Epichlorohydrin	Water	ng	53.90377	57.56315
Ethane, 1,1,1-trichloro-, HCFC-140	Water	pg	4.85E-06	4.96E-06
Ethane, 1,2-dichloro-	Water	ng	46.64441	64.3855
Ethanol	Water	ng	229.3038	216.9681
Ethene	Water	µg	1.023712	0.95815
Ethene, chloro-	Water	pg	737.283	876.3773
Ethyl acetate	Water	pg	90.37818	78.25623
Ethylamine	Water	pg	970.9071	919.7129
Ethylene diamine	Water	pg	317.2509	322.6538
Ethylene oxide	Water	ng	27.41843	27.35909
Fluoranthene	Water	pg	670.5206	567.882
Fluorene	Water	pg	247.1348	209.3051
Fluoride	Water	µg	449.0213	470.1972
Fluosilicic acid	Water	ng	982.8642	868.0442
Formaldehyde	Water	ng	295.9704	265.41
Formamide	Water	pg	340.4251	320.9784
Formate	Water	ng	119.9992	114.7209
Formic acid	Water	pg	98.82102	93.17586
Glutaraldehyde	Water	ng	370.6724	306.3875
Glyphosate	Water	ng	1.913733	1.845607

Heat, waste	Water	J	145.6508	142.9929
Hydrocarbons, aliphatic, alkanes, unspecified	Water	µg	4.766006	4.637951
Hydrocarbons, aliphatic, unsaturated	Water	ng	440.9144	429.0522
Hydrocarbons, aromatic	Water	µg	24.17165	22.82888
Hydrocarbons, unspecified	Water	µg	58.67071	49.59462
Hydrogen-3, Tritium	Water	Bq	109.686	158.5149
Hydrogen carbonate	Water	µg	2.18447	3.766975
Hydrogen chloride	Water	µg	7.517317	6.681391
Hydrogen peroxide	Water	ng	13.04543	13.87016
Hydrogen sulfide	Water	µg	1.329292	1.326993
Hydroxide	Water	µg	17.17665	17.20364
Hypochlorite	Water	ng	287.7127	278.0737
Indeno(1,2,3-cd)pyrene	Water	pg	0.023404	0.019822
Iodide	Water	µg	19.58315	20.16856
Iodine-131	Water	µBq	181.5579	245.6129
Iodine-133	Water	µBq	9.157345	44.32306
Iron	Water	mg	210.1151	220.7704
Iron-59	Water	µBq	16.54798	20.17284
Isopropylamine	Water	pg	442.7601	418.9804
Lactic acid	Water	pg	40.508	34.85045
Lanthanum-140	Water	µBq	10.92157	74.16351
Lead	Water	µg	28.06166	27.25277
Lead-210	Water	mBq	20.38406	16.78792
Lithium	Water	mg	75.32497	61.98836
m-Xylene	Water	µg	2.123054	1.747189
Magnesium	Water	mg	71.63875	65.34938
Manganese	Water	mg	1.376338	1.43954
Manganese-54	Water	mBq	0.288266	1.301541
Mercury	Water	ng	202.5288	206.0622
Methane, dichloro-, HCC-30	Water	µg	9.80099	8.141911
Methanol	Water	µg	1.819366	1.5682
Methyl acetate	Water	pg	131.4932	124.2086
Methyl acrylate	Water	ng	12.38397	13.425
Methyl formate	Water	ng	-4.08872	-3.81706
Methylamine	Water	pg	585.7512	561.6961
Metolachlor	Water	pg	11.54544	11.13446
Molybdenum	Water	µg	286.8153	307.6298
Molybdenum-99	Water	µBq	0.160466	24.76172
Monoethanolamine	Water	ng	3.347821	3.368366
Naphthalene	Water	pg	49.55467	41.96919
Nickel	Water	µg	63.7358	64.28819
Niobium-95	Water	µBq	67.31615	103.3236
Nitrate	Water	mg	5.417807	6.081343
Nitrite	Water	µg	7.546829	8.173898

Nitrobenzene	Water	ng	5.753414	5.642395
Nitrogen, atmospheric	Water	µg	17.87337	20.67931
Nitrogen, organic bound	Water	µg	48.77374	42.10134
o-Xylene	Water	µg	1.54626	1.272488
Oils, biogenic	Water	µg	6.416286	6.187888
Oils, unspecified	Water	mg	4.678987	4.197521
Organic carbon	Water	ng	35.02768	34.4652
PAH, polycyclic aromatic hydrocarbons	Water	ng	627.4781	598.8209
Pendimethalin	Water	pg	7.44E-06	7.90E-06
Phenanthrene	Water	pg	556.2128	471.0717
Phenol	Water	µg	35.66423	29.98552
Phosphate	Water	mg	96.29214	101.1284
Phosphorus	Water	µg	8.270957	7.999262
Polonium-210	Water	µBq	325.1282	292.2293
Polychlorinated biphenyls	Water	pg	0.134617	0.142107
Potassium	Water	mg	24.20591	25.43523
Potassium-40	Water	µBq	149.506	140.1731
Propanal	Water	pg	297.774	281.385
Propene	Water	µg	2.722106	2.411218
Propiconazole	Water	pg	-1.18453	-1.14264
Propionic acid	Water	ng	5.516713	5.20972
Propylamine	Water	pg	129.8848	122.9494
Propylene oxide	Water	ng	54.39193	56.49298
Protactinium-234	Water	mBq	2.172175	3.684613
Pyraclostrobin (prop)	Water	pg	0.001157	0.001116
Pyrene	Water	pg	505.1256	427.8045
Radioactive species, alpha emitters	Water	µBq	3.525468	3.861219
Radioactive species, Nuclides, unspecified	Water	mBq	173.28	292.5822
Radium-224	Water	mBq	1.833079	1.783827
Radium-226	Water	Bq	0.813012	1.295767
Radium-228	Water	mBq	134.2147	111.002
Rubidium	Water	ng	366.6158	356.7655
Ruthenium-103	Water	µBq	6.245714	6.61766
Scandium	Water	µg	11.72007	12.3448
Selenium	Water	µg	31.27737	33.49587
Silicon	Water	mg	19.22779	20.27616
Silver	Water	µg	147.526	121.5503
Silver-110	Water	mBq	0.118155	17.90888
Sodium	Water	mg	778.268	654.9571
Sodium-24	Water	µBq	218.7147	236.118
Sodium chlorate	Water	pg	4.08E-05	4.03E-05
Sodium formate	Water	ng	-2.63651	-2.5643
Solids, inorganic	Water	mg	450.0239	474.7968
Strontium	Water	mg	4.616338	3.976431

Strontium-89	Water	µBq	80.40102	434.8364
Strontium-90	Water	mBq	3.833881	6.400353
Sulfate	Water	g	2.306473	2.432811
Sulfide	Water	ng	524.7984	542.9238
Sulfite	Water	ng	964.2684	935.6899
Sulfur	Water	µg	227.3546	190.6133
Suspended solids, unspecified	Water	g	3.183105	2.627877
t-Butyl methyl ether	Water	ng	0.906391	1.058488
t-Butylamine	Water	pg	934.4023	893.3009
Technetium-99m	Water	µBq	62.18872	582.0198
Tefluthrin	Water	pg	1.95E-11	2.07E-11
Tellurium-123m	Water	µBq	34.40692	34.41153
Tellurium-132	Water	µBq	1.845096	1.845345
Thallium	Water	ng	204.4073	175.989
Thorium-228	Water	mBq	7.332326	7.135317
Thorium-230	Water	mBq	183.908	311.9591
Thorium-232	Water	µBq	24.62671	23.28803
Thorium-234	Water	mBq	2.173029	3.686056
Tin	Water	µg	7.826634	6.460694
Titanium	Water	µg	25.3893	23.86303
TOC, Total Organic Carbon	Water	mg	10.82587	9.280466
Toluene	Water	µg	115.5447	95.74161
Toluene, 2-chloro-	Water	ng	2.288049	2.020859
Tributyltin compounds	Water	ng	121.1673	116.5655
Triethylene glycol	Water	µg	4.029674	3.332605
Trimethylamine	Water	pg	276.4006	261.0803
Tungsten	Water	µg	23.33869	24.4829
Uranium-234	Water	mBq	2.51409	4.264596
Uranium-235	Water	mBq	2.80516	4.758331
Uranium-238	Water	mBq	5.189643	8.703814
Uranium alpha	Water	mBq	84.81629	143.8735
Urea	Water	pg	519.1345	491.118
Vanadium	Water	µg	13.71573	15.11044
VOC, volatile organic compounds, unspecified origin	Water	µg	17.63394	20.73391
Water, AR	Water	mm 3	6.33E-11	1.09E-10
Water, AT	Water	cm3	-96.1005	-106.39
Water, AU	Water	cm3	49.82234	42.5354
Water, BA	Water	cm3	88.53791	80.73053
Water, BE	Water	mm 3	59.08609	-394.234
Water, BG	Water	cm3	3.312186	3.045781
Water, BR	Water	cm3	256.0376	240.9777

Water, CA	Water	cu.in	-70.348	-65.1422
Water, CH	Water	cm3	579.4029	836.9406
Water, CL	Water	cm3	93.67801	90.13475
Water, CN	Water	cu.in	382.3239	365.8806
Water, CO	Water	mm3	-2.97402	-2.86359
Water, CY	Water	mm3	59.44689	57.16318
Water, CZ	Water	cm3	4.93552	4.487112
Water, DE	Water	cm3	8.709394	8.639484
Water, DK	Water	mm3	27.01425	31.76661
Water, ES	Water	cm3	12.66918	11.14911
Water, Europe without Switzerland	Water	cm3	3.790937	4.187957
Water, Europe, without Russia and Turkey	Water	mm3	34.62463	32.26956
Water, FI	Water	mm3	-43.678	-26.8819
Water, FR	Water	m3	2.750068	2.50009
Water, GB	Water	cm3	2.999767	2.9603
Water, GLO	Water	cm3	60.08007	56.03598
Water, GR	Water	cm3	12.68751	11.47104
Water, HR	Water	mm3	-252.747	-315.262
Water, HU	Water	mm3	609.7678	571.1966
Water, IAI Area, Africa	Water	mm3	35.79647	31.63189
Water, IAI Area, Asia, without China and GCC	Water	mm3	47.13298	41.64884
Water, IAI Area, EU27 & EFTA	Water	mm3	128.9888	113.9823
Water, IAI Area, Gulf Cooperation Council	Water	mm3	191.3427	169.0807
Water, IAI Area, Russia & RER w/o EU27 & EFTA	Water	mm3	91.65337	80.99009
Water, IAI Area, South America	Water	mm3	18.18859	16.07176
Water, ID	Water	cm3	3.240496	3.069119
Water, IE	Water	cm3	3.94645	3.685961
Water, IL	Water	mm3	2.83E-06	2.94E-06
Water, IN	Water	cm3	372.078	357.6486
Water, IR	Water	cm3	555.5569	533.5486
Water, IS	Water	cm3	70.23294	62.08098
Water, IT	Water	cm3	-93.608	-103.736
Water, JP	Water	cm3	-31.9473	-35.7469
Water, KR	Water	cm3	709.074	681.5352

Water, LT	Water	mm3	293.3225	274.4304
Water, LU	Water	cm3	-4.23327	-4.77481
Water, LV	Water	mm3	-42.3862	-66.3363
Water, MA	Water	mm3	1.840935	1.616995
Water, MK	Water	cm3	16.12489	14.32172
Water, MT	Water	mm3	43.46491	40.59665
Water, MX	Water	cm3	516.344	494.9726
Water, MY	Water	cm3	1.699874	1.596831
Water, NL	Water	cm3	3.378316	3.687691
Water, NO	Water	cm3	15.35153	13.66946
Water, NORDEL	Water	mm3	9.45E-06	8.23E-06
Water, NP	Water	cm3	10.42211	10.01401
Water, OCE	Water	mm3	8.666458	7.657536
Water, PE	Water	mm3	627.7733	603.2084
Water, PG	Water	mm3	0.466008	0.45725
Water, PH	Water	mm3	5.802031	4.913901
Water, PL	Water	cm3	-20.0187	-19.4453
Water, PT	Water	cm3	54.24689	45.51135
Water, RAF	Water	mm3	69.85204	68.78909
Water, RAS	Water	mm3	281.1563	217.8342
Water, RER	Water	cm3	15.25673	14.49
Water, RLA	Water	mm3	88.75992	74.31872
Water, RME	Water	mm3	686.8784	676.426
Water, RNA	Water	mm3	214.8795	364.7668
Water, RO	Water	cm3	36.90561	32.99053
Water, RoW	Water	m3	1.743198	1.74412
Water, RS	Water	cm3	102.1665	95.53676
Water, RU	Water	cm3	-161.26	-179.115
Water, SA	Water	cm3	2.736638	2.62982
Water, SE	Water	cm3	29.64701	26.20839
Water, SI	Water	cm3	-1.45688	-1.6987
Water, SK	Water	cm3	12.09022	10.35801
Water, TH	Water	dm3	90.08876	356.3163
Water, TR	Water	cm3	467.0393	447.1775
Water, TW	Water	cm3	394.6519	378.5583

Water, TZ	Water	mm3	0.061122	0.059973
Water, UA	Water	cm3	416.2065	387.9785
Water, UCTE	Water	mm3	0.052893	0.054295
Water, UCTE without Germany	Water	mm3	1.34E-05	0.012681
Water, US	Water	cu.in	38.40232	65.1651
Water, WEU	Water	mm3	-0.02925	-0.02823
Water, ZA	Water	cm3	13.14173	12.57224
Water/m3	Water	mm3	17.35378	15.33472
Xylene	Water	µg	59.9724	49.91553
Zinc	Water	µg	224.028	195.2987
Zinc-65	Water	mBq	0.00932	2.538873
Zirconium-95	Water	µBq	36.54359	39.98607

APPENDIX D

Life Cycle Impact Assessment Data

Table D1: Environmental impact assessment results of 1 MJ of electricity energy 2020 and 2036 (medium voltage) via 18 midpoint indicators

Impact category	Unit	Electricity energy mix 2020	Electricity energy 2036
Global warming	kg CO_2 eq	0.317	0.295
Stratospheric ozone depletion	kg CFC11 eq	8.58E-8	7.92E-8
Ionizing radiation	kBq Co-60 eq	0.000971	0.00233
Ozone formation, Human health	kg NOx eq	0.000499	0.000494
Fine particulate matter formation	kg PM2.5 eq	0.00028	0.000286
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000508	0.000501
Terrestrial acidification	kg SO_2 eq	0.000676	0.000688
Freshwater eutrophication	kg P eq	3.18E-5	3.34E-5
Marine eutrophication	kg N eq	6.08E-7	6.27E-7
Terrestrial ecotoxicity	kg 1,4-DCB	0.0913	0.0876
Freshwater ecotoxicity	kg 1,4-DCB	0.000166	0.000144
Marine ecotoxicity	kg 1,4-DCB	0.000299	0.000261
Human carcinogenic toxicity	kg 1,4-DCB	0.000997	0.00104
Human non-carcinogenic toxicity	kg 1,4-DCB	0.00714	0.00633
Land use	m^2a crop eq	0.00281	0.00279
Mineral resource scarcity	kg Cu eq	0.000145	0.000146
Fossil resource scarcity	kg oil eq	0.0969	0.0866
Water consumption	m^3	0.00105	0.00203

Table D2: Environmental impact of general T8 LED lamp model in Energy mix 2020 (3 lifespans)

Impact category	Unit	Early failure	Random failure	Ideal
Global warming	kg CO_2 eq	90.12702	1351.905	3605.081
Stratospheric ozone depletion	kg CFC11 eq	1.98E-05	0.000296	0.000791
Ionizing radiation	kBq Co-60 eq	0.012684	0.190259	0.507358
Ozone formation, Human health	kg NOx eq	0.137385	2.060779	5.49541
Fine particulate matter formation	kg PM2.5 eq	0.073722	1.105823	2.948862
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.140049	2.10074	5.601974
Terrestrial acidification	kg SO_2 eq	0.17943	2.691448	7.177195
Freshwater eutrophication	kg P eq	0.008209	0.123136	0.328362
Marine eutrophication	kg N eq	0.000152	0.002275	0.006068

Terrestrial ecotoxicity	kg 1,4-DCB	26.45815	396.8722	1058.326
Freshwater ecotoxicity	kg 1,4-DCB	0.049348	0.740216	1.97391
Marine ecotoxicity	kg 1,4-DCB	0.088411	1.32616	3.536428
Human carcinogenic toxicity	kg 1,4-DCB	0.255865	3.837979	10.23461
Human non-carcinogenic toxicity	kg 1,4-DCB	1.914485	28.71727	76.57938
Land use	m^2a crop eq	0.223935	3.359021	8.957389
Mineral resource scarcity	kg Cu eq	0.035765	0.536472	1.430592
Fossil resource scarcity	kg oil eq	28.19502	422.9252	1127.801
Water consumption	m^3	0.277436	4.161533	11.09742

Table D3: Environmental impact of industrial high bay LED lamp model in Energy mix 2020 (3 lifespans)

Impact category	Unit	Early failure	Random failure	Ideal
Global warming	kg CO2 eq	67.91487	1018.723	2716.595
Stratospheric ozone depletion	kg CFC11 eq	1.49E-05	0.000223	0.000596
Ionizing radiation	kBq Co-60 eq	0.009558	0.143369	0.382317
Ozone formation, Human health	kg NOx eq	0.103526	1.552892	4.141045
Fine particulate matter formation	kg PM2.5 eq	0.055553	0.833289	2.222104
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.105534	1.583005	4.221345
Terrestrial acidification	kg SO2 eq	0.135209	2.02813	5.408347
Freshwater eutrophication	kg P eq	0.006186	0.092789	0.247436
Marine eutrophication	kg N eq	0.000114	0.001715	0.004572
Terrestrial ecotoxicity	kg 1,4-DCB	19.93743	299.0615	797.4974
Freshwater ecotoxicity	kg 1,4-DCB	0.037186	0.557787	1.487432
Marine ecotoxicity	kg 1,4-DCB	0.066622	0.999323	2.664861
Human carcinogenic toxicity	kg 1,4-DCB	0.192806	2.892094	7.712251
Human non-carcinogenic toxicity	kg 1,4-DCB	1.442652	21.63979	57.7061
Land use	m^2a crop eq	0.168745	2.531177	6.749805
Mineral resource scarcity	kg Cu eq	0.02695	0.404256	1.078017
Fossil resource scarcity	kg oil eq	21.24624	318.6937	849.8498
Water consumption	m^3	0.20906	3.135907	8.362418

Table D4: Environmental impact of general T8 LED lamp model in Energy mix 2036 (3 lifespans)

Impact category	Unit	Early failure	Random failure	Ideal
Global warming	kg CO_2 eq	79.16007	1187.401	3166.403
Stratospheric ozone depletion	kg CFC11 eq	1.64E-05	0.000246	0.000656
Ionizing radiation	kBq Co-60 eq	0.704914	10.57371	28.19656

Ozone formation, Human health	kg NOx eq	0.134495	2.017428	5.379809
Fine particulate matter formation	kg PM2.5 eq	0.07687	1.153048	3.074794
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.136451	2.046759	5.458025
Terrestrial acidification	kg SO_2 eq	0.185105	2.77657	7.404187
Freshwater eutrophication	kg P eq	0.009019	0.135283	0.360756
Marine eutrophication	kg N eq	0.000161	0.00242	0.006453
Terrestrial ecotoxicity	kg 1,4-DCB	24.56606	368.4909	982.6423
Freshwater ecotoxicity	kg 1,4-DCB	0.037774	0.566614	1.51097
Marine ecotoxicity	kg 1,4-DCB	0.068969	1.034529	2.758743
Human carcinogenic toxicity	kg 1,4-DCB	0.277831	4.167465	11.11324
Human non-carcinogenic toxicity	kg 1,4-DCB	1.503167	22.5475	60.12666
Land use	m^2a crop eq	0.21324	3.198602	8.529604
Mineral resource scarcity	kg Cu eq	0.036615	0.549223	1.464594
Fossil resource scarcity	kg oil eq	22.94437	344.1656	917.7749
Water consumption	m^3	0.777611	11.66417	31.10444

Table D5: Environmental impact of high bay industrial LED lamp model in Energy mix 2036 (3 lifespans)

Impact category	Unit	Early failure	Random failure	Ideal
Global warming	kg CO_2 eq	59.65077	894.7615	2386.031
Stratospheric ozone depletion	kg CFC11 eq	1.24E-05	0.000185	0.000494
Ionizing radiation	kBq Co-60 eq	0.531185	7.967777	21.2474
Ozone formation, Human health	kg NOx eq	0.101348	1.520225	4.053934
Fine particulate matter formation	kg PM2.5 eq	0.057925	0.868875	2.316999
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.102822	1.542328	4.112874
Terrestrial acidification	kg SO2 eq	0.139485	2.092274	5.579396
Freshwater eutrophication	kg P eq	0.006796	0.101942	0.271846
Marine eutrophication	kg N eq	0.000122	0.001824	0.004863
Terrestrial ecotoxicity	kg 1,4-DCB	18.51166	277.6748	740.4662
Freshwater ecotoxicity	kg 1,4-DCB	0.028465	0.42697	1.138586
Marine ecotoxicity	kg 1,4-DCB	0.051971	0.779565	2.07884
Human carcinogenic toxicity	kg 1,4-DCB	0.209358	3.140377	8.374339
Human non-carcinogenic toxicity	kg 1,4-DCB	1.132705	16.99058	45.30821
Land use	m^2a crop eq	0.160686	2.410294	6.42745
Mineral resource scarcity	kg Cu eq	0.027591	0.413865	1.103639
Fossil resource scarcity	kg oil eq	17.28964	259.3447	691.5857
Water consumption	m^3	0.585966	8.789486	23.43863

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