Evaluating Environmental and Social Impacts of Fluorescent Lamp Recycling Processes in Thailand

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การประเมินผลกระทบทางสิ่งแวดล้อมและสังคมจากกระบวนการรีไซเคิล หลอดไฟฟลูออเรสเซนต์ใน ประเทศไทย

น.ส.เอลลา นันดา สารี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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เอลลา นันดา สารี : การประเมินผลกระทบทางสิ่งแวดล้อมและสังคมจากกระบวนการรีไซเคิล หลอดไฟฟลูออเรสเซนต์ในประเทศไทย . (Evaluating Environmental and Social Impacts of Fluorescent Lamp Recycling Processes in Thailand) อ.ที่ปรึกษาหลัก : ดร.วัชราภรณ์ สุนสิน

ในช่วงหลายสิบปีที่ผ่านมาประเทศไทยได้มีการใช้หลอดฟลูออเรสเซนต์เพื่อให้แสงสว่างเป็นจำนวนมากซึ่งจะเห็นว่าในการจัดการหรือกำจัดหลอดไฟฟลูออเรสเซนต์ที่ใช้แล้วอย่างไม่เหมาะสมไม่เพียงก่อให้เกิดผลกระทบต่อสิ่งแวดล้อมอันเนื่องมาจากการปนเปื้อนสารปรอทและโลหะอื่น ๆ สู่สิ่งแวดล้อม แต่ยังส่งผลกระทบต่อสุขภาพของมนุษย์ด้วย แผนแม่บทสำหรับการจัดการของเสียของประเทศไทย (ปี พ.ศ. 2559-2564) ได้มีการสนับสนุนให้มีการดำเนินการจัดการของเสียอุตสาหกรรมโดยคำนึงถึงการลดผลกระทบดังกล่าวซึ่งในอดีตไม่ได้มีการคำนึงถึงประเด็นความท้าทายทางด้านสังคมของผู้ประกอบการธุรกิจรีไซเคิลซึ่งอาจจะมีส่วนช่วยในการชดเชยในกระบวนการรีไซเคิลอย่างยั่งยืน

งานวิจัยนี้มีวัตถุประสงค์เพื่อหาปัจจัยที่มีผลต่อการสร้างกระบวนการรีไซเคิลหลอดฟลูออเรสเซนต์ที่ใช้แล้วอย่างยั่งยืน โดยใช้การประเมินวัฏจักรชีวิตต่อสิ่งแวดล้อม (ELCA) ด้วยโปรแกรม SimaPro8 และ ReCiPe และการประเมินวัฏจักรชีวิตต่อสังคม (SLCA) ตามแนวปฏิบัติของ UNEP/SETAC 2009 ร่วมกับการสัมภาษณ์แบบกึ่งโครงสร้างกับตัวแทนผู้ประกอบการธุรกิจรีไซเคิล (n=2) จากผลการศึกษาพบว่า การใช้พลังงานไฟฟ้าในกระบวนการรีไซเคิลนี้ได้ส่งผลกระทบต่อสุขภาพของมนุษย์(14.96 μPt) ระบบนิเวศ (0.74 μPt) และการสูญเสียทรัพยากรธรรมชาติ (0.0086 μPt) แต่ในทางกลับกัน กระบวนการรีไซเคิลก็ช่วยเพิ่มประสิทธิภาพเชิงบวกในด้านสภาพการทำงานที่เหมาะสม อย่างไรก็ตามผู้ประกอบการมักจะประสบปัญหาการขาดแคลนวัตถุดิบในการรีไซเคิล นอกจากนี้จากการศึกษาวิจัยยังขาดข้อมูลผลกระทบจากปรอทเนื่องจากมีข้อจำกัดในเรื่องของการเข้าถึงข้อมูลและความยินยอมจากผู้ประกอบการต่างๆ ในการให้ข้อมูล ดังนั้นจากการศึกษาวิจัย จึงเห็นว่าควรมีการเตรียมความพร้อมเชิงองค์กรเพื่อปฏิบัติตามมาตรฐานความปลอดภัยทั้งทางด้านสิ่งแวดล้อมและความปลอดภัยอาชีวอนามัยซึ่งได้รับการสนับสนุนโดยผู้ประกอบการทั้งในและนอกระบบ นอกจากนี้ควรมีการคำนึงถึงปัจจัยด้านการวางแผนการจัดหาเงินทุนที่ยั่งยืนเพื่อพัฒนากระบวนการรีไซเคิลในประเทศไทย

สาขาวิชา	การจัดการสารอันตรายและสิ่งแวดล้อม	ลายมือชื่อนิสิต	....
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For the past decade, Thailand has had intensively installed Fluorescent Lamp (FL) for lighting purposes. Improper handling or disposal of a spent fluorescent lamp can cause not only environmental damage by releasing mercury and other metals to the environment but also human health impact. Master Plan on Solid Waste Management (2016-2021) of Thailand encouraged industrial waste management to reduce such impacts with less consideration of the social challenges experienced by the formal recyclers that might offset the sustainability of the recycling process.

This research aimed to identify enabling factors to improve the recycling process of SFLs using environmental life cycle assessment (ELCA) with SimaPro 8 and ReCiPe impact analysis, and social impact assessment (SIA) using UNEP/SETAC 2009 Guideline combined with semi-structured interviews with the formal recycling business representatives (n=2). The results showed that electricity consumption in the process contributed adversely to human health (14.96 μPt), ecosystem damage (0.74 μPt), and resource depletion (0.0086 μPt). Contrary, it has positive impacts on decent working conditions. In addition, the formal business struggled with the low material supply. The results displayed limited information on mercury impacts due to data availability and confirmation with other stakeholders. The research suggested that institutional capacity to comply with environmental and occupational safety standards supported with informal-formal partnership and sustainable financing schemes is the enabling factor to improve the recycling process in Thailand

Field of Study:	Hazardous Substance and Environmental Management	Student's Signature ....
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Ella Nanda Sari

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER I

INTRODUCTION

1.1 Background and Importance of Studies

Thailand is a large energy consumer in Southeast Asia. The use of energy has been dominated by electricity purposes dominating for 30% (EGAT 2018). In the electricity user sector categories, industries have been the highest value of energy share for the last 18 years. In 2019, the share reached 43% even though lower than last year. The rise of the large electricity demand is associated with industry development (Thailand Board of Investment, 2020). The share of electricity in industries was highly contributed for lighting purposes for about 58%. Thailand is likely dependent on energy imports therefore there was a need for energy conservation and transformation to renewable sources to secure domestic consumption. As the largest consumer, industries `have carried out a prior action in 2011 to conserve energy under the 20-Year Energy Efficiency Development Plan (2011 - 2030) (Ministry of Energy, 2019). Moreover, the authorities have been replacing energy-consuming lighting equipment in households, commercial, and government buildings to secure the national energy supply. Such measures were undertaken through the Energy Efficiency Development Plan (2015-2036).

For the past decade, the country has had intensively installed Fluorescent Lamp (FL) and High-Intensity Discharge (HID) for lighting purposes but Light Emitting Diode (LED) started to replace for higher energy efficiency and longer lifespan in 2010. In 2016, the replacement of 200,000 36 Watts T8 FL at government buildings with 23-Watt LED was made by the Pollution Control Department (PCD) and the Electricity Generating Authority of Thailand (EGAT). Regardless of this effort, industries still prefer FL due to a lower installment cost. This has caused electrical wastage.

According to a life cycle comparison study, FL caused higher adverse health and environmental impacts compared to LED, particularly from the mercury concentration. Fluorescent lamp relies on mercury as the luminary agent through conversion of electrical energy into visible lights. Mercury is a hazardous element that adversely impacts humans and the ecosystem when it releases improperly. To support the lighting function and protect human health, the concentration of mercury should be below 2.5 mg RoHS (Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment) (Hobohm et al., 2017). The mercury concentration has changed over time and according to manufacturers and models. For instance, the lamps produced before 1992 contained >40 mg and decreased to <21 mg after 1997 (Lecler et al., 2018; Thavornvong, 2016).

Spent FL (SFL) is considered as hazardous waste under Notification of Ministry of Industry Re: Industrial Waste Disposal B.E. 2548 (2005) with a code of 16 02 15 HA (hazardous component removed from discarded equipment). Hazardous waste requires special treatment before being released to the environment to prevent its likelihood of causing adverse impacts to the surroundings (UNEP 1985). The research focused on industrial waste of FL because the ICS (Industry, commercial, and service) sector dominated 52% of FL installment (Wongsoonthornchai, Kwonpongsagoon, & Scheidegger, 2016). Meanwhile, proper management of electronic waste (E-waste) from industrial discharge is still far from efficient due to low enforcement, unclear E-waste management, and limited technology capability (Apisitpuvakul, 2007; Chanatip Pharino, 2017). Therefore, SFL is still concerning.

SFL recycling is strongly encouraged to prevent SFL from posing adverse impacts. Based on environmental life cycle assessment (ELCA), SFL recycling increased 77.40% of human health, 21.99% resource protection, and 1.03% ecosystem quality than landfilling (Thavornvong, 2016). Similar results were identified in other SF recycling studies in Thailand (Apisitpuvakul, 2007; Wongsoonthornchai et al., 2016). Such benefits were associated with lower electricity use and mercury release. Such environmental benefits directed the Ministry of Environment and Natural Resources to target a 100% treatment rate of industrial waste in the Master Plan on Solid Waste Management (MPSWM) (2016-2021) and promoted the 3R (Reduce, Reuse, and Recycle) Action Plan to achieve the goal (Pollution Control Department, 2015).

However, such a goal was irrelevant to practices on the ground and experiences of the stakeholders in the value chain, particularly formal recycling business. They were positively contributed to environmental protection and working safety (Gunarathne, de Alwis, & Alahakoon, 2020; Henzler et al., 2017). However, across developing countries in Asia, they remain to face challenges in control and monitoring of emissions, irregular supply flow, and capable technology (Gunarathne et al., 2020; Pathak, Srivastava, & Ojasvi, 2017). Addressing their challenges would sustain the recycling business that fits the local condition rather than imposing a higher recycling rate without suitable problem solutions (Henzler et al., 2017).

This argument was supported by the Sustainable Recycling Industry approach (Mathias, 2017) and integrated sustainable E-waste management (Gunarathne et al., 2020). The two approaches highlighted the consideration of environmental, social, political, and other aspects to create sustainable management. Moreover, UNEP/SETAC Guidelines (2009) as a tool for Social Impact Assessment (SIA) were developed to complement ELCA to provide analysis of social impacts of a service or product. The application of the guideline in different topics has been identified, e.g., waste treatment (Garcia-Sanchez & Guereca, 2019), bio-based products (Falcone & Imbert, 2018), and informal E-waste recycling (Umair, Björklund, & Petersen, 2015). Similar to ELCA, the guideline consists of four steps analysis goal/functional unit definition, inventory analysis, impact assessment, and interpretation.

The inventory consists of the stakeholders involved in the evaluated service/product and the social impacts categories they might encounter in the process/relationship of the service/products. Moreover, impact assessment means the measurement of the selected impact categories in each stakeholder. The impact interpretation is rather subjective, thus requires confirmation with the stakeholders analyzed or an expert’s judgment (Falcone & Imbert, 2018). An example of the guideline application on the informal E-waste sector elaborated that the social impacts of informal E-waste recycling corresponded with discriminative salary and low health and environmental protection to the workers. However, it had the potential to the local economy and employment (Umair et al., 2015).

Similarly, the informal sector dominated 90% of E-waste collection in Thailand, and they had to be considered in improving SFL management and create sustainable E-waste management in the country. Evaluation of the environmental and social aspects in the recycling of SFL was expected to result in the formulation of enabling factors for the initial creation of sustainable recycling in the Master Plan. Especially studies in this focus in Thailand largely argued from the impacts of quantitative measurement (e.g. increased waste collection, treatment, and sucre disposal) than the social experience by the formal business (Apisitpuvakul, 2007; Thavornvong, 2016; Wongsoonthornchai et al., 2016).

1.2 Objectives

1.2.1 To evaluate environmental and social impacts of recycling processes for SFL

1.2.2 To identify the challenges experienced by formal recycling business in the business

1.2.3 To identify the correlation of environmental and social impacts and the challenges to formulate the enabling factors for the creation of sustainable recycling processes to support industrial waste management regulations

1.3 Hypotheses

1.3.1 Formal recycling had positive contributions to environmental protection and decent working conditions for the workers and local community

1.3.2 With the existing technology in the recycling practice, the increased recycling rate can increase the mercury exposure to the workers and the local community

1.3.3 The formal recyclers remain to experience challenges such as lower material supply and competition with informal recyclers that hinder making the process sustainable

1.3.4 Extended Producer’s Responsibility (EPR) is still preferred to manage E-waste recycling sustainably and public awareness of the environmental impacts

1.4 Research Question

1.4.1 What are the environmental and social impacts of SFL recycling processes in Thailand?

1.4.2 What are the challenges faced by the formal recycling business that hindered creating a sustainable recycling process?

1.4.3 What are the enabling factors for a sustainable SFL recycling process in Thailand?

1.5 Scope of the Study

The study's scope included the assessment of the recycling practice of SFL in a recycling plant located in Chonburi Province, Thailand. Only SFL is generated by the industries processed by this recycling plant. The recycling process is only the one in the facility excluding the collection and transportation process due to the data limitation.

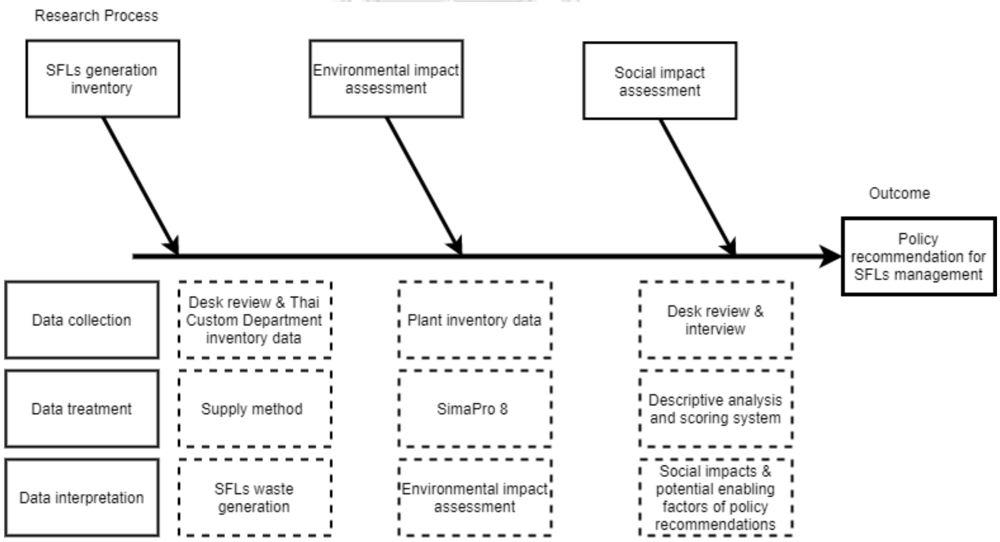

Figure 1 Scope of the study

The research design consisted of three stages: a preliminary study estimating the SFL generated in the upcoming years and followed by the environmental and social impact assessment. This step generated enabling factors for brief policy recommendations of a sustainable recycling practice of SFL. Data throughout the process was collected using quantitative and qualitative approaches depending on the research process and objective.

The quantitative approach highlights the measurement and analysis of causal relationships between variables of collected data, not the process using the statistical approach. This covered the preliminary stage in the waste generation calculation, environmental impact assessment with SimaPro, and scoring system the interview results in the social impact assessment. On contrary, the qualitative approach focused on the qualities of the entities and relationships that are not experimentally measured. This approach, sometimes, complement the quantitative method to understand the process. In this research, the method applied in the social impact assessment to describe the interview results. Desk review and semi-structured interviews allowed the generation of the outcome in the social impact analysis. A semi-structured interview is a method in qualitative research using structured questions on a certain topic to guide the direction of the conversation. The interviewer may have the authority to create an order for the questions. It is used to delve deeply into the topic and understand thoroughly from the interviewee's perspective (Falcone & Imbert, 2018; Harrell & Bradley, 2009).

CHAPTER II

LITERATURE REVIEWS

2.1 Fluorescent Lamps Market Share and Management in Thailand

Fluorescent lamps are lighting sources that generate light through an electric current and mercury vapor (Peng, Wang, & Chang, 2014). Liquid mercury adds to the lamps compounded with other metals forming solid form (amalgam) to convert electrical energy to radiant energy in the ultraviolet range (Wongsoonthornchai et al., 2016). This ultraviolet excites the white phosphor in the glass tube and re-radiates the ultraviolet light into a visible light spectrum that humans see. Besides these light-generating substances, FL contains a ballast part that supports the lighting operation (Thavornvong, 2016).

The mercury content in the lamp varies over time, types, and countries of origin (Xiaofeng Zheng, 2016). The type of FL divides into three: linear/tubular, compact, and circular (Peng et al., 2014). Tubular FL dominantly was installed in commercial and industries because the light creates low brightness reducing direct glare that is suitable for large indoor buildings such as hospitals, industries, and offices. In tubular models, type T5 and T8 36 Watt largely installed in professional buildings replacing the previous model T12 with the highest lifespan of 7,000 - 24,000 hours and efficacy of 30-110 lumens/watt (Homeres, 2019; T. Li et al., 2018; Silveira & Chang, 2011; Thavornvong, 2016; Turye, 2013).

After being introduced in the Thailand market in 1996 to replace incandescent lamps for energy-saving reasons, FL was dominating 58% of total lighting installed (420 million lamps) in 2014 (Refer to Figure 2). Industries, commercials, and service sectors (ICS) were the primary users accounting for 52% of the usage in 2010 (International Institute for Energy Conservation-Asia, 2016; Wongsoonthornchai et al., 2016). Considering the average use of FL in Thai industries is 14 hours/day with six working days/week; FL will be disposed of after 4.57 years with 15,000 hours lifespan calculation. This information indicated that 58% (244 million) of FL used in 2014 should have entered a treatment facility in 2018. A forecast study showed there would be 299 million units of SFL in 2018. There was no available data representing the ICS sector's share use in the same year (Thavornvong, 2016).

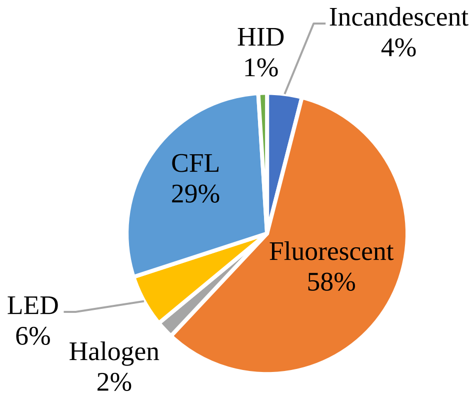

Figure 2 Market share of the fluorescent lamp in Thailand in 2014

Source: (International Institute for Energy Conservation-Asia, 2016)

The market share of the FL has been declining since 2016 compared to 2010 due to the 30% energy intensification program's implementation under Energy Efficiency Development Plan (2015-2036). Replacement of 200,000 units of 36 Watts T8 FL at government buildings with 23-Watt Light Emitting Diodes (LEDs) during 2015-2016 was carried out (Energy, 2015; Thavornvong, 2016). Even though the number of FL production would diminish in 2036, the country still has to deal with waste. It has become a concern particularly SFL generated from industries because the business is growing as economic growth and global demand (The Office of Industrial Economics, 2019) and SFL requires specific treatment for the hazardous elements it contains.

2.1.1 The importance of SFL management on mercury release reduction

SFL, in Thailand, is categorized as hazardous waste under the Notification of Ministry of Industry Re: Industrial Waste Disposal B.E. 2548 (2005) with waste code 16

02 15 HA (Waste from electrical and electronic equipment that the hazardous component removed from discarded equipment), Hazardous Substance Act 2013 in Section 5.3 (Liumpetch, 2018; The Minister of Industry, 2005), and draft Act on the Management of the Waste Electrical Products and Electronic Equipment. Referring to the Notification of Ministry of Industry Re: Industrial Waste Disposal B.E. 2548 (2005) hazardous waste means the waste having hazardous constituents, being contaminated with a hazardous substance, or having hazardous characteristics. For FL itself, mercury it contains for the lighting function has been controlled strictly due to the toxic characteristic.

SFL is considered hazardous waste if it contains mercury >20 mg/kg waste and equals or exceeds 0.2 milligrams per liter from the extractable mercury concentration. Naturally, mercury is toxic, persistent, and bio-accumulative in the environment that has increase concern on SFL. The mercury released from FL can be through broken lamps during transportation, storage, feeding into the recycling machine, and during incineration and at the landfill. Once in the environment, it will convert microorganisms into methylmercury, a possible carcinogen to humans (group 2B) according to International Agency for Research on Cancer (IARC). Besides, it can enter and deposit in the living organisms. It has been found that mercury of 4.9 -215 μg/kg (dry weight) was identified in the rice plantations located 174 km^2 from the mining activities. The studied rats fed the rice from this area were posing brain damage (Wang et al., 2012; Budnik & Casteleyn, 2019; Knezović, Trgo, & Sutlović, 2016).

In addition to the workers' urine contained mercury found in a recycling facility in Wisconsin and other countries since 1992 (Erica Wilson & Meiman, 2018; Hu & Cheng, 2012). Several symptoms found among the workers include difficulty in breathing, loss of memory, tremor and other muscle-related issues, and irritability. A safe level parameter for the mercury concentration in the body was 20.0 μg/g creatinine of the biologic exposure index by the Governmental Industrial Hygienists (ACGIH). Moreover, mercury was found deposited in aquatic animals, birds, and predatory organisms (Erica Wilson & Meiman, 2018; Wongsoonthornchai et al., 2016).

Mercury is categorized as one of the hazardous air pollutants (HAPs) related to the Clean Air Act of the US. Environmental Protection Agency (EPA). Incineration and landfill release 30% of mercury from the lamps, contrary recycling only release 2%. Mercury air pollution caused premature death to newborns and ended back to the environment affecting ecosystems (Peng et al., 2014). Mercury released from the broken lamps analyzed remains for 8 hours to 10 weeks in the air (Peng et al., 2014; Wongsoonthornchai et al., 2016). Poor ventilation in the recycling facility endangers the workers from exposure to mercury dust (> 0.025 mg/m_3 averaged over an 8-hour work shift according to ACGIH threshold limit value), together with other hazardous metal dust from the lamps such as lead, yttrium, and barium. At last, the occupational exposure at the recycling facility could be carried until home through personal vehicles, uniforms, and footwear (Zimmermann et al., 2014).

In the context of Thailand, mercury released from the FL life cycle was calculated as 84% of the mercury leaked going to land, 12% to air, and 4% to water Based on the Mathematical Material Flow Analysis (MMFA) calculation of 562 kg mercury released to the environment (Wongsoonthornchai et al., 2016). Moreover, garbage workers in the hazardous waste management facility in Southern Thailand and Ubon Ratchathani were detected with mercury in the urine, which was related to poor personal hygiene and the use of PPE (Somsiri Decharat, 2012). Therefore, the management of SFL was critical to prevent or reduce such environmental and health impacts.

The management of SFL focused on the comparison of the benefits of FL elimination. For the end disposal management, it did not apply to the existing treatment facility. China and India for instance highlighted the importance of EPR for the management while Japan focused on improved recycling technology (Apisitpuvakul, 2007; Henzler et al., 2017; Peng et al., 2014; Quayin Tan, 2014). IN Thailand, EPR implementation and recycling were tried to implement. While the monitoring of mercury for the industrial complex was also important to control the emissions/discharge from the industries.

In 2007, fluorescent lamp treatment under household hazardous waste was started by PCD and Bangkok Metropolitan Administration (BMA) through different voluntary alternatives such as collection facility establishment, awareness-raising, separation, storage, transportation, recycling, and treatment/disposal. BMA established the drop-off centers in several locations and transferred the waste every 15 days to the primary transfer station locations in Nong Kham, Saimai, and On Nut. After the collection target is achieved, a private company legalized by the Department of Industrial Work (DIW) transferred the waste to a final disposal site or treatment, i.e., incineration or recycling (Chanatip Pharino, 2017).

However, the collection amount was often under target (expected: 249 tons/day vs. actual: 1 ton/day) and alter the business. The low collection is associated with low separation activities mixing the hazardous waste and the municipal and lack of cross-institutional between the government and private collaboration (Chanatip Pharino, 2017). A large number of safe disposal facility is still owned by the private and it requires a high amount of treatment fee (Manomaivibool & Vassanadumrongdee, 2011). In addition to that, the trade-off cost between the waste treatment and improper disposal is 150,000 Baht/ton vs. 200,000 Baht or jail up to 2 years according to Factory Act and Hazardous Waste Act (Liumpetch, 2018).

2.1.2 The fragmented management of SFL within the authorities

Fluorescent lamp waste characteristic has a mix between solid – industrial and hazardous, which alter the concentrate focal point for the management. The management can be under policies of solid waste, E-waste, and hazardous waste. Such circumstances fragmented and discontinued the collaboration between the stakeholders in the collection, transportation, separation, and final disposal.

Moreover, it would prolong and challenge the incentive mechanism to the on-the-ground stakeholders in the management, low investment due to unsettled policies especially under E-waste bill, knowledge transfer, and capacity building. Such factors hindered the management's continuity in result improper or illegal disposal (Manomaivibool & Vassanadumrongdee, 2016).

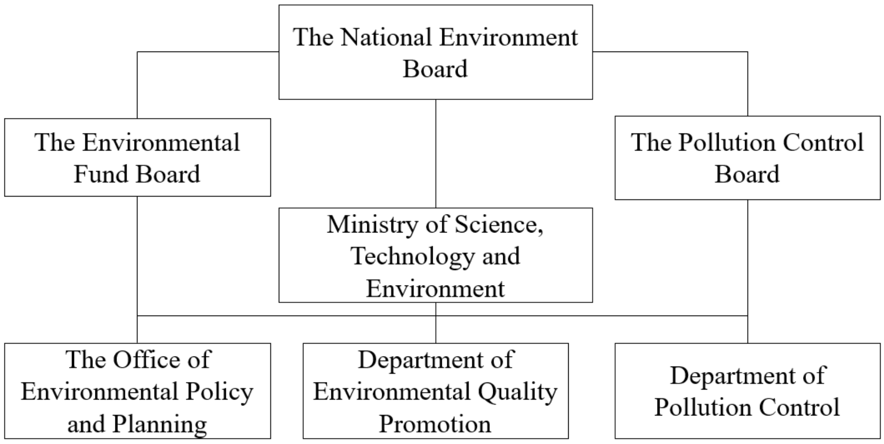

Figure 3 National structure of governmental bodies in environmental management

Source: (Chanatip Pharino, 2017)

The environmental quality supervision of SFL is led by the National Environment Board (NEB) that proposes, supervises, and controls the cabinet's environmental quality. The Board compromised of three divisions: The Environmental Fund Board (TEFB), Ministry of Science, Technology, and Environment (MSTE), and the Pollution Control Board (PCB). Under those, two implementor departments and one office, the functions are existing, i.e., The Office of Environmental Policy and Planning (OEPP), Department of Environmental Quality Promotion (DEQP), and Department of Pollution Control (PCD) (Chanatip Pharino, 2017).

The National Committee assigned the Ministry of Natural resources and Environment to coordinate and monitor the Act's implementation (Kamuang & Siriratpiriya, 2017) However, this Act excludes fluorescent lamps generated by industries (Article 3) that intersects the Department of Industrial Work responsibility. Besides that, the funding mechanism for SFL management under the WEEE Act on the Management of Waste Electrical and Electronic Equipment and Other End-of-Life Products is still unclear and remains pending.

Its funding scheme was based on the EPR scheme, a take-back system, where the manufacturers/producers were responsible for waste collection funds and establishment of take-back facilities and became the player of collaboration with other stakeholders (Manomaivibool & Vassanadumrongdee, 2016). Such a funding scheme distinguished the new draft Act more than the previous, which focused on the government's collection funds. However, under this Act, the government still holds power for product levy fees in the National Environmental Fund that distributes the fund to the local take-back depots established by the private sectors and authorized recyclers to purchase waste from consumers.

EPR is defined as a "policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling, and final disposal of the product" (Pathak, Srivastava, & Ojasvi, 2019). The responsibilities are compromised of liability, physical, financial, and informative responsibilities, in which the financial responsibility is the basis to levy fees on the producers to subsidize downstream management (Carisma, 2009).

The new funding scheme (Figure 4) provides an advantage for the producers to plan takeback obligations, recycling targets, recycling actors in the product chain to transform the system based on their knowledge and experience. Additionally, to increase a substantial lobby with multinational corporates (MNCs), triggering the support harmonization of WEEE regulations and requirements. This most significantly would not depend on the capacity of governmental bodies regulating the management in the day-to-day operating system.

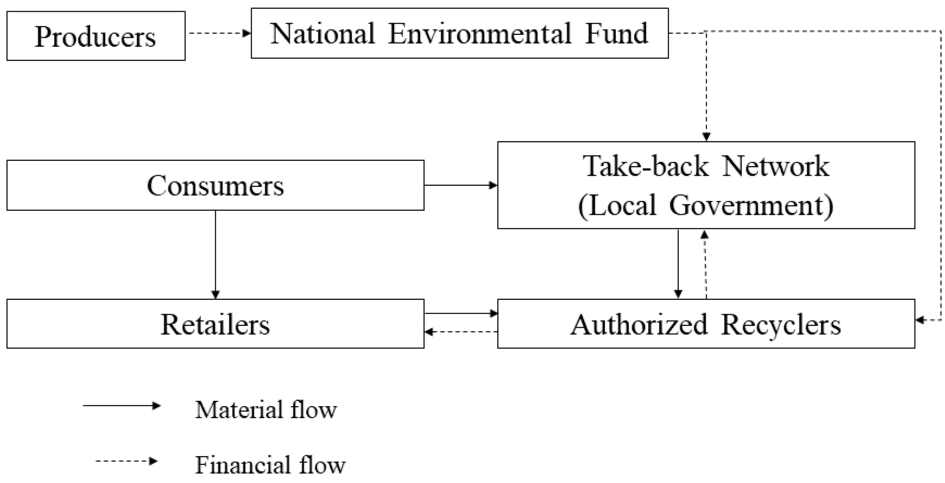

Figure 4 National environmental fund scheme

Source: (Hande, 2019)

However, the debate arose about the standard compliance applied for different producers and to what extent the individual producer take-back system should be regulated in the law and the collaboration between the producer, the Environmental Fund Office, and the local administration (Manomaivibool & Vassanadumrongdee, 2016). Based on Figure 4, the linkage between producers and Environmental Board lied in the report of the management plan consisting of the development of an information distribution channel, take-back or collection channel, convenience of consumers, financial support of the collection, and transportation (Manomaivibool & Vassanadumrongdee, 2016). Master Plan on Solid Waste Management 2016-2021) tackles the occurrences of illegal dumping by reducing hazardous/municipal/infectious waste from the source and improving capabilities and solid waste management.

Similar to the draft Act that focuses on reducing the source, MPSW promotes the principle of 3R (Reduce, Reuse, and Recycles) for the action place (Pollution Control Department, 2019). Because reduction from the source is no longer relevant for SFL due to reducing the market share, recycling with EPR mechanism has would be relevant for SFL management. Such MPSW and the draft Act could be used as a framework to improve the management of SFL.

2.1.3 Extender Producers' Responsibility in the SFL management

The EPR scheme initially developed in the 1990s has contributed to the increased recycling rate and reduced public spending on waste management. The responsibility of the product life cycle has now been put to the producer instead of the authorities and taxpayers. The number of 90% of E-waste in Thailand was collected by the informal sector, which would cripple the implementation of EPR in the legalized SFL management (Manomaivibool & Vassanadumrongdee, 2011; Pollution Control Department, 2019). Another limitation of the EPR system applied in the E-waste bill was that it did not explicitly mention the implementation of EPR. Common implementation programs of EPR were either through the collection, recycling, and financial mechanism (Manomaivibool & Vassanadumrongdee, 2011; Sasaki, 2018).

In Thailand, instead of the producers handling independently the product treatment, the authority has proposed to collect the product fee from the government fund to subsidize the buy-back mechanism (Sasaki, 2018). The subsidies were given to the local collection centers established by the local government or private sectors and formal recyclers. However, the treatment facility of industrial waste was still low that hindered the revenue and rotation of the fund finding the end-user payer was back as a possible option (Chanathip Pharino, 2017). Unfortunately, an increase in illegal dumping has shown increased in Japan when end-user payers reimplemented (Tojo, 2004).

Discussion on the EPR implementation in the country has much focused on the economical instruments and benefits. While the driving factors were beyond that. According to Xiong Zheng, Xu, and Feng (2017) ranking the different driving factors reported on EPR implementation using analytic network process (ANP) score showed that the five top factors were EPR-related regulation (0.534 ANP score), followed by the consciousness of senior executives (0.14448), corporate image (0.14282), the opportunity of the new market (0.07556), and pressure from the consumer (0.02925).

The regulation was the most significant since it serves as the guidance for legal promotion and implementation. However, third parties, i.e. financial institutions and civil also had a role in the promotion. society Unlike the first factor, the second and third factors were easily influenced changed according to the market condition.

Successful implementation of EPR has been seen in Germany and Austria for instance. Germany lies the responsibility of manufactures to dispose and retailers to collect the waste from consumers. Consumers must pay collection fees but not transportation, dismantling, disposal, and landfill cost. Collection centers were located in various places such as supermarkets, pharmacies, electronics stores, and communities throughout the country. The key driver of the success was the infrastructure and adequate collection. However, for Austria, this key was an incentive fee for the consumers that return the waste. Before the purchase, consumers pay two types of fees, the refundable fee for returning and nonrefundable to fund the recycling. This concept was not applicable in Thailand with low collection centers and waste return rates together with an unwillingness to return the waste. However, Thailand's funding scheme was similar to Taiwan and China where the local government establishes local collection centers and the rest was a burden to manufactures (Peng et al., 2014).

Recommendations in the research studies highlighted funding scheme, expansion of collection centers, and recycling activities, which was unable with the existing challenges in Thailand with lower treatment facility number, collection centers, tight competition with the informal sectors, and low revenue. Particularly in low middle-income countries with a higher percentage of waste entered the informal business, a partnership between formal and informal recycling business was tried in India, Peru, Ghana, Nigeria, and South Africa. Such partnership was aimed to provide integrated solutions that realize social conditions among different sectors to generate health and fund benefits as well as guarantee a sustainable waste management process (Hinchlife et al., 2020).

A model that was implemented in India was a direct collaboration with informal collectors to formal recyclers. This was tackling receiving waste from remote and distant areas. Besides, they provided formalization and capacity building for a bigger capacity for informal collectors. An important key to success is if all the stakeholders perceive the benefits. Informal sectors can feel the benefits when interface agencies/intermediate agencies channel the waste from informal sectors to formal recyclers (Hinchlife et al., 2020). This method has never been identified in Thailand and could be a resourceful source to explore.

2.2 Master Plan on Solid Waste Management (2016-2021)

the Ministry of Natural Resources and Environment drafted this policy in 2015 as the primary strategy to manage waste in the country, with the main principle of 3R to reduce waste generation and increase waste utilization. This promotion aimed to change public perspectives of used products from waste to additional income sources and reduce production costs to promote a circular economy (Chanatip Pharino, 2017). Such action reduced the occurrences of improper and illegal disposal by producers or consumers.

Industrial waste dominated 80% (2.8 million tons) of the total hazardous waste generated in 2016 that accounted for 3.462 million tons. This number was higher by 0.49% from the previous year. Forty percent of the waste entered different end-of-life management such as waste-to-energy (29.8%), disposal (24.6%), and processed and reuse (21.9%). Contrary, the PCD report stated that incineration only made up 1%, far behind open dumping (about 64%) and landfill (35%). The widespread illegal disposal was in result of the high cost of proper waste disposal and lower fines for polluters (Pollution Control Department, 2019).

The increasing economic growth and technology in urban areas have influenced the records of complaints filed to the Pollution Control Department/Bangkok Metropolitan Administration/Department of Industrial Waste regarding multiple pollution sources (e.g., air pollution, noise, and vibration, wastewater, trash/garbage/and hazardous waste) for rapid mitigation actions. From the total of 19.422 files entered, the top three for the problem source were business (42%), residential area/building (29%), and factories (13%). To prevent the increasing pollution caused by improper disposal during 2011-2015 (up to 11,452 associated complaints in 2014) towards various industries and governmental agencies (e.g., 812 complaints to the Department of Industrial Work, 420 complaints to Pollution Control Department, and a small amount (34%) of industrial hazardous waste in 2014 (Pollution Control Department, 2019). None of them specifically related to fluorescent lamps from the seven reported industrial illegal dumping cases because most FL input exported.

Besides targeting an improvement of an industrial hazardous waste collection of 100% by 2021, it, as well, covers other areas of waste management in:

- >75% of the municipal solid waste disposed of appropriately by 2021
- 100% of the residual waste enter proper disposal by 2019
- >30% of the household hazardous waste generated collected and disposed of properly by 2021.
- 100% of the infectious waste have proper disposal by 2020.
- >50% of Local Administrative Organizations manage municipal solid waste and household hazardous by 2021 (Pollution Control Department, 2015)

They implemented such targets integrated into the 3R action plan framework by implying three principles: waste and product reduction since the manufacturing process, waste reduction at consumption process, and waste recycling into energy and other recyclable materials. The third principle is that the disposal stage of waste supports sustainable recycling for industrial waste, especially SFL, through multiple public-private partnerships, recycling business promotion, and capacity building. These points are the key highlights to consider and explore to increase industrial waste treatment, as mentioned in MPSWM. Different instruments implement those strategies that include science and technology, capacity building, economic instrument, laws and regulations, and international cooperation. Based on these regulation frameworks, Thailand has already had action maps to improve waste treatment (Pollution Control Department, 2019).

The advantage of such MPSW is that it applies systematic waste management in three areas of 1) waste reduction at source through maximizing the use of materials and longer life span and environmentally friendly product design, 2) facilitation of area 1 through increase of collection efficiency, efficient and proper treatment, and unique waste management in a particular area such as tourist destination, and 3) the promotion of waste management by promoting separation and recycling activities by product costumers and manufactures, developing knowledge and database system of waste product it covers (Chanatip Pharino, 2017).

Such measures were aiming for proper waste disposal as a result of public health protection. While pinpointing facilitation initiatives through a higher environmental-focus target, it fails to regulate incentives for stakeholders carrying out separation and recycling that still caused improper waste management preferences. One example is the low trade-off cost between the illegal dumping fine and treatment cost. Another reason is that it fails to acknowledge the stakeholders' social challenges to facilitate them in the target achievement (Hoornweg and Bhada-Tata 2012). Therefore, recycling promotion to solve solid waste is still facing challenges in the improvement.

2.3 Benefits and Challenges of E-waste Recycling Processes in Thailand

When the above E-waste and solid waste regulation frameworks focused on waste reduction from the source, with the increasing economic growth associated with waste generation, recycling is an alternative to compensate for waste problems in the waste management hierarchy (Figure 5). Recycling was an initiative promoted for solid waste management. It aims to reduce waste and slow down the depletion of natural resources because of mass production for today's socially networked society (Kim, Hwang, & Park, 2009). When waste reduction from the source was promoted in the developing countries, insufficient collection systems, low environmental awareness, and weak law enforcement encountered the promotion. Waste prevention was seen as argumentative to economic development; therefore, recycling has been promoted as an alternative to the current economic growth.

Besides becoming an alternative, recycling opens an opportunity for green jobs and employment sources (Chanatip Pharino, 2017).

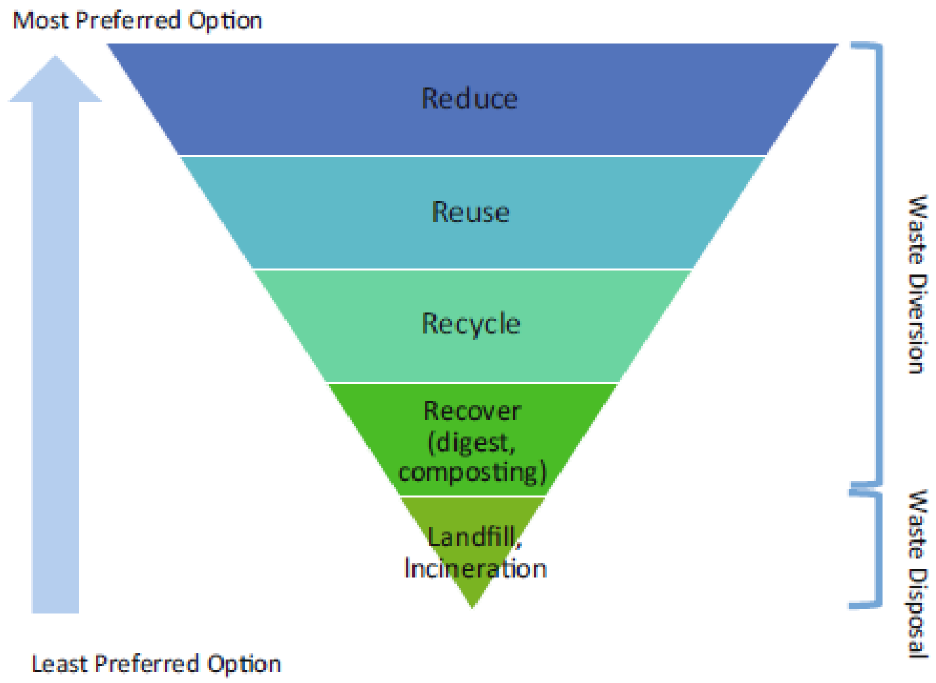

Figure 5 Waste management hierarchy

Source: (Chanatip Pharino, 2017)

Based on the category, recycling activity consists of formal and informal. Formal recyclers are those of a licensed company that deals with many used products from affiliated clients and complies with environmental laws and regulations, including health protection for the workers. In contrast, informal recyclers are lack such components. It has no operating permit that causes the loss of environmental and occupational protection. They usually occurred in the area attached to their house, which possessed cross-sectional health hazards to the family members and neighborhood. In Thailand, such exposure primarily caused heavy metals (Cu, As, Cd, and Pb) contamination in the surface soils, which were identified in several districts covering more than 300 informal-separating houses in

Buriram Province (Amphalop, Suwantarat, Prueksasit, Yachusri, & Srithongouthai, 2020).

Despite the adverse impacts, informal recyclers were still more preferred by the customers after a product's use because they can give a higher incentive for a given product. Formal recyclers were depending only on the larger industries for the material supply, and the waste collection relies on the municipalities. When the municipalities experienced budget deficiency, the was collection fee became higher. The transportation cost also depends on the transportation distance. This would burden industries located far from the treatment facility (Gunarathne et al., 2020; Manomaivibool & Vassanadumrongdee, 2016; Pollution Control Department, 2019).

As illustrated in Figure 6, waste flows through different steps before recycling. Each step associates and influences one another. In addressing issues in recycling, the assessment shall consider other steps for a holistic understanding (Fujimori et al., 2012). Besides, stakeholders in the system (e.g., informal and formal recyclers, government, and the public) should be involved as well for the system to be as efficient and cost-effectively as possible and comply with environmental standards and health protection.

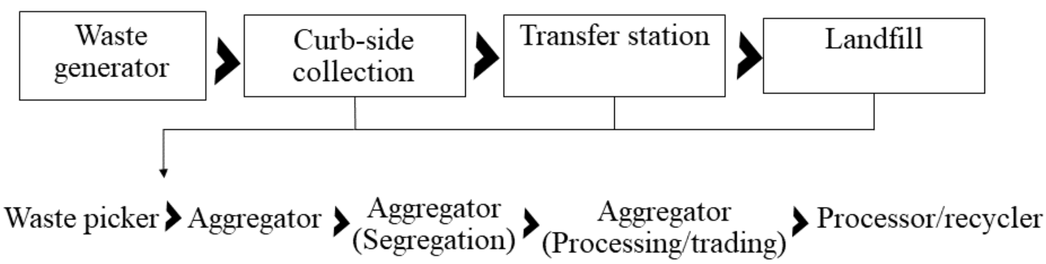

Figure 6 The flow of informal E-waste recycling activities

Source: (Hande, 2019)

2.3.1 Benefits of SFL recycling to mercury release reduction

For SFL, recycling is beneficial to environmental and human health because it prevents and reduces the release of mercury and heavy metals from the lamps to the environment and humans. Studies showed that recycling increased 77.40% of human health, 21.99% resource protection, and 1.03% ecosystem quality than landfilling (Thavornvong, 2016). Similar results identified such benefits as lower electricity use and mercury release (Apisitpuvakul, 2007; Wongsoonthornchai et al., 2016). The increasing recycling rate has also shown reduced the total mercury release to the air, water, and land concerning human exposures. Therefore, policy formulation targeted a higher recycling rate for the benefit.

However, a recycling practice in Thailand has a lower recycling rate of 8% compared to Japan 10%, Taiwan of 90%, and Germany 80%. There is still no technology available to recycle mercury. The current practice sends the filtered mercury to Japan for recycling (Lecler et al., 2018; Lee et al., 2014; Thavornvong, 2016). The technology limitation existed in the national report of 2014 to the Secretariat of the Basel Convention, where Thailand listed eleven disposal facilities, including three secure landfills and fifty-five recovery facilities, with no clear indication on which facilities are capable of mercury waste (Erica Wilson & Meiman, 2018).

FLs contain metallic mercury in the form of liquid at room temperature and are easily vaporized. Therefore, the release occurs in the form of vapor and liquid (Lecler et al., 2018; Peng et al., 2014; Q. Tan & Li, 2016; Xiaofeng Zheng, 2016), and its occupational exposure occurs through breathing and skin contact during the recycling process through broken bulbs outside the machine, improper machine air filtration, leakage of the mechanical seal and during maintenance. The Standard of its exposure for 8 hour working time is 0.1 milligrams per cubic meter of air (mg/m^3) based on the Occupational Safety and Health Administration permissible exposure limit (OSHA PEL). While US National Institute for Occupational Safety and Health (NIOSH) suggests the exposure is limited to 0.05 mg/m^3 over a 10-hour workday, and The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a more stringent limit to an average of 0.025 mg/m^3 over an 8-hour workday (United States Department of Labor, 2012a).

Mercury toxicity from SFL is taken into consideration based on the mercury state (liquid or solid), the life span of the lamps since it determines the amount of mercury entering the recycling process, and the present amount of mercury in SFLs itself (Xiaofeng Zheng, 2016). Exposure to mercury causes mild tremors, impaired memory, skin irritation, and respiratory problems (United States Department of Labor, 2012a). A study from Wisconsin reported that the worker urine samples containing creatine index (a marker for mercury contamination) (>23.8-71.2 μg/g creatinine, exceeding ACGIH biological index exposure 20 μg/g creatine) suffering from breathing difficulty, memory loss, irritability, insomnia, headaches, and weakness.

Mercury release from the recycling process also has become a concern since mercury is bio-accumulative and bio-magnified, potential deposition to aquatic organisms and food chain could occur (Azevedo et al., 2018; Budnik & Casteleyn, 2019; Knezović, Trgo, & Sutlović, 2016; Park et al., 2018). Plant rice in an area of 174 km^2 from a mining area in China contained 4.9-215 μg/kg (dry weight). The studied rats fed with the rice were posing brain damage (Wang, Feng, Anderson, Xing, & Shang, 2012).

Figure 7 illustrated the recycling activity of SFL in Thailand. The collected lamps from the transfer station were put into drums waiting to be fed into the Bulb Eater. It is a machine to crush the lamp while removing the airborne mercury. Feeding to the Bulb Eater is done manually by an operator equipped with PPE. In the Bulb Eater drum, lamps are crushed into the glass and aluminum-end caps while a three-stages of filtration capture mercury vapor. The three stages ensure a higher degree of filtration by different types of filters: bag filter, High-Efficiency Particulate Arrestor (HEPA) filter, and activated carbon (Air Cycle Foundation, 2013). The activity in each filtration stage is described as follows:

1^{st} stage filter: Particulate is filtered by industrial bag filter with 99.99% of removal efficiency of dust size 1 Micron

2^{nd} stage filter: Dust from the 1^{st} stage is filtered through HEPA with 99.99% removal efficiency of dust size 0.3 Micron. In this step, the air is almost free from particulate but still contains mercury vapor requiring another filtration.

3^{rd} stage filter: The remaining mercury vapor is captured by sulfur-containing activated carbon and changed into mercury sulfur that is non-hazardous. This filter has a more sensitive filtration capacity (0.00005 mg/m^3) than the OSHA standard (0.1 mg/m^3)

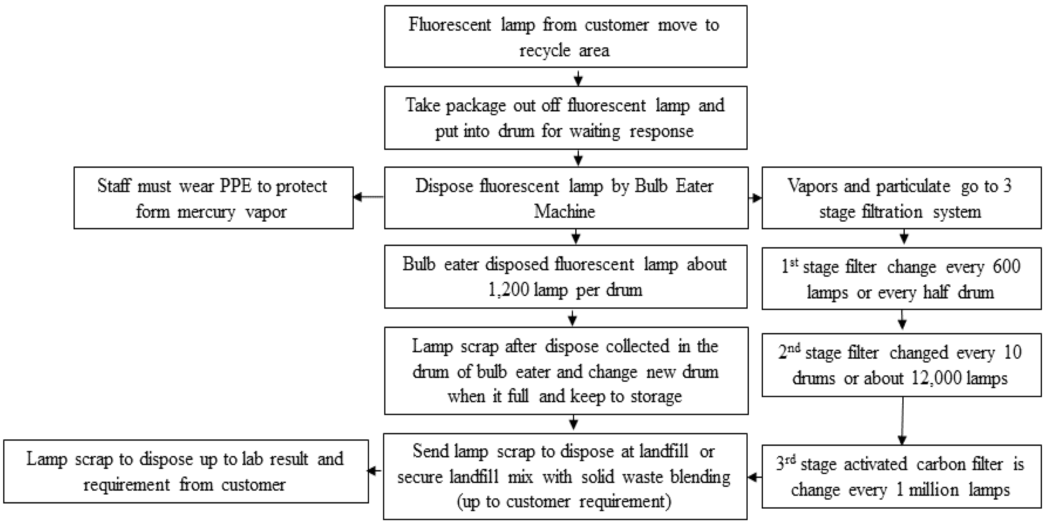

Figure 7 SFL recycling process at the studied plant

Source: The studied recycling plant

After use, the 1st and 2nd stage spent filters are kept in sealed bags and put in a storage drum to ship to another company that can recycle the mercury following the Notification of Ministry of Industry Hazardous waste manifest system B.E. 2547 (2004). According to the client's request, 3rd stage spent filters combined lamp scraps with kiln cement for secure landfills. Before the disposal process, the lamp scraps consisting of three different parts will be separated from thallium end caps worth economic value. Then the scraps will be tested for mercury vapor mercury compliant to USEPA standards of <20 mg/kg sample. If the residues contained more than the standard number, they would undergo the filtration process again.

2.3.2 Challenge of formal SFL recycling

Although formal recycling provided advantages of higher material recovery, it still faces secondary pollution, occupational health, the safety of products made from recycling materials, insufficient technical standards, and society's security. Occupational health in the recycling process of SFL has been found associated with dust contamination containing mercury, lead, and yttrium during the recycling, especially at the crushing processes and dismantling, generating health problems such as increased mercury-and cadmium blood levels affecting nervous systems and causing respiratory symptoms (Ceballos & Dong, 2016). Moreover, a mercury-containing waste recycling facility found the migration of mercury to the surrounding area up to 2 Kms (Ismail & Hanafiah, 2019). Improve the capability of formal recycling activities requires support to facilitate and tackle other challenges that contribute to the low investment in recycling activities, which is low material supply (Chanatip Pharino, 2017).

Low material supply caused the formal sector's inability to compete with the informal sector to collect waste from the customers. The informal sector provided better incentives to the customers for any purchased waste. Such irregular material flows also resulted in insufficient data of waste generation and collection, hindering formulation, implementation, and monitoring (Manomaivibool & Vassanadumrongdee, 2016). Additionally, policy makers' capacity building to formal business affects the business's ability to participate in waste management. As mentioned in the previous part, governance for solid waste, including E-waste management in Thailand, is still fragmented among the governmental bodies that contribute to the recycling challenge. Hence, it concluded that the formal recycling business's challenges lie in the technical and social aspects that compromise technology improvement, material supply, and governance (Gunarathne et al., 2020).

2.4 Sustainable E-waste Recycling and the Enabling Factors

Since the challenges in SFL recycling are complex concerning multi-facet and multi-stakeholders and highly contextual, an approach to address such challenges should reflect the complexity and local circumstances (Wilson et al. 2013) and tackle the fragmented solution out by policymakers. Several international frameworks for solid waste management, including E-waste that can suit local conditions, have been available by Marshall and Farahbakhsh (2013) (Figure 8). Integrated Sustainable Waste Management Model (ISWMM) that they developed provided a systematic approach to waste management through consideration of multiple dimensions, stakeholders in the value chains, and elements.

The multidimensional integration results in better management alternatives and produces cost-effective options in the value chain of waste management. The management framework incorporates different aspects in the management to fit the local context. This framework has been used in Sri Lanka (Gunarathne et al., 2020) to explore E-waste management's dynamics to formulate the most possible alternatives mitigating the challenges. The assessment using this framework identified E-waste management's challenges in Sri Lanka was similar to Thailand, which was about the insufficient collection by the formal sectors at the local level and no data of waste recycled by the entities (Pollution Control Department, 2019).

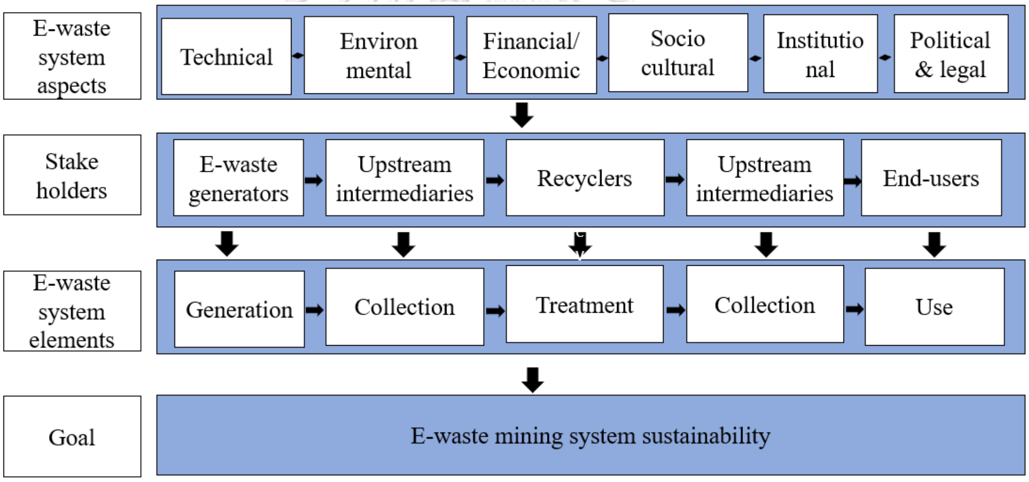

Figure 8 Integrated E-waste management framework
by Marshall and Farahbakhsh (2013)
Source: (Gunarathne et al., 2020)

Such condition was influenced by the uncoordinated relationship between formal and informal sectors. The insufficient local collection by the formal entities resulted in more waste being supplied to the informal business. The lower supply was unfavorable for the formal sector since it prevents business continuation from investment (Hinchlife et al., 2020; Johnso; & Trang, 2019; Pollution Control

Department, 2019). Regardless of the role of informal sectors in filling the gaps, they have generated pollutions due to a lack of occupational safety standards, monitoring, and inadequate skills and knowledge (Fujimori et al., 2012).

As long as the role of informal sectors in waste management is underestimated, it would be difficult to address the real issues and create sustainable waste management, particularly FL in this case. It is for this reason that they collect 90% of E-waste in Thailand and a key role in the next stream of waste management. An alternative to creating sustainable E-waste management, recycling, and mining has been discussed largely was to support the formalization of informal recyclers. Furthermore, the existence of related regulations, law enforcement, adoption of the extended producer responsibility principle, capacity building, awareness creation, education, import controls, industry regularization, and public-private partnerships (Gunarathne et al., 2020; Henzler et al., 2017; Hinchlife et al., 2020) was identified as among of many enabling factors for sustainable E-waste management.

2.5 Environmental Life Cycle Analysis (ELCA) and Social Impact Analysis (SIA) for the Identification of Enabling Factors

Based on the previous description of aspects or dimensions involved in the sustainable recycling process, the environmental aspect tends to receive greater attention than social and others, even though the business stakeholders' social peril still faces unclear solutions. It is then necessary to assess the environmental and social impacts from the MPSWM target to understand the trade-off results with the current socio-economic situation and technology availability under the sustainability concept. There has not been a study conducted in Thailand regarding the industrial waste management target, specifically SFL, and includes environmental and social challenges from the formal recyclers.

ELCA has successfully assessed the environmental impact of a product and technology during the last decade. Efforts have been carried out to integrate economic and social LCA in sustainability analysis (Gnansounou, 2017). However, each of them could be used individually to analyze a product/system impact. Environmental and life cycle costing analysis was initially developed and depends on quantitative analysis and has roots in technical, engineering-oriented disciplines that tend to pursue quantitative metrics. Meanwhile, social life cycle analysis (SLCA) was later introduced as a supporting tool to describe and quantify the social impacts of a product or service. SLCA was used to describe a life cycle analysis of a system, which required a large amount of time and resources in the application. Another option such as social impact assessment (SIA) was available to simplify the social impact assessment to selected stakeholders, only at a certain stage of a product/service. Both methods have a common assessment tool that is UNEP/SETAC Guidelines (2009) (Lehmann, Russi, Bala, Finkbeiner, & Fullana-i-Palmer, 2011).

The social impact indicators varied among different research scope (e.g., human rights, health, and safety, child labors, discriminations.) and according to the experiencing stakeholders involved (such as the workers, local community, public, business management, suppliers, consumers) (Stamford, 2020; Torabi & Ahmadi, 2020). The measuring indicators for social impacts are difficult to measure and collect. Therefore, the application was rare (Balanay & Halog, 2019).

2.5.1 Environmental life cycle assessment (ELCA)

ELCA is an evaluation tool that works according to ISO 14040 and 14044 through four steps: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. To process that, a set of data from a process/system is required to measure the environmental impacts. Software such as SimaPro and the impact indicator tools, i.e., ReCiPe, IMPACT 2002+, Eco-indicator 99, generates information of the degree of environmental damage from the input data.

a. Goal, functional unit, and scope determination. This step shows the depth of the study that is seen from the system boundary studied, i.e., cradle to grave (from the raw material extraction to disposal), cradle to cradle (material extraction to another new product), or gate to gate (a specific process). A functional unit refers to what is studied within the materials flow.

b. Inventory analysis means collecting information of material flow (output and input) in the process to understand the potential impacts generated per functional unit chosen. Inventory data is entered into the SimaPro database to be assessed using the software's impact assessment method.

c. Impact assessment quantifies the environmental impacts from each inventory. This step is done through an impact assessment method such as Eco-indicator 99, Recipe 2016, or Impact 2002+. Above three methods calculate three major endpoint impacts (e.g., human health, resource depletion, and ecosystem damage) and the measurement units allow direct comparison (Stavropoulosa, Giannoulisa, Papacharalampopoulosa, Foteinopoulosa, & Chryssolouris, 2016). The differences are Eco-indicator 99 has11 midpoint indicators and 3 end point impact indictors, while ReCiPe, a global approach for an impact assessment, covers 18 midpoint and three endpoint indicators (represented in Figure 9). Impact 2002+ is, however, rather an old method and a European approach with 14 midpoint and four endpoint indicators and a familiar tool to assess climate change.

In contrast with the above methods, Eco-indicator is no longer available in SimaPro 8.0 and 9.0. In impact assessment, impacts are categorized into midpoint and categorized into three impact endpoints groups: human health, resource depletion, and damaged ecosystem. Weighting values in each category are different; therefore, the impacts cannot be compared; however, through the normalization option in the assessment, it could be identified as the rank of impacts – which category gives the most significant impact.

d. Interpretation. It evaluates the results from previous data and is used to draw conclusions and recommendations and to ensure the completeness, accuracy, and validity of the data to answer the study objectives. The whole process would show the hotspots contributing to policy recommendations' impacts to reduce the environmental impacts (Gnansounou, 2017; La Rosa, 2016; Mannan, 2012; Pini et al., 2019; PRé Consultants, 2013, 2014).

ELCA results provide a systematic analysis of the hotspot of the process that contributes to environmental damage significantly for us to make a decision. It also helps decision-making through comparing different products or systems based on extensive computational and sufficient data analysis. In contrast, it has limitations in the applicability of a decision support tool in policymaking as it lacks social and economic context in the problem analysis (ScienceDirect, 2017). ELCA lacks the integration of social aspects of stakeholder perspectives in the value chain that determine the management's dynamic. Therefore, another method such as SIA fills the social contexts gap came into place.

Such points were shown in multiple LCA studies on a recycling process of SFL in Thailand, i.e., Apisitpuvakul (2007) calculating potential impacts from different recycling rates (0% to 100%), Wongsoonthornchai et al. (2016), and Thavornvong (2016) comparing the potential impact from SFL recycling process with LED replacement. Those studies showed the hotspots contributing to the impacts; Apisitpuvakul (2007) highlighted electricity as one of the top contributors to human health, while Wongsoonthornchai et al. (2016) and Thavornvong (2016) pinpointing mercury danger to human health, ecosystem quality, and resource depletion. In detail, Apisitpuvakul (2007) recommended economic aspect integration in the analysis to determine the best management practices of SFL among various recycling rates.

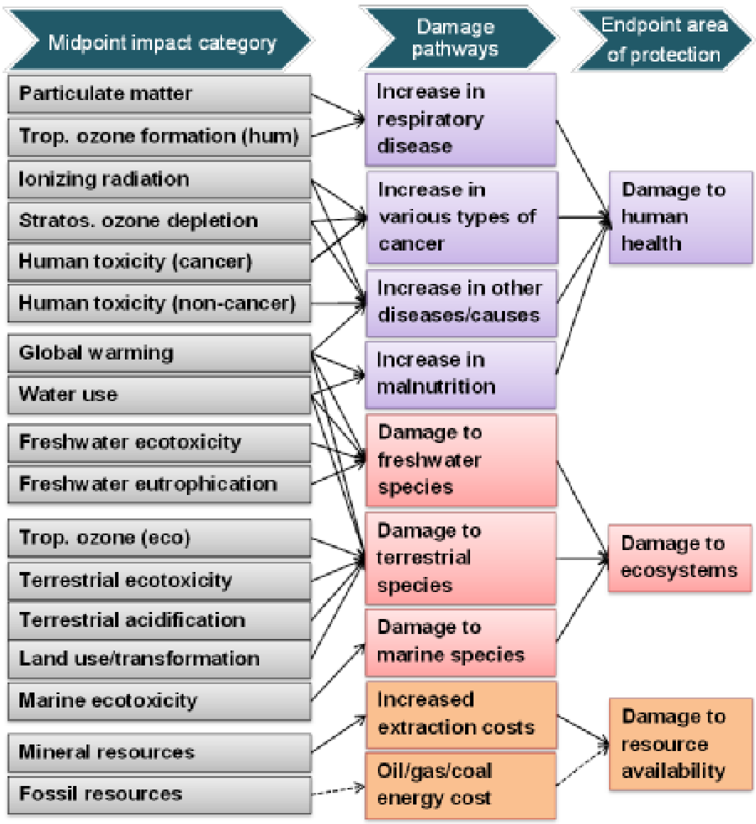

Figure 9 ReCiPe impact assessment indicators

Source: (National Institute for Public Health and the Environment, 2011)

2.5.2 Social impact assessment (SIA)

SIA is an analytical approach to analyze, manage, and monitor the social impacts of a development or project to bring a more sustainable social and ecological environment (Bonilla-Alicea & Fu, 2019; Kamakia, 2015). Social impacts are defined as positive and negative consequences resulted from social relations (interactions), activity (production, consumption, or disposal), or action taken (United Nations Environment Programme, 2009). SIA is different than SLCA in terms of objective and scope. For the objective, SIA focused on the estimation of impacts from a policy/program rather than along a product/service life cycle. Secondly, SIA has a smaller scope of impact analysis that occurs only at a single process/plant.

Both have a similar assessment procedure that focused on the impacts of selected stakeholders considering particular characteristics such as political situation, community changes, and others in the context. There is no agreement on the procedure (Lehmann et al., 2011)

There are no standardized practices for both approaches but UNEP/SETAC Guidelines (2009) are mainly used for references supported with relevant case studies to align with ISO 14040/14044. The guideline provided common indicators, measurement, and stakeholder classification for the analysis. It is necessary to filter out the classifications according to the research plan. Otherwise, the data collection would be time and cost-consuming (Umair et al., 2015). The determination of the selected impact and stakeholder category shall reflect the primary and secondary evidence.

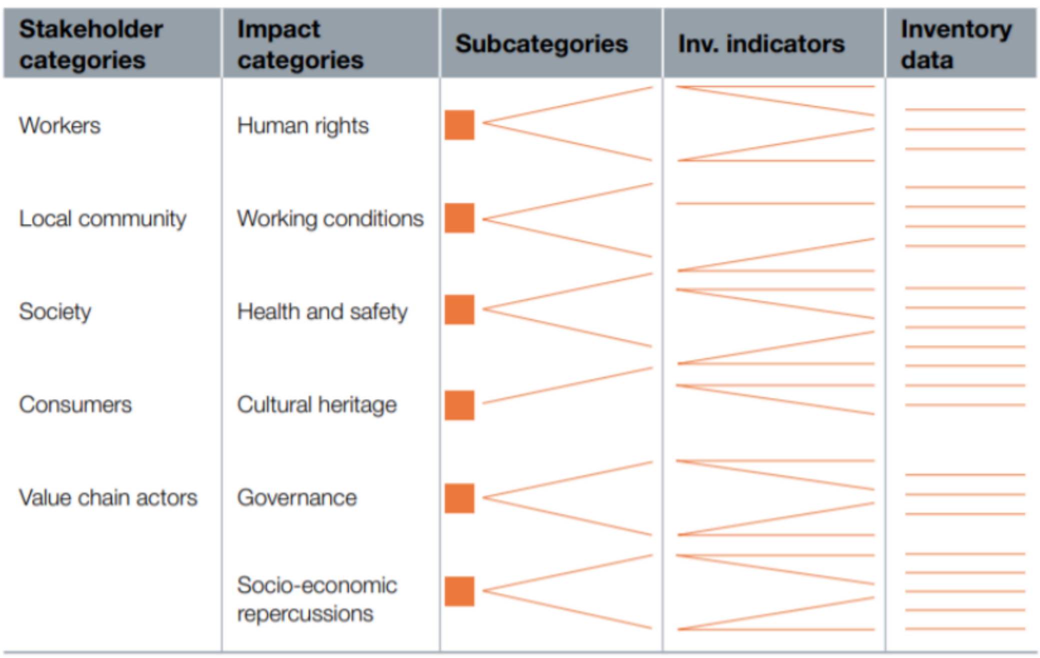

Figure 10 Inventory procedure in UNEP/SETAC Guidelines (2009)

Source: (United Nations Environment Programme, 2009)

This guideline recommended four steps in conducting impact assessment studies; objective and scope identification, inventory analysis, evaluation, and interpretation. Inventory means the classification of affected stakeholders (workers, local community, society, value chain, and consumers) with relevant social issues generated from a service/product that occurs to them. Social indicators measure the magnitude of the impacts. The measurement is usually converted into a scoring system. This scoring system assists to quantify the qualitative data from stakeholders assessment and represents what social issues that become their concerns (de Souza et al., 2016; Garcia-Sanchez & Guereca, 2019; Ibáñez-Forés, Bovea, Coutinho-Nóbrega, & de Medeiros, 2019; Jørgensen, Finkbeiner, Jørgensen, & Hauschild, 2010).

The application of the guideline was carried in Mauritius to compare four disposal routes for used polyethylene terephthalate (PET) bottles. The inclusion of social impact indicators provided a holistic understanding and decision of an efficient environmentally and socially beneficial (Foolmaun & Ramjeeawon, 2012). The study scope and system boundary followed the ELCA to maintain the consistency of the results, interpretation, and comparison. For instance, it was to explore the social impacts in the same assessed scope for the environmental impact analysis.

Other studies in the topic of waste treatment (Garcia-Sanchez & Guereca, 2019), bio-based products (Falcone & Imbert, 2018), and informal E-waste recycling (Umair et al., 2015) that used the guideline collected the data through questionnaires and surveys covering the study scope, budget, and time. Convenience sampling such as purposive non-probability commonly used for the fast, inexpensive, and easy advantages in the data collection. The scoring systems for the questionnaire answers were subjective according to suitable and context chose. The score could be in numerical order 0-4, in percentage, or color to indicate the level of compliance to the impact measurement parameter. No standardized data aggregation to calculate the impacts.

For the case of E-waste management, the analysis has focused on the activities of informal recycling activity and impacts generated. The evaluation of positive and negative impacts is giving the advantage of a holistic review of the study. However, several issues have been found out in the data collection, which the willingness and confidentiality of the informal sectors to provide primary data. Such an issue was commonly encountered by citing secondary sources, either by applying other stakeholder's opinions or similar studies in a different location (Umair et al., 2015).

Umair et al. (2015) study chose workers, local community, society in the country, and other value chain actors such as importers, business owners/sellers, and employers in the assessment with social impact categories such as fair salary, health, and safety, the economic opportunity to the country, local employment. The social impact for each stakeholder is different. The scoring system as mentioned earlier showed both positive and negative impacts of E-waste management by informal recyclers that provided a more realistic view and encourage to development of a business model sustainably.

Analysis of social impacts of E-waste management in the developing countries have been developed for the informal sector and could apply to one another but not the formal recyclers. Thailand that 90% of the E-waste entered the informal sector, SIA implementation to the formal sector would be interesting and a starting point for the next sustainability evaluation of SFL recycling. The application of ELCA and SIA in one study could give a general overview of the identified struggles from a deeper perspective (Gunarathne et al., 2020; Umair et al., 2015).

CHAPTER III

RESEARCH METHODOLOGY

3.1 Conceptual Framework

The research outcome of this study was to identify enabling factors in the sustainable recycling of SFL in the Thailand context based on environmental and social impact assessment. This was to provide recommendations to the Master Plan targeting a 100% industrial waste treatment. To understand the importance of this goal, the significance of the formal recycling of SFL should be highlighted. Formal recyclers contributed positively to the environmental and social aspects as mentioned in the figure below. Unfortunately, few challenges experienced by the formal recyclers in the real implementation were identified that tackled their benefits and become sustainable, such as lack of control and monitoring of the missions, irregular supply, and lack of technologies.

Reconsidering the challenges and benefits of formal recyclers, the higher target of recycling seemed to be unsustainable without addressing the challenges alternatively providing solutions that suit the local context. The framework of Integrated Solid Waste Management (ISWP) by Marshall and Farahbakhsh (2013) was helpful to answer such research objectives. It serves as legitimate and scientific guidance for the assessment of environmental and social impact assessment in this study since limited studies integrating both aspects in the national SFL recycling analysis.

The environmental and social impact assessment was the fundamental part of the research to evaluate the master plan. In Figures 1 and 11, the first stage of the research was preliminary calculating SFL generation in the country. This was a complementary step to the environmental impact assessment. It was carried in a quantitative approach – following ISO 14040 and 14044 using SimaPro 8 software and ReCiPe and IMPACT 2002+ impact assessment as provided by the software. This step generated environmental impact analysis according to SimaPro 8 results and other things to consider for the enabling factors creation.

Supplementary, UNEP/SETAC Guidelines (2009) were used for the social aspect assessment and to answer research objective number 2. A qualitative approach for the social impact analysis enabled desk review and semi-structured interviews to explore the impacts from the formal business perspective and secondary resources. The results of the interviews completed with the desk review were scored to quantify the impacts and display them in a numerical environment. This stage produced not only the description of the impacts but also other important findings in the interview answers, which were the challenges and expectations from the formal business.

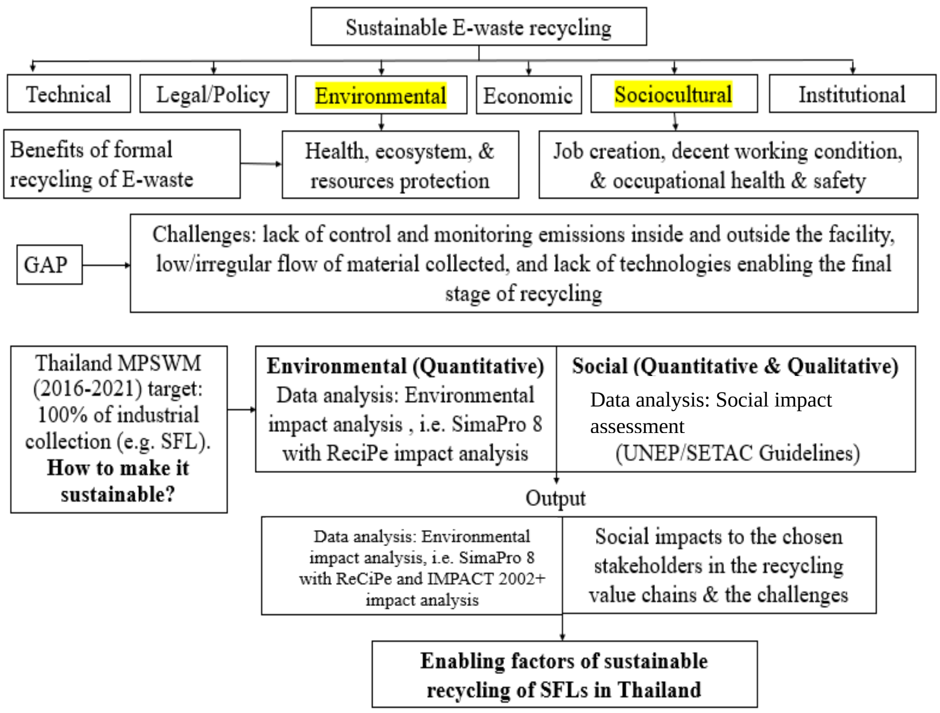

Figure 11 Theoretical research framework

Both results from the previous stage were used to formulate enabling factors for a sustainable recycling process of SFL to provide recommendations to the Master Plan target. Up to this stage, research objective number 3 was addressed.

Recommendations were trying to argue the urgency of a higher rate of industrial treatment/recycling without considering the challenges the business face. Moreover, such formulation served evident-and-science-based recommendations into the policy. All data was analyzed and presented corresponding to the research method in each stage. Details of each stage were described below.

3.2 Preliminary Research

Preliminary research included estimation of SFL generation in the next few years. The replacement of FLs with LED was started in 2016, and it was influenced by the development of technology and economic growth that prefer energy-saving lights. The rapid technology development to satisfy consumer demand for energy-saving lights is a consequence of the lighting product's shorter life span (Pollution Control Department, 2019; Thavornvong, 2016). The rapid replacement of FLs to LED resulted in increasing SFL in the landfill. Additionally, E-waste is a severe problem in Thailand due to poor management generating adverse environmental impacts. Therefore, it is necessary to understand the trend and status of the SFL generation to formulate social and technical responses (Pollution Control Department, 2019; Simachaya, 2019). The most recent method to estimate waste generation shortly was obtained from the U.S. Environmental Protection Agency that uses historical sales data (Thavornvong, 2016).

Besides the supply method, several other available methods are based on disposal-related analysis; time spent analysis, factor analysis (using determinant factors for correlation), and input-output analysis. The disposal-related analysis method relies on empirical data from collection channels, treatment facilities, and disposal sites, which for this study it would be challenging for time and resource allocation (Thavornvong, 2016). Time spent analysis considered consumption and collected data during a particular time, including consumer behavior characteristics during those times. Consumer behavior must be considered since it is directly affected the amount of product consumption in the market (Katsamaki, Willems, & Diamadopoulos, 1998). The factor analysis is far complex as it requires a big set of data of the determinant factors (e.g., knowledge, waste collection fee, the size, and several consumer households) to check the correlation (Akurugu, 2018; Zou, Tai, Wang, Sun, & Che, 2019). These methods were not yet applicable to the study in terms of study objective, time, and resources availability compared to supply method.

The supply method's principle is analyzing waste generation through sales and relying on the analysis of product life span than consumer behaviors that caused the declining sales number. The method applies to FLs since they have a constant life span and are easy to calculate. Furthermore, there are two phases in determining the amount of waste generated, namely sales and reuse. For lighting equipment, no reuse or refurbishment value exists that pushes them directly into the waste stream. Therefore, the supply method does not include reuse (refurbishment) in the calculation. Using the market supply method as shown in the formula presents the amount of SFL generated for the next SFL collection review and monitoring. Such estimation was then used to analyze the existing waste collection number in Thailand for future potential impact assessment (Quayin Tan, 2014; Thavornvong, 2016).

Waste generation = Total sales = Production – Export + Import

(Quayin Tan, 2014)

Whereas:

Waste generation = The amount of SFL discharged (Piece)

Production = The amount of SFL produced (Piece)

Export = The amount of exported SFL (Piece)

Import = The amount of imported SFL (Piece)

Data of exported and imported FL in 2017-2019 obtained from the Thai Customs Department database is available on their official website (Thai Customs, 2019). FL production was referred to Thavornvong (2016) because of no government bodies' data. The years selected were due to the limited available information in Thavornvong (2016). The general life span calculation (4 years) was chosen based on 15,000 hours of FL use in 14 hours/day for six days/week in industries. The sales calculation was estimated the same amount of waste generated.

The results of this stage were primarily used to show the significance of the amount of waste dealt by the country. The information later indirectly evaluated the condition and challenges in the waste collection that directly or indirectly contribute to the understanding of the preferred EPR system as an enabling factor in the sustainable recycling and improved recycling process itself.

3.3 The Environmental and Social Impact Assessment

The environmental and social impacts of current SFL recycling practices were assessed using life cycle assessment within the disposal stage (recycling process only) and supported with a secondary literature review to understand the potential impacts of an increasing recycling rate as targeted by the government. Social impact assessment enabled the identification of enabling factors for creating sustainable SFL recycling businesses that expand the benefits of recycling processes beyond the ecosystem.

3.3.1 The environmental impact assessment using ISO 14040 and 14044

The inventory data was obtained from the studied company inventory in 2019, which was further input into SimaPro 8 database to generate ReCiPe and IMPACT 2002+. Impact assessment. Appendix A showed the inventory data from the recycling plant and Appendix B displayed input to SimaPro. Table 1 described the details of each step in the ELCA according to ISO 14040 and 14044. Inventory analysis illustrated the input and output data in the SimaPro 8.

Table 1 Steps of environmental impact assessment (ELCA)

Steps	Sub-categories	Amount	Unit	Details
Objective	Scope: Gate to Gate			System

Steps	Sub-categories	Amount	Unit	Details
and scope	Functional Unit: per 1 Kg SFL recycled (T8 36 watt 92 lumens/watt, life span 20,000 hours)			boundary: recycling activities
Inventory analysis	Input (average of electricity consumed and fluorescent feed in 2019)			
	Electricity	1.97	kWh/Kg SFL	
	Fluorescent lamp	4,245	Kg	
	Output (Amount of waste, mercury in lamp scraps, filters, and waste packaging disposed of in 2019)			
	Light bulb waste, mercury-containing	8050.33	Kg	
	Hazardous waste, recovery	8.235	Kg	
	Hazardous waste, incineration	4,655	Kg	
	Packaging waste, contaminated	6,368	Kg	
	Mercury	7.54	Mg	
Impact assessment	Models linked to SimaPro 8 and ReCiPe and IMPACT 2002+ impact assessment			
Interpretation	Used in policy recommendations associated with the goal and scope of the study			

Limitation: Should add details of input materials such as mercury concentration and other metals in the fluorescent lamps, including emissions of mercury in the air samples and excluded incineration process. Suggestions refer to Appendix A and section 4.6

3.3.2 Social impact assessment (SIA)

The recycling process's social impacts were carried out with open-end and semi-structured questionnaires (Attached in Appendix D) to the recycling plant management and business management to assess impact categories for the selected stakeholders (i.e., workers & local community). Impact categories (illustrated in Table

2) corresponded to UNEP/SETAC Guidelines after reviewing social issues experienced by stakeholders in formal and informal recycling value chains in some Asian countries. Scores are given to the answers (From 0 to 4) indicating higher compliance to the local/national regulations, international standards (e.g., Occupational Safety and Health Administration (OSHA) for mercury concentration in the dust. See Table 2 and specific goals in the relevant fields (Garcia-Sanchez & Guereca, 2019; Umair et al., 2015). Results were shown in a radar chart showing "hotspot" issues. Some definitions in this section include:

Stakeholders: A cluster of people that are expected to have shared interests due to their similar relationship to the investigated products (Umair et al., 2015). Based on UNEP/SETAC Guideline, stakeholders include value chain actors, workers, the local community, society, and consumers. However, the inclusion of the stakeholders depends on the study scope, limitations, and objective. In this study, workers and local community were chosen considering the focus of the study on the formal recycler and the direct impact of their process to the groups exposed closely to the process, i.e., workers and local community (Ceballos & Dong, 2016; Henzler et al., 2017; Quanyin Tan, Song, & Li, 2015). The participants were chosen based on randomized sampling (Sharma, 2017) according to specific criteria, as follows:

Workers: Workers involved in the recycling and transportation activities. The number of participants was based on the willingness of the workers to be interviewed. It was expected to represent the crushing/feeding processing, filter disposal, and waste transportation (Sharma, 2017; Umair et al., 2015).

Local community: People that live in the province of Chonburi, in a radius of 5 Kms from the recycling plant, regardless of the employment status. For health and safety assessment, only adults (>26 years old) that have been living in the area for at least since 2016 were chosen. This was considering their understanding and experiences with the plant. The year 2016 opted to consider the different recycling rates as encouraged in MPSWM (2016-2021). The number was following the participant's willingness to be involved in the interview. However, there would be 30 people to validate the results statistically (Foolmaun & Ramjeeawon, 2012; Garcia-Sanchez & Guereca, 2019; Umair et al., 2015)

Business management (The recycling plant management representative and business center Director): The business representatives were engaged in understanding their perspectives and challenges in the recycling business (Henzler et al., 2017). Random sampling was also purposely planned to determine the number of participants involved based on the criteria of their knowledge, availability, and willingness.

Before the interview, the pandemic and lockdown started to occur, limiting the interview's human interaction. Adjustments to the questionnaires then were done that aimed at the business management and recycling plant only to answers. However, the questionnaires covered the issues experienced by the workers and local community that wanted to be evaluated.

The questionnaires were given to the two respondents (n=2), one from the recycling plant represented by a supervisor of the recycling activity and one from the leader of the business management. Such an adjustment was made to understand the worker's and local people's experiences as close as possible, even though some facts might have been concealed.

Table 2 Social impacts of electronic waste management community and society in Asia

Stake holder categories	Impact categories	Measurement	Scores		References
The local community	Safe and healthy living condition	Health and safety effects caused by the recycling plant	1	There are no initiatives to protect the community and cause health issues among the people.	(Chareonsong, 2014; Fujimori et al., 2012; Ilankoon et al., 2018; Umair et al., 2015) with modification

Stake holder categories	Impact categories	Measurement	Scores		References
			2	A complaint is from the community that does not cause severe health impacts like odors	
			3	Meet the requirement to guarantee the safe living environment surrounding the plant and no complaints from the people	
			4	There are health emergency initiatives from the plant for the community	
	Local (provincial)	People hired from the local	1	There are no local people	(Cao et al., 2016; Ismail & Hanafiah,

Stake holder categories	Impact categories	Measurement	Scores		References
	employment and contribution to the local economy	community		as workers	2019; Nguyen, Ha, & Huynh, 2016) with modification
			2	Few local people employed	
Workers	Fair salary	Staff salary	1	No wage	(Fujimori et al., 2012; Ismail & Hanafiah, 2019; MSNA Group, 2016; Umair et al., 2015) with modification
			2	Below the minimum wage	
			3	Reach the minimum wage 325 THB/day for 8 hours working time and 48 hours in a week	
			4	More than the minimum wage with other social benefits	
	Working hours	The average working hours in a week	1	More than 48 hours and more than additional 36 hours a week	(Cao et al., 2016; B. Li, Du, Ding, & Shi, 2011; MSNA Group, 2016; Umair et al.,

Stake holder categories	Impact categories	Measurement	Scores		References
				without compensation	2015) with modification
			2	More than 48 hours but less than additional 36 hours a week with compensation higher than 1.5 to 3 times of regular average hourly wage rate	
			3	Maximum 48 hours a week with compensation	
			4	Less than 48 hours a week with compensation	
	Health & safety	The concentration of mercury in indoor air and enforcement to	1	More than OSHA PEL limit (0.1 mg/m3 air for an 8 hour/day	(Erica Wilson & Meiman, 2018) (United States Department of Labor, 2012b)

Stake holder categories	Impact categories	Measurement	Scores		References
		use personal protective equipment (PPE)		workday), no PPE enforcement + amount of work injuries/year	
			2	More than OSHA PEL limit + PPE enforcement + several work injuries/year	
			3	OSHA PEL limit + PPE enforcement + very few work injuries/year	
			4	Less than OSHA PEL limit + regular monitoring + PPE enforcement + no work injuries/year	
	Management	The presence	1	Lack of proper	(Cao et al., 2016;

Stake holder categories	Impact categories	Measurement	Scores		References
	performance monitoring program	of programs undertaken by institutions to improve		actions aimed at monitoring the plant management operation by authorities. Standards are not in compliance with the government's standards	Ismail & Hanafiah, 2019; Nguyen et al., 2016) with modification
			2	Do not comply with the government standards and actions/plans to achieve the standards	
			3	Comply with the government standards	
			4	Comply with the government	

Stake holder categories	Impact categories	Measurement	Scores		References
				standards and plans of improvement	

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Preliminary Research - Estimation of Fluorescent Lamp Waste Generation

Estimation of SFL generated used supply method as explained in the research method by calculating total FL sales generating from production added with import number subtract with the export number during 2017-2019. Waste generation was assumed to equal total sales (100% of a product becomes waste after use with no additional lighting equipment purchasing). The year scale was limited in 2017-2019 due to data from government agencies and literature studies to complete the information. Production data was generated from Thavornvong (2016) as insufficient information given by the National Statistical Office of Thailand and the Office of Industrial Economics. Import and export data was generated from the Thai Customs Department database. The information on domestic sales was presented in Table 3. The information enabled the prediction of the number of SFL in the upcoming years using the FL life span calculation.

Table 3 Situation of fluorescent lamp sales in Thailand during 2017-2019

Year	Production (Piece)[2]	Import (Piece)[1]	Export (Piece)[1]	Total sales (Piece)
2017	17,980,000	3,190,000	34,889,893	20,099,893
2018	16,370,000	2,730,000	33,283,083	19,643,083
2019	14,303,800	2,540,000	30,613,583	18,849,783
Total	48,653,800	8,460,000	98,786,559	58,592,759

Source: (Customs, 2020; Thavornvong, 2016)[1], (Thavornvong, 2016)[2]. Limitation: Production data in 2017-2019 generated from secondary literature Thavornvong (2016)

Table 3 displayed that the number of FL production in the whole country was decreasing from 2.27% in 2018 to 4.04% in 2019, followed by a more significant decrease in export in 2019 for 13% and import from 14.42% to 6.95% in the same years. According to Thavornvong (2016), the decline of FL production was expected to occur approximately 2% in 2019 and reached 4% in the next year, based on a survey of 11 lighting companies. The different numbers might obtain due to differences in export and import number. However, a similar pattern in the decreasing production in 2019 was observed due to LED replacement. Furthermore, 2019 became a breakthrough year where the sales of LEDs starting to be higher than FLs. Such phenomenon was promoted by technology development resulting in a cheaper price (International Energy Agency, 2020; International Institute for Energy Conservation-Asia, 2016; Thavornvong, 2016). Meanwhile, a decrease in export occurred due to energy deficiency in 2019 that caused Thailand to fulfill the domestic energy demand firsthand. All factors resulted in the decreasing total sales of FLs (IRENA, 2017).

According to the supply method, total sale equals the potential amount of waste generated, which informed that nearly 19 million pieces of SFL would be disposed of in a particular year (Table 4). Based on the average lifespan of tubular FL for 15,000 hours and the average use of FL in Thai industries for 14 hours/day with six working days/week, it was calculated that SFL would be disposed of after 4.57 years of use. This information explained that the 19 million SFL is required to dispose of and enter a treatment facility in 2023. The literature on FLs growth rate until 2021 expected the total sale would decline to 17 million pieces in 2021.

Interestingly, a stagnant decline rate of FL sales from 2019 to 2021 was observed at 4%, where such a pattern was found in International Institute for Energy Conservation-Asia (2016) and Thavornvong (2016). Such similarity confirmed that the supply method had the advantage of estimating solid waste generation for a product that experienced decline based on the constant product life cycle without considering consumer behavior dynamics, reuse, and other determinant factors to product sales. However, the estimated SFL generation's information has not yet been found to influence better E-waste management decisions.

Table 4 Estimation of SFL generation in Thailand during 2021-2025

Year generation	Estimated total sales (Piece)	Estimated growth rate (%)	Estimate lifetime (year)	Year dispose	Estimated disposal (Piece)
2017	20,099,893	0	4	2021	20,099,893
2018	19,643,083	-2	4	2022	19,643,083
2019	18,849,783	-4	4	2023	18,849,783
2020	18,095,791	-4*	4	2024	18,095,791
2021	17,371,960	-4*	4	2025	17,371,960
Total	94,060,510				94,060,510

*Source: (Thavornvong, 2016). Limitation: Secondary data

This information could help policymakers determine an optimum SFL disposal mechanism (minimize environmental impacts while meeting financial constraints). The information should include data on the population number, geographical characteristics, local E-waste management regulation, recycling plants inventory (e.g., material/energy input and output, transportation activities, current recycling rate, the value of environmental impacts, and costs & benefits in the recycling plant activities), and the existing recycling technology. A similar approach has been conducted by Apisitpuvakul (2007) that used the SFL generation data with all the details to improve the recycling practice in Thailand. The information generated describes the efficient and practical location for waste collection, recycling plant, and disposal in Thailand considering cost, time, and transportation route to comply with local regulation and geographical characteristics. However, this was based on the ideal 100% SFL collection, which was not the reality in Thailand, in which 90% of E-waste collected entered informal recycling.

4.1.1 The importance of waste generation data to the waste collection

The collection center had focused on a centralized collection system (Office of Industrial Economics (n.d.) but it changed since 2019 where PCD under the Environmental Board, has developed 22 drop-off centers in 22 provinces to decentralize waste collection. However, the decentralized mechanism under the new bill on WEE, Public Health Act B.E. 2535, and Factory Act, giving the responsibility to the local government for the establishment and management of collection centers, was not always the best solution.

The issue was industrial waste treatment and landfilling that they were only targeting a large WEEE industrial for a strict Factory Act control. Smaller industries could not follow this and had the option to either conduct illegal disposal or turn to the local collection centers. Collection centers were allowed to charge a service fee to the consumers, which was unfavorable. The consumers turned toward informal collectors who provided incentives per given product (Manomaivibool & Vassanadumrongdee, 2011).

The alternative in the new E-waste draft was to provide subsidies to the local collection centers and authorized recyclers to provide an incentive to the consumers and cover the fee of storage, transportation, treatment, and disposal generated from the product levies charged to the producers. In return, they have to transfer immediately o the treatment facility. Such a scheme was criticized as not a policy transfer implementation but policy innovation to collect funds. EPR system in Thailand would face the same hurdle over the years without looking for an alternative outside the financial incentive (Manomaivibool & Vassanadumrongdee, 2011).

Agreed to Xiong Zheng et al. (2017) that incentive was not the most significant driver for EPR implementation but other social factors, for instance, social image. A successful example of this was when Suankaew Foundation, a leading organization collecting E-waste and a philanthropic entity of a Buddhist temple in Thailand informed the public the products they turned back voluntarily would contribute to social causes. Social responsibility image and collaboration with local entities as in this example were correlated with the finding of Xiong Zheng et al.

(2017). It calculated that corporate social image resulted in a priority point of 0.14282 lower than 0.534 (EPR-related laws and regulations) and 0.14448 (consciousness of senior executives) as the top three contributors to establishing and developing the EPR system based on the analytic hierarchy process.

Meanwhile, Carisma (2009); Chotichanathawewong and Thongplew (2009); Hinchlife et al. (2020) stressed the importance to link and build a partnership with informal recyclers. This was considering 90% of E-waste was collected by them. In addition to the civil society organizations that have a close relationship with them at the local level (Office of Industrial Economics, n.d.). This was highlighted by Apisitpuvakul (2007) suggesting that various recycling chain stakeholders should promote an efficient collection system.

The general principle of such partnership for EPR from India lesson learned was purchasing E-waste collected by the informal waste collectors and aggregators to transport them to the formal recyclers while establishing digital payment and records of the waste flow. In addition, a partnership with the local civil society to engage the small waste collector was identified in this study. As a result, 5000 informal aggregators engaged, and 2,000 tons of E-waste were collected under this scheme in India over two years (Hinchlife et al., 2020).

India and Thailand have similar characteristics that would allow the implementation of the scheme (Henzler et al., 2017). Thailand has already had a legal bill enforcing the EPR scheme as an instrument to manage E-waste and the Ministry of Finance prepared the funding scheme. Moreover, EPR take-back system was still preferable by the formal recycler to help them improve their performance in the recycling business with the expectation of the ability to control the informal sectors.

Thailand has been ready with the existing regulations, authority existence, and data records to adopt that scheme. Pilot study and dialogue across the authorities in the Ministry of Environmental Board to define and distribute the purchasing fee is the point that should be taken place now to address the off-track waste collection. It has been evident, data and monitoring in waste flow would benefit the collection system and finally EPR mechanism to reduce the environmental impacts from improper handling of SFL (Manomaivibool & Vassanadumrongdee, 2011).

If such fragmented waste collection could be addressed, it would sustain the management of SFL particularly the recycling process to fulfill the gap in the material supply (Gunarathne et al., 2020; Henzler et al., 2017; Johnso; & Trang, 2019). In addition, Apisitpuvakul (2007) stated the estimated waste number helped determine the optimum recycling rate. This information, even though was not further explore, could be used to revise the Master Plan target and support the formulation of the enabling environment for sustainable recycling for SFL.

This research was limited to analyze the environmental impact of the current recycling practice that could be a reference for future research on the optimum. One approach to obtain information on how much a particular recycling activity contributes to environmental impacts was ELCA. The next section described in detail using ELCA assessment of the impact of the current formal recycling activity from the pilot study.

4.2 Environmental Impact Assessment of the Recycling Process

Recycling is an alternative more preferred than landfilling in the waste management hierarchy (Chanatip Pharino, 2017). SFL recycling has believed to generate environmental protection through LCA studies (Apisitpuvakul, 2007; Thavornvong, 2016; Wongsoonthornchai et al., 2016). In this research, the potential environmental damage from the recycling inventory (i.e., input and output materials/energy in the process) was analyzed following ReCiPe and IMPACT 2002+ indicators avai0lable in the SimaPro 8 database of 1 kg SFL functional unit. IMPACT 2002+ was selected to complement ReCiPe for the quantification of climate change potential in the assessment. According to material flows in the recycling practices (Figure 12), process inputs were categorized as fluorescent lamp waste and electricity. Simultaneously, the outputs included lamp scraps ready to dispose of, mercury filters used during the recycling, and packaging bags used for scrap disposal.

Details of impacts identified through ReCiPe and IMPACT 2002+ assessment were further explained in the next subsection.

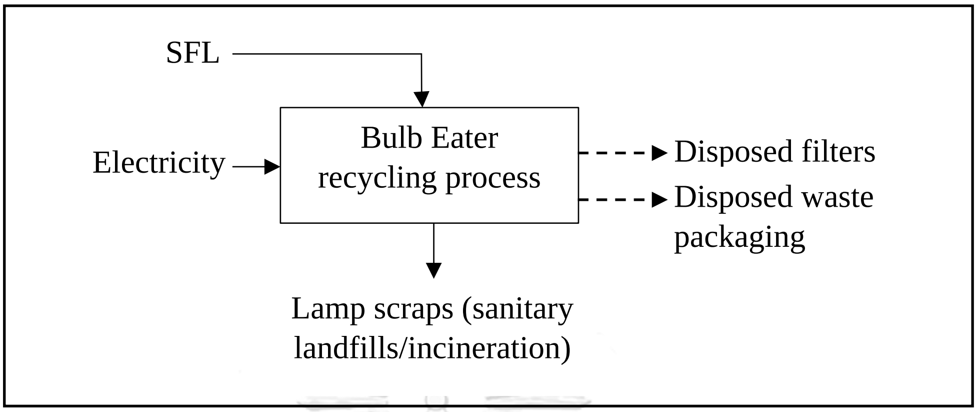

Figure 12 Material and energy flow in SFL recycling processes

Limitation: Add details of SFL components in the input system and emissions of mercury to the air samples and SLF components. Exclude filters and waste packaging

4.2.1 Results of environmental impacts from the formal recycling process according to ReCiPe

ReCiPe endpoint damage assessment (Figure 13) showed that three environmental impact categories (i.e., human health, ecosystem damage, and resource depletion) were analyzed for disposed of fluorescent lamps and electricity consumption. However, only electricity consumption showed an impact score of more than 0 to all impact categories, i.e., human health (8.87×10^{-10} DALY) and resource depletion (1.21 x 10-6 USD 2013) except ecosystem damage (0 species. yr). Damage assessment endpoint demonstrated substance in input and output materials or energy in an activity that damages the environmental aspects. Each impact category has a different unit that does not compare the category since it uses different references. In ReCiPe, there reference year of 2000 and at the European level is used.

Since damage assessment does not allow comparison, the normalization divides each category's total with a reference value that enables them to compare.

Based on this, Figure 14 illustrated that human health was the most affected (3.74131E-08), then ecosystem (1.84144E-09), and resources (4.30715E-11) from the recycling process. However, it displayed that electricity consumption most likely shared 100% of the impact fraction in all impact categories. In detail, SFL only shared a value of 5.45501E-12 in the human health category, 3.39589E-16 in an ecosystem, and 0 in resources.

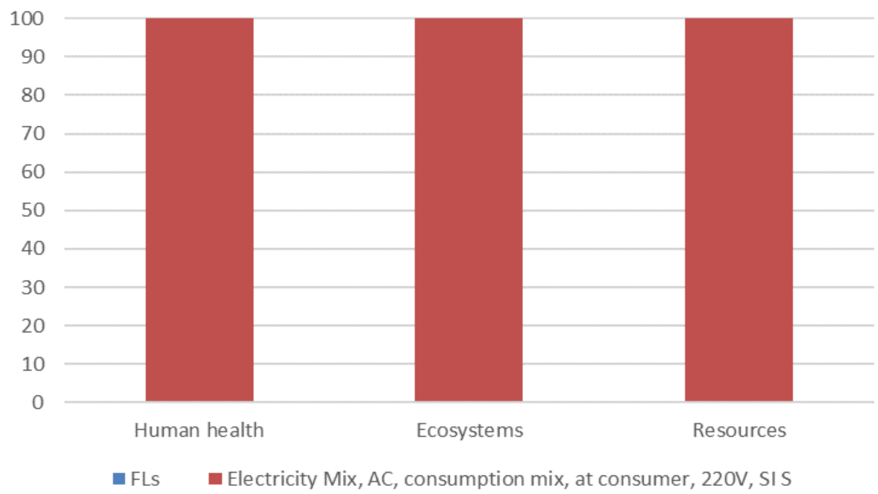

Figure 13 ReCiPe damage assessment results show impacts to all endpoint impact categories

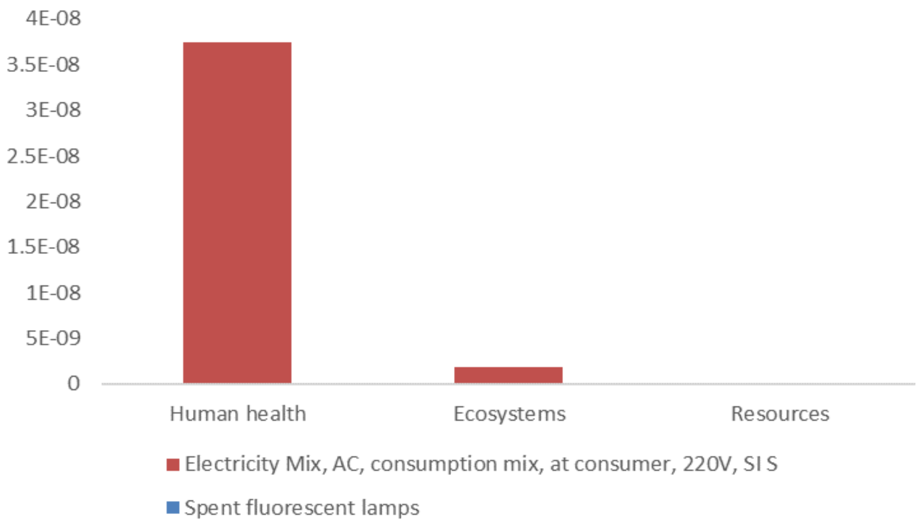

Figure 14 Comparison of impact degree between three endpoint impact categories based on ReCiPe endpoint normalization analysis

The results were found in Apisitpuvakul (2007); Thavornvong (2016); Wongsoonthornchai et al. (2016), in which human health was the hot spot to consider for the impact. Only Apisitpuvakul (2007) informed that electricity shared a significant impact than other emissions, while the other two studies focused on mercury and other substances in the FL. In the impact analysis, Thavornvong (2016) used Eco-indicator 99, another method that does not include in this research. Sangwan, Bhakar, Naik, and Andrat (2014) also utilized Eco-indicator 99 in the assessment and showed that fluorescent lamps had a major impact on human health compared to other impact categories.

Meanwhile, both results were unable to compare the impact degree between the categories; a single score assessment (Figure 15 and Table 5) provided such information by multiplying the value in the normalization phase with weighting factors in each category result in a single unit. It was identified that human health was the most affected by electricity consumption (14.96 μPt), followed by ecosystem damage (0.74 μPt) and resource depletion (0.0086 μPt). Thus, it provided information to pay attention to electricity use in the process.

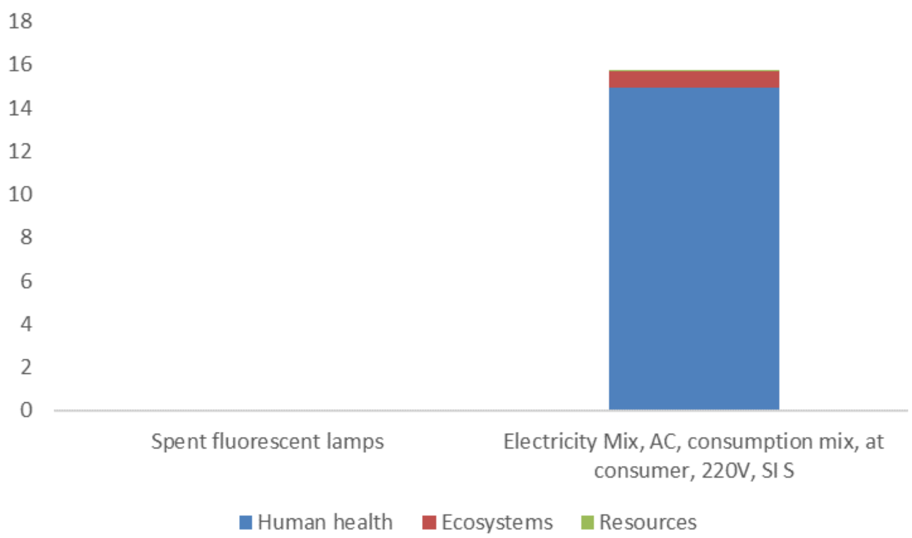

Figure 15 Comparison of impact degree between process inputs to

the endpoint impact categories based on ReCiPe endpoint single score

μPt unit describes the environmental impact but defined dimensionless value. The unit of 1 μPt was an analogy of one-thousandth of the yearly environmental load of one average inhabitant. Table 5 provided the value of each impact category and material in the same unit. The unit showed in μPt that has become standard in LCA.

The weighting factors follow the European standard as used by ReCiPe. It was a limitation in this calculation as it might not fully represent the closest estimation and concerns in another continent. The weighting factors for each material/energy is subjective and vary according to geographical and socioeconomic criteria, which caused the different representation between countries or regions. For instance, an impact category of respiratory effects has a great significance in areas that suffer from high emission rates and have a higher weighting factor. Therefore, in LCA, the weighting process to result in a single score calculation is optional but essential when several solutions need to be compared (Menoufi, 2011).

Table 5 Values of material input impacts to the endpoint impact categories based on ReCiPe endpoint single score

Damage category	Unit	Spent fluorescent lamps	Electricity consumption	Total
Human health	μPt	2.18E-03	14.96	14.96
Ecosystem damage	μPt	1,34E-07	7.4E-01	7.36E-01
Resource depletion	μPt	0	8.61E-03	8.61E-03
Total	μPt	2.18E-03	15.71	15.71

If further explored, a single score also succeeded in comparing the damage degree between the electricity consumption and disposed lamps, consequently enabling the quantification of overall environmental damage from the whole recycling process. Previously mentioned, disposed lamps showed 0 contribution score to any environmental damage; that might be influenced by the small impact degree.

However, after the unit transformation, disposed lamps had a small impact score (refer to Table 5) and yet still shared a lower damage degree (less than 1%) to the total damage score (15.71 μPt). Health risks shared up to 95% of the total damage score (Figure 16), meaning that measures related to electricity consumption in the recycling processes should be developed to protect human health as the primary concern in the current SFL recycling practice. The information providing pathways of how human health was altered should be grasped and derived from ReCiPe midpoint normalization results to formulate such measures.

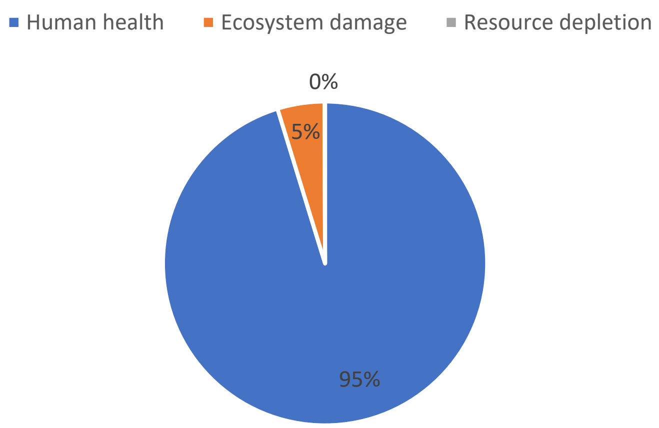

Figure 16 Total percentage of each endpoint impact category in ReCiPe single score analysis

Midpoint assessment showed the pathways in which human health was influenced. Based on Figure 17 and Figure 9 of impact classification, human health was risked through the potential effects of global warming (2.30318E-08), ozone depletion (4.69005E-11), ionizing radiation (5.8006E-08), a human carcinogen (1.18967E-08), and non-carcinogen (1.51685E-08), and fine particulate (4.46001E-08) formed from the electricity consumption.

These midpoint pathways were consistent with the Eco-indicator 99 impact analysis, which displayed human health was altered through carcinogen, climate change, ionizing radiation, ozone layer depletion, and respiratory effects (Sangwan et al., 2014). Other midpoint methods analysis is cumulative energy demand (CED) and the global warming potential (GWP). CED informs carbon energy consumption in MJ-equivalent (MJ-eq) and GWP refers to carbon footprint or potential global warming in kg CO_2-Equivalents (CO_2-Eq) (Welz, Hischier, & Hilty, 2011). Fluorescent lamps resulted in 19 g CO_2-Eq/hour of lighting use based on coal-based electricity. The value was reduced to up to 0.3 g CO_2-Eq/hour with an electricity mix with a non-fuel-based source. The use of electricity mix had an impact on global CO_2 emissions.

The casual relationship between midpoint and endpoint was the midpoint shows the cause-effect chain starts with a specific activity leading to emission and consequently primary changes in the environment. Later, it causes biological changes as the endpoint. The endpoint is known as the damage-oriented approach (Affeldt, Leung, & Yang, 2016). The ReCiPe endpoint showed that the recycling process affected human health the most through various pathways such as global warming, ozone depletion, fine particulate according to midpoint assessment. Moreover, renewable energy in the electricity source is promising to reduce the impact of global warming of SFL recycling; supporting the finding of this research.

The results were consistent with Apisitpuvakul (2007) and Sangwan et al. (2014) that used the Eco-indicator 99 method with a functional unit of per one FL, Thavornvong (2016) and Sangwan et al. (2014); Wongsoonthornchai et al. (2016) utilizing material flow analysis of per kg mercury and Welz et al. (2011) applying GWP method for the midpoint assessment with per hour of lighting operation functional unit The differences in a functional unit should be considered in the comparison.

A comparison and confirmation with IMPACT 20002+ in this study were conducted to test the robustness of the ReCiPe results. Briefly in Figure 18, the single score results displayed similarity as well. ReCiPe and IMPACT 2002+ use the same midpoint and endpoint assessment and validity approach for the European region. However, IMPACT 2002+ is an old method and has not been discussed. Another difference notifies in the midpoint impact category for renewable energy and climate change of the endpoint (Menoufi, 2011).

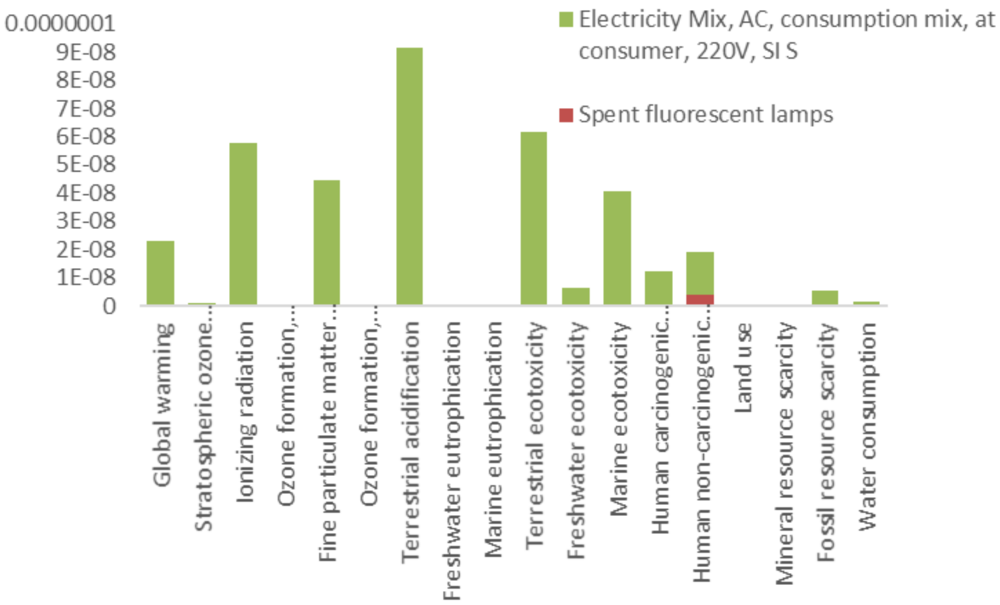

Figure 17 Pathways of recycling processes alter human and ecosystem based on ReCiPe midpoint assessment

4.2.2 Results of environmental impacts from the formal recycling process according to IMPACT 2002+ assessment

Similar results of endpoint damage assessment and normalization were found between these two models. The endpoint damage assessment produced four environmental impact categories (i.e., human health, ecosystem damage, climate change, and resource depletion) that the score in each unit 100% shared by the electricity consumption with 2.06E-05 DALY, 0.6 PDF*m2*yr, 13.08 kg CO_2 eq, and 252.21 MJ primary respectively. Normalization generated in human health as

0.002898239, 4.42E-05 in the ecosystem, 0.00132 in climate change, and 0.00166 in resource depletion.

Table 6 The value of impacts in each impact category based on IMPACT 2002+ singe score values

Damage category	Unit	Spent fluorescent lamps	Electricity consumption	Total
Human health	nPt	0.40	38.07	38.47
Ecosystem quality	nPt	17.34	0.58	17.91
Climate change	nPt	0	17.36	17.36
Resources	nPt	0	21.80	21.80
Total	nPt	17.73	77.81	95.55

A difference with the ReCiPe impact assessment was observed in the single score, in which the disposed of lamp compromised a higher share around 22% in the total environmental impact score as shown in Table 6, and this value was 90% higher than the ReCiPe score. The result still displayed that human health was primarily altered by the recycling process (38.47 nPt). Another distinguishing point was that the disposed lamps had a detectable impact on the ecosystem quality (17.34 nPt) and the value was larger than electricity consumption (0.28 nPt).

The difference might result from the different weighting systems used in the process. The reCiPe had a larger value of human health impact than resource depletion and ecosystem damage contrary to IMPACT 2002+. Both approaches use the same triangle weighting process while they only can compare three categories. Hence, IMPACT 2002+ resulted in a lower magnitude value. This has been argued in a study comparing different impact assessment tools in SimaPro 8 in a manufacturing machine.

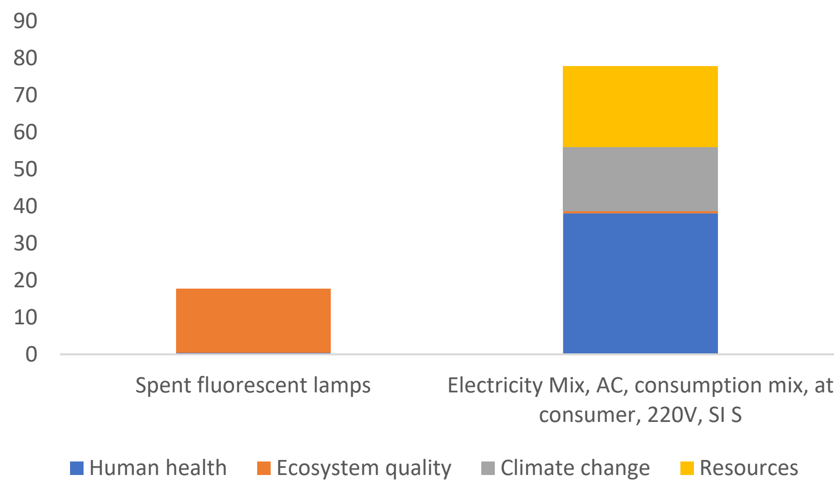

Figure 18 Comparison of impact degree between process inputs based on IMPACT 2002+ single score

The argument of the ReCiPe had a higher value on human health was identified in this research and illustrated in Figure 19. Human health had a small share (40%) of the overall impacts, followed by climate change (23%), ecosystem quality (19%), and resource depletion (18%). Climate change IMPACT 2002+ enriched the observation of the recycling process's impact on climate change as an emerging issue to evaluate nowadays.

In conclusion, ReCipe and IMPACT 2002+ results showed that recycling activities adversely alter all the environmental impact categories in ReCiPe (human health, ecosystem damage, and resource depletion) and IMPACT 2002+ (human health, ecosystem damage, resource depletion, and climate change). The significant contributor to the damage was the consumed electricity shown on the value of ReCiPe endpoint single score 15.71 µPt. Then number outweighed 100% of the overall total impact score (Table 5). In the percentage, the disposed of lamp scrap had a lower significance. IMPACT 2002+ results, similarly, displayed a higher significance of electricity in the endpoint single score but the disposed of lamp scrap shared a larger share (22%) in the total environmental impact score (95.55 nPt).

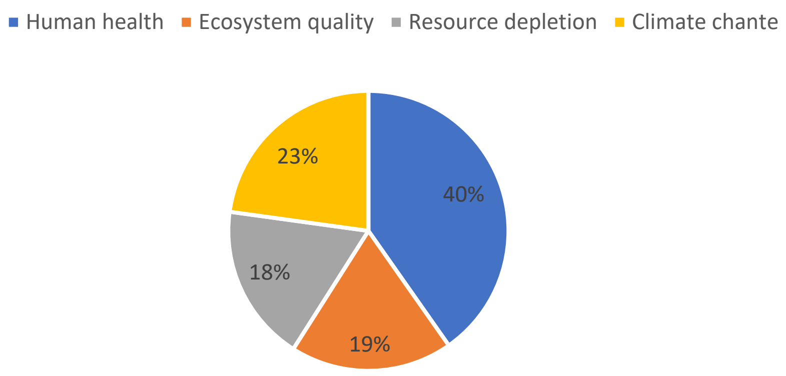

Figure 19 Percentage of impact degree between each process inputs based on IMPACT 2002+ single score

Impact reduction shall put a higher consideration on the electricity consumption and the source. ReCiPe single score displayed that measure put into effect on electricity would reduce the impacts of altered human health (14.96 μPt), followed by ecosystem damage (0.74 μPt) and resource depletion (0.0086 μPt). This scenario LCA was based on current practice calculation.

This analysis stage only informed the hot spot in the process, which was electricity altering most human health. The type of environmental impacts the recycling process caused were elaborated in the detail below based on midpoint impact assessment and secondary literature review.

- Human health

Energy sources to produce electricity played a compelling contribution to the mechanism of human health alteration. Natural gas (69.22%) and coal (19.10%) dominate Thailand's energy source (Zainorizuan et al., 2017) and have been reported associated with numerous occurrences of global warming, human carcinogen and non-carcinogen, and fine particulate (Burchart-Korol, Pustejovska, Blaut, Jursova, & Korol, 2018). According to ReCiPe normalization results, electricity consumption influenced human health through ionizing radiation, fine particulate, and global warming. This association was closely caused by greenhouse gases (GHGs) and heavy metals emitted during the energy combustion for electricity production. Without any measures to mitigate the emissions and energy transformation to renewable energy, those occurrences will keep increasing by an increase in electricity consumption.

During the combustion of fossil fuels, radionuclides emitted and entered the human body. The body transformed radionuclides into ionizing radiation (i.e., superoxide ($O_2\bullet^-$). The superoxide disrupts body redox levels and potentially causes cancer and DNA damage. Such cancer incidents are commonly found among workers in the power plants for chronic exposure, i.e., 16 years even though with lower exposure dose (<50 millisieverts (MSV)) than the International Commission of Radiation Protection (ICRP) standard (Abdalla; & Zimmerman, 2018; Huijbregts; Songwon Seo1, 2018). Also, the combustion emitted heavy metals and GHGs depositing in the atmosphere. Through chemical reactions, the suspended particulates aggregated into larger delicate particulate matters (2.5 to 10 micrometers in size (PM_{10} or $PM_{2.5}$), with such characteristics particulates, easily enter and clog in human lungs and the blood, causing adverse health problems (Akurugu, 2018; Wongwatcharapaiboon, 2020). In Bangkok, it reported 4,000 to 5,500 cases were associated with premature deaths based on a 10 million population calculation relating to outdoor PM_{10} exposure. The reduction of annual PM_{10} concentration would reduce the occurrences.

Besides causing health problems, fossil fuel combustion emissions cause climate variability correlating with prolonged droughts or intense rainfalls in coastal and developing countries. Thailand suffered from 57% of crop yield production in 2017 and is predicted to experience economic loss of 9.8 to 13.9 billion Baht and an annual 3.6 to 15% yield crop reduction by 2050 (Bartlow et al., 2019; Dietz, 2020; Jones, 2018; UNDP, 2017). Those would consequently disturb food systems for human consumption since the environment is no longer sufficient to sustain food production with high nutrition values and equal distribution (Institute, 2008; Ministry of Natural Resources and Environment of Thailand, 2016).

These two examples explained, in brief, the broader impacts of how compounds released from natural gas and coal during the production of electricity might influence human health. They alter human health either through the direct inhalation of the gases or indirect consequences from climate change pressures. The keynotes to spot are efforts to mitigate the emissions during electricity consumption or transform to renewable energy sources, e.g., solar, biofuels, and wind. Discussion of the promotion and adaptation of renewable energy has been raised in Thailand to tackle climate change.

- Resource depletion

Referring to the normalization results (Figure 14), resource depletion occurred due to excessive fossil extraction and water use for electricity production. These findings could explain why Thailand promotes renewable energy, whereas fossil-based fuels were not fast enough to renew and require more considerable energy input to process. Thailand experienced domestic energy insecurity in 2014 that forced the government to increase energy import and enforce the 30% share of renewable energy consumption by 2036 (e.g., solar PV and wind power) (IRENA, 2017). This existing government's focus could be the potential guidance for SFL stakeholders to promote sustainable SFLs recycling practices that align with its energy target.

Boyland (2018) analyzed that Thailand likely can even reach a 37% share of renewable energy use and mitigate GHGs. However, it has missed the social barriers to sustain the energy, such as fragmented institutional settings, power resilience to move forward renewable energy from some stakeholder groups in the energy sector, and social equity and inclusion of workers and communities reliant on the industries. Therefore, considerations of social dynamics in the transition and adaptation of renewable energy should also be understood to plan sustainable solutions.

- Ecosystem damage

Unlike the previous two sections, ecosystem damage was dominantly influenced by fluorescent waste, according to the IMPACT 2002+ single score assessment. Such damage was caused through the disruption of the terrestrial and marine ecosystems

(Illustrated in Table 7). Terrestrial ecotoxicity and aquatic ecotoxicity were calculated as emissions into the air, water, and soil that are equivalent to Triethylene glycol into water. Cited from Wongsoonthornchai et al. (2016), the land has become the largest mercury respiratory from landfilling; from 562 Kg of mercury was released through SFL disposal, 85% entered the land, 12% to air, and the rest to water. Although it has become the major global pollutant, mercury contamination in soil was least studied due to the variation of soil characteristics and aging period of contamination that hinders the standardized maximum detrimental effects.

Mercury in soil has been reported to reduce soil alkalinity and change surface water composition reducing base saturation. Such imbalance in soil attracts fatty metals deposition making them available for plant uptakes, disturbs microbe activity, and affects soil fertility (Arunakumara, Walpola, & Yoon, 2013). Plant updates of heavy metals result in results transfer to the human body through ingestion. However, this is determined by the amount and time of exposure. While in the marine ecosystem, the pollutants acidify oceans' surface water resulting in profound effects on marine nutrient cycles, population dynamics, and food systems (Turye, 2013). Acidification in Thai marine zone has been reported associated with coral bleaching and reduction of the country's GDP, which corals are a prominent contribution to Thailand's tourism and fisheries, besides creating habitat support, reducing storm waves associated with floods, and protecting shores (Pengsakun et al., 2019; Sutthacheepa; et al., 2018).

Table 7 The impact value of material inputs to each impact category based on IMPACT 2002+ characterization results

Impact category	Unit	Disposed lamps	Electricity consumption	Total
Aquatic toxicity	kg TEG water	1.78E-02	7.18E-03	2.48E-02
Terrestrial ecotoxicity	kg TEG soil	2.99E-02	2.02E-05	3.01E-02

Impact category	Unit	Disposed lamps	Electricity consumption	Total
Terrestrial acidification	kg SO2 eq	0	5.76E-06	5.76E-06
Aquatic acidification	kg SO2 eq	0	3.95E-06	3.95E-06
Aquatic eutrophication	kg PO4 P-lim	0	9.21E-10	9.21E-10

4.2.3 Considerations of the given limitations on LCA analysis for the formulation of the sustainable recycling process

ELCA has been evident to show potential rather than actual environmental impacts. ReCiPe and IMPACT 2002+ showed that electricity consumption contributed significantly to the damage compared to the fluorescent lamp; meanwhile, the plant emits mercury into the air and lamp scraps. This research only recorded mercury concentration in the lamp scraps and excluded the air concentration due to data confidentiality. In contrast to the literature review, mercury is found in the soil, air, and groundwater of the surrounding formal recycling plant (S. Decharat, 2018; Wongsoonthornchai et al., 2016). Thus, the uncertainty and sensitivity of the results should be considered. Alternative data input was elaborated further in section 4.6

The recycling plant uses Bulb Eater technology to recover the mercury from the glass tube, which does not release mercury into wastewater. The technology applies dry extraction using a bag filter, High-Efficiency Particulate Arrestor (HEPA) filter, and activated carbon that requires no water for the extraction (Environmental Protection, 2021). Although the Bulb Eater claimed to acquire >90% removal of mercury vapor and dust >0.3 microns, US EPA encouraged to clarify clearly under what circumstances to use Bulb Eater.

The device still exposed the operators to mercury above the OSHA PEL of 0.1 mg/m^3 values when opening the feeder when the drum was full. The study evaluated 9 out of 12 air samples collected from the feeder device contained 3 times of OSHA PEL. The recommendation was given to separate the ventilation of the recycling room from the general building to prevent cross-contamination and accumulation of dust in the material surface and workers' bodies (US EPA, 2019; Zimmermann et al., 2014).

It was problematic since there was no data of the mercury release concertation and building layout from the studied recycling plant for estimating the actual exposure. Workers in the studied recycling plant were protected with PPE as in the following figure. However, exposure can still occur at cutting the aluminum end cap and crushing the bulbs at the same Bulb Eater. Broken lamps before the feeding expose mercury vapor and remained in the air for 8 hours after the breakage (Wongsoonthornchai et al., 2016). The concentration of mercury inside the drum was initially 0.033 mg/m^3 and increased to 0.169 mg/m^3 four minutes after a lamp was broken (US EPA, 2019).

Figure 20 The worker operating the Bulb Eater at the recycling plant

Source: The studied recycling plant

The next condition occurred when there was a device malfunction such as when the feeding tube was not properly connected to the drum-top assembly due to losing gasket. For this occurrence, a concentration of 0.074 ug/m^3 mercury was detected in one operator's shoulder sample (US EPA, 2019). Associated with lack of hygiene, the workers can digest the dust or inhalation. Moreover, mercury dust was identified in the workers' shoes and cars that brought the contamination to home (Erica Wilson & Meiman, 2018; Zimmermann et al., 2014).

The third exposure condition was during changing the drum when it is full and had to continue to another drum. The full capacity of each drum in the studied plant is approximately 1,2000 tubes, with 5 drums a day. Although the drum only was opened for 10 minutes, it released mercury vapor at an uncontrolled rate. Minimizing the opening time reduced the mercury release (US EPA, 2019). The workers exposed to the mercury above OSHA PEL have been found associated with physical tremor to the workers, breathing difficulty, memory loss, insomnia, headaches, weakness, and muscle twitches (Erica Wilson & Meiman, 2018; Zimmermann et al., 2014)

Besides improving ventilation systems in the recycling facility, US EPA recommended conducting regular device monitoring based on standardized test methods to ensure the repeatability and accuracy of the test. The standard operation of the device, the behavior of the workers, and the layout of the building determine the mercury release to the ambient air in the recycling facility (US EPA, 2019; Zimmermann et al., 2014). To a larger extend, uncontrolled mercury release caused deposition in the environmental matrix. Mercury is classified as hazardous air pollution (HAPs) related to the Clean Air Act of the US. Environmental Protection Agency (EPA). Incineration of waste containing mercury caused mercury deposition in the soil and water. Mercury air pollution caused premature death to newborns and ended back to the environment affecting ecosystems (Peng et al., 2014).

Regardless of the adverse impacts, Bulb Eater has advantages to sustain the recycling business by allowing waste volume reduction through crushing and safer shipment. Thus, reducing shipping and storage costs. The studied plant required 1.71 Baht per recycled tube (Appendix A). Considering 6,000 tubes recycled per day, the total recycling cost per day in the studied plant was around 10,260 Baht. Compared to non-recycling (no mercury recovery, only crushed the SFL and solidified it into cement and sent to landfills) in Apisitpuvakul (2007), this cost was higher (1.4 Baht per recycled tube). However, the total disposal cost per ton of SFL required by the studied plant was 332,506 Baht, which is higher than the fine (200,000 Baht) of illegal dumping in the Hazardous Waste Act (Liumpetch, 2018).

The recycling plant installed devices for indoor mercury control, but there is no mercury parameter mentioned in Environmental Impact Assessment (EIA) Guideline from the industrial discharge, which has loosened strict mercury control in Thailand. Mercury might deposit in the recycling plant's surrounding environment, but there was no actual and robust evidence to show the health impacts (Ismail & Hanafiah, 2019; Salam, Shomope, Ummi, & Bukar, 2019; UNDP, 2017). Potential health impacts only refer to literature studies.

To present potential impacts, ELCA requires enough data for computational calculation. Otherwise, it is critical when a hazardous substance is not presentable. Although the above calculation failed to present a more representable mercury impact, the impact assessment succeeded in showing the hotspot (i.e., electricity) and its impact, which could be a starting point for policymakers the attention. The second limitation is the consideration of ELCA uses a European weighing reference in the impact assessment, which caused the impacts were not presentable and cannot address the localized impacts (Muthu, 2014).

Through midpoint assessment, electricity consumption highlighted that energy source was critical in mitigating the impacts and promoting a sustainable recycling practice. Domestic regulation and energy production capacity seem to be capable of reaching renewable energy transition. However, social dynamics such as fragmented collaboration in the government, power resilience to move forward renewable energy from some stakeholders in the energy sector, and social inequity hinder the adaption of the transition (Boyland, 2018).

4.3 Consideration of Environmental Benefits from Increasing the Recycling Rate

Recycling reduces environmental impacts by preventing hazardous material leaks to the environment. Increasing the recycling rate expands the benefits. As evidence, a shift from 100% secure landfill to 70% secure landfill + 30% recycling reduced significantly total environmental impacts up to 5 points of the single score (Thavornvong, 2016). Furthermore, an increase from an 18% recycling rate to 50% for the industrial waste of FL + 10% recycling of household waste of FL reduced 22% of mercury release to ambient air (Wongsoonthornchai et al., 2016).

Apisitpuvakul, Piumsomboon, Watts, and Koetsinchai (2008) demonstrated that the process would require a lower electricity input by increasing the recycling rate. This scheme theoretically demonstrated the benefit of the government's target of a full recycling rate. However, with the current weak local waste collection and no precise EPR mechanism, the achievement of optimum benefits from a higher recycling rate might encounter. Therefore, this research proposed an alternative that addresses the limitation in energy and collection centers with the existing governmental structure.

The transition and adaption of renewable energy experienced challenges in the collaboration, not knowing which stakeholders should discuss. It recommends engaging the Ministry of Natural Resources and Environment as the regulator and technical advisor of environmental quality protection with several Ministries, such as

- The Ministry of Public Health controlling occupational risks,
- Ministry of Interior decentralizing the mechanism,
- Ministry of Finance is formulating economic instruments for the management,
- Ministry of Industry is tracking the industrial waste flow (Kamuang & Siriratpiriya, 2017; Ministry of Natural Resources and Environment of Thailand, 2016)

Moreover, the collaboration within The Environmental Board and local stakeholders including non-formal stakeholders shall be taken and emphasize mechanisms to increase the collection rate that would sustain the recycling business if a higher recycling rate would pertain.

4.4 Social Impact Assessment of the SFL Recycling Process

This section described the social impacts of the current recycling practice as pieces of evidence to argue the Master Plan target and provide recommendations. SIA complemented the ELCA to describe the stakeholders' perceptions in the recycling stage. Appendix D presented the questionnaires used to assess the stakeholders' social impact, and Appendix E continuously illustrated the given answers' scoring. Each of the social impact categories was elaborated as follows.

4.4.1 Local community

4.4.1.1 Safe and healthy living conditions

The safe and healthy condition measured the health risks and complaints from the people residing in a radius of 5 Km from the recycling plant. Due to the COVID-19 situation, only the recycling plant management answered the questions regarding this impact category. Based on the questionnaire answers and scored to reflect Table 2, the local community's health and condition scored point 3 since installed devices exist to monitor the mercury release. The company carries out a regular inspection with a third party. However, it is unclear whether there were complaints or health risks arisen. The assumption made for score three was that there were no significant complaints of discomfort or health risks from the community.

The indicator for score 3: Meet the requirement to guarantee the safe living environment surrounding the recycling plant and no complaints from the people.

Score 3 showed quite positive feedback; however, excluding parameters for mercury vapor release in the EIA Guideline should be considered. Such exclusion caused difficulties in monitoring the mercury deposition's actual health impacts in the environmental matrix, especially after immediate exposure. Deposition of mercury in the soil can contaminate the groundwater and infiltrate crops, which the community might consume.

Besides mercury, heavy metals (e.g., Aluminum, Copper, Argon, Zinc, and Phosphorous) in the fluorescent lamps are also the potential agents to cause health risks to the surrounding community. Secondary literature showed that elemental dust inhalation causes respiratory illness to the community near a formal recycling plant in the Philippines, India, and China (Fujimori et al., 2012). ELCA analysis also proved recycling process risks people’s health through fine particulate inhalation, carcinogen, and non-carcinogenic effects.

The assessment had a limitation in showing the actual health risks without actual field observation and health risk assessment to emphasize the inefficiency of Bulb Eater and current working practice (Fujimori et al., 2012; Q. Tan & Li, 2016). Regardless of such limitation, the assessment resulted in a score of 3 for protecting the local community’s health by regular mercury monitoring carried out by the plant. There were no complaints reported from the community according to the questionnaire answer. However, future research shall compile health risk assessments to support the findings and consider the time length of mercury exposure (Ahmad; et al., 2018).

4.4.1.2 Local employment and contribution to the local economy

The highest score (Score 4) was given to this indicator since the studied recycling plant encouraged local employment for convenience in mobility and understanding of the local geography. Such conditions support the business effectiveness, mainly for the collection and transportation. Transportation route and distance determine the cost-effectiveness of the collection and recycling process.

Among 120 people in the recycling and transportation activities, 30-40% were employed from the province, and 25 people are in the management team. The formal recycling plant has been evident to provide job opportunities for the locals, improve socioeconomic conditions, and contribute positively to the country's development. Such data showed that the formal recycling plant had created jobs.

"Score 4 for the local employment and contribution to the local economy: There are initiatives to engage local workers."

The recycling plant sells the lamps' the recovered materials (e.g., end caps, aluminum, etc.) from the lights to other domestic or international business partners contributing to the national economy. For example, the plant sells lamp scraps to Japan. Economic data was unavailable. As a reference, the e-waste industries in Guiyu, China, generated almost 1.2 billion RMB (Renminbi, a Chinese currency) (approx. US$152 million), which accounted for over 90% of local fiscal income. Another example is Pakistan for its copper market from e-waste recycling (Umair et al., 2015).

More jobs and access to the re-used materials from recycling contributed to the economic development, which becomes the first weapon to tackle poverty. The reduction of poverty would benefit national development. Unfortunately, there is no clear association between economic development to protecting the safety and health of the workers and the local community.

4.4.2 Workers in the recycling facility

4.4.2.1 Decent working conditions (fair salary and overtime)

One of the benefits of a formal recycling plant is the assurance for decent working conditions following legal labor law and regulation. Studied recycling plant provides social benefits along with the basic salary (Score 4), and overtime was set corresponding to department role and function. Compensation for overtime work was given in compliance with national guidelines (Score 4) to ensure worker's welfare. The answer given did not provide what labor regulation followed and the setup for overtime.

Score 4 for a fair salary: More than the minimum wage with other social benefits

Score 4 for overtime: Less than 48 hours a week with compensation

The processing activity runs for six days/week with 12 hours/day, comply with ILO Working Convention. The plant provides overtime compensation to the workers and other social benefits that support decent working conditions. Working hours were identified since it was associated with worker's health. Negative health impact indirectly socioeconomic repercussions, since the workers bear health expenses due to lack of social security (Umair et al., 2015). Therefore, assessment of their decent condition determines the sustainability of the recycling process. The concept of sustainability is to prosper the people, environment, and economy (Stamford, 2020).

The assessment's limitation was that it did not hear the worker's satisfaction in the paid wage. Such measurement indicators enabled double-check between the business and worker's perspective. Rather than a measure based on a specific regulation,

Foolmaun and Ramjeeawon (2012) measured the fair salary by the worker's satisfaction in wage. This method helps to provide information for confidential data. To summarize, the recycling plant has positive contributions to fair salary and work time associated with health improvement. However, this information needs to be confirmed with the workers' perception of wage satisfaction. The research recommended using worker's satisfaction in wage instead for the indicator measurement.

4.4.2.2 Health and safety

Health and safety were measured using personal protective equipment by the workers and the mercury concentration in the air. Score 2 for workers' health and safety concerning the exposure to mercury vapor in the recycling room and unclear standards to comply with indoor mercury control. Creating decent and safe working conditions in the plant requires government facilitation under legal enforcement and facilitation. Otherwise, this might be concerning and varying among recycling plant stakeholders.

Score 3 for worker's health and safety: OSHA PEL limit 0.1 mg/m^3 air for an 8 hour/day workday + PPE enforcement + very few work injuries/year

The business has encouraged PPE use, staff training for mercury emission monitoring (Score 3), and regular health check; although the questionnaire answer did not mention the type of the health checkup. It is significantly important because exposure to mercury in the recycling facility of SFL was prominent (Erica Wilson & Meiman, 2018; Pini et al., 2019; Zimmermann et al., 2014).

Mercury exposure commonly occurs during transportation, storage, and treatment. The broken lamps collected from the collection center were the first point of exposure. Thus, transporters and collectors shall be accommodated with PPE as well. When the lamps enter the storage room before the recycling, the broken lamps keep releasing the pollutants, especially when they break during transfers and if the storage room is too confined. In this case, airflow in the storage and recycling plant is necessary (Zimmermann et al., 2014). However, the building layout from the recycling plant is unavailable.

In the recycling plant, the operator at the feeder had a great exposure from handling the lamps. Material input to the Bulb Eater was manual. Based on Figure 20, the workers wear PPE, including uniforms, goggles, gloves, ventilators, and boots. However, the workers could still be exposed to indoor mercury concentrations above OSHA PEL, especially from the release in the feeder and opening the drum when the drum is full. Once the lamps are opened or crushed in the recycling process, the mercury instantly exposes the workers with a 2%-14% percentage or 33% in the first 8 hours (Wongsoonthornchai et al., 2016; Zimmermann et al., 2014). Since mercury vapor is a fine particulate, inhalation is unavoidable (Zimmermann et al., 2014).

The dust can accumulate in the uniforms as well. Without more pro hygiene, mercury could enter the body through oral when the workers do not wash their hands and faces before breaks. Mercury is very worrisome since there is no visible sign of contamination. The mercury dust in the worker's clothes, boots, and cars potentially contaminates the family members (Erica Wilson & Meiman, 2018). Mercury exposure caused a physical tremor, breathing difficulty, memory loss, insomnia, headaches, weakness, and muscle twitches (Zimmermann et al., 2014).

Moreover, mercury dust was present on the surface floor and other materials outside the recycling facility. To mitigate risks to workers, the recycling plant needs to apply engineering control technology and regular and appropriate cleaning of the surface with correct disposal of the cleaning equipment to reduce the cross-contamination to another facility. A clear protection program policy needs to be implemented (Erica Wilson & Meiman, 2018).

4.4.3 Recycling business perspective

Figure 21 summarized the social impact assessment score from the given answers. Based on the scoring system (Appendix E), the formal recycling process of SFL had an average score of 3 to the impact category of community's and worker's health and safety. The highest score (Score 4) was for local employment and fair salary. The information implies the positive contributions of a formal recycling plant to promote them in the national E-waste management but requires supports to tackle the limitations.

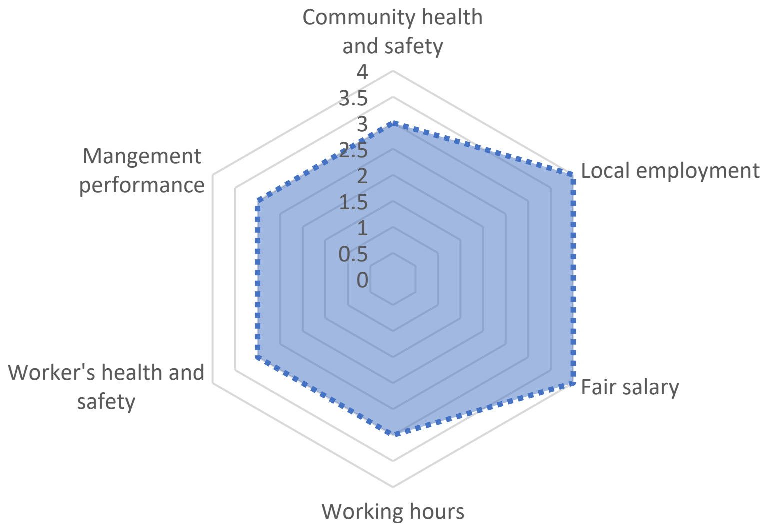

Figure 21 Scoring of social impact assessment of SFL recycling processes based on questionnaire answers and scoring system in Table 15

This concern was assumed related to the worker's willingness to use PPE all the time due to convenience and the plant's stringent enforcement (Erica Wilson & Meiman, 2018). There is mercury monitoring with a third party at the plant, but it was unclear about the procedure. Besides relying on mercury emission checking, the Bulb Eater maintenance and cleaning schedule determine the worker's health protection. Building layout and ventilation, as well as the length of working time, contribute to this issue.

Another stakeholder that might be impacted directly by an unsustainable recycling process was the local community's deposition of mercury and other hazardous materials of FLs in the environmental matrix. The community's assessment supports the potential impacts analyzed by ELCA, which the hazardous materials might deposit in the nearby recycling facility impacting humans indirectly in the location. In contrast with the worker's health analysis, the determination of community's health was more challenging to assess due to the actual history assessment of the environment in the recycling plant

The challenges captured through the questionnaire enrich the analysis of the impacts of SFL recycling in Thailand, which focused on environmental aspects only. These challenges assist policymakers in improving the recycling process and a higher recycling rate target and protecting human health.

4.4.4. Challenges faced by formal SFL recycling business based on the questionnaire answers

Besides the above challenges, the formal business has stated their challenges to perform efficiently and effectively to protect health and the ecosystem was associated with government support, unclear legal mechanism of E-waste management, and low material supply. Such barriers were similar in Sri Lanka, India, and Pakistan, where the informal recycling business treats much of the waste (Gunarathne et al., 2020; Henzler et al., 2017; International Labor Organizations, 2019; Umair et al., 2015).

The summary of the questionnaire answers confirmed the applicability of Integrated E-waste Management by Marshall and Farahbakhsh (2013) that the E-waste problem is multifacet including various aspects, stakeholders, and elements. These three points were layering technical, social, and institutional experienced by different stakeholders in various waste management.

- The insufficient government support

This matter was in Appendix D, Question Part 2, no. 3. The government support covered terms of capacity building, knowledge transfer, and funding. Capacity building from the authorities for formal business, mainly the smaller-scale were essential for labor specialization, skills development, and knowledge transfer on waste segregation and material recovery (Visanathan & Ananth, 2019).

The business assumed that insufficient capacity-building came from a lack of ability and fragmented responsibility in the government. The importance of capacity building for recycling promotion was in line with the third principle of the 3R Action Plan for the Master Plan; disposal stage of waste driving force were multiple public-private partnerships, recycling business promotion, and capacity building (Gunarathne et al., 2020; Chanatip Pharino, 2017; Pollution Control Department, 2019). Thus, when the policymakers plan to increase the recycling rate, they should consider integrating capacity building on renewable energy in the recycling process, building and equipment maintenance, and worker’s health protection.

The business representative quoted that government facilitation in capacity building and funding under a legal umbrella would positively impact the formal recycler. Based on Figure 3, National Environmental Board is responsible for environmental quality monitoring. There are three department implementors The Office of Environmental Policy and Planning, the Department of Environmental Quality Promotion, and the Department of Pollution Control. It was unclear who is responsible for the capacity building. The National Committee assigned the Ministry of Natural resources and Environment functions to coordinate and monitor the Act's implementation, and it was assumed DIW and PCD are responsible in this case.

- Unclear E-waste management

Since SFL is E-waste and hazardous waste, management is critical. The unclear funding mechanism and classification of waste attributed to the postponement of the 2017 draft Act on the Management of the Waste Electrical Products and Electronic Equipment. Business quoted that the legal umbrella for E-waste is the basis for strengthening health control by preventing illegal dumping, material flow monitoring, and partnership mechanism to receive capacity building and funding (Appendix D, Question Part 2, no. 4 & 6). However, the Draft Act does not include the technical issues of the recycling technology and recycling facility. Xiong Zheng et al. (2017) stated the legal regulation in E-waste was the priority for the promotion.

EPR take-back system has been managing E-waste under the WEEE Act "the Management of Waste Electrical and Electronic Equipment and Other End-of-Life Products," where the manufacturers/producers are responsible for the end-of-life management. MoF collected the manufacturers' funds and holds power to distribute them for the consumers' payment and recycling activity. The EPR system faces hurdles due to the flawed collection system at the local level that hurdles the materials flow to the formal recycler (Manomaivibool & Vassanadumrongdee, 2016). Many factors influenced this inadequate system.

A critical key in the funding scheme was that irregular material flow to the formal recyclers would put the E-waste management business too risky and unattractive for investment. Irregular flow influenced by 90% of E-waste collected and entered informal recyclers. Formal businesses only treat waste from extensive and strict industries (Appendix D, Question Part 2, no. 1-2). Without an adequate collection system, EPR implementation would face challenges and difficulty in accommodating a higher recycling rate.

The low material supply would low the recycling capacity. The lower capacity means a lower output or material to resel for revenues. Consequently, the business struggles to compete with the informal sectors for material supply and less investment. Domination of informal recycling actors in E-waste management is because of a better incentive to the costumers and no restriction of consumers to sell to informal sectors despite associated with various social issues such as child labor, unsafe and discriminated working conditions, environmental safety non-compliance, and urban slum (Fujimori et al., 2012; Ismail & Hanafiah, 2019; B. Li et al., 2011).

The business representative expected the government to enhance its role by creating EPR systems that control the informal sector in the SFL management and investment (Appendix D, Question Part 2, no. 4-7). Such inclusion to arrange partnerships between both actors or formalize the informal sector to control SFL flow.

4.5 Identification of Enabling Factors for Sustainable SFL Recycling in Thailand

This section reflects the challenges experienced by the formal stakeholder based on ELCA and SIA analysis to formulate enabling factors to mitigate the barriers experienced by the formal recycling business of SFL. This was to achieve a sustainable recycling process in Thailand and prepare for the increasing recycling rate target in the MPSWM (2016-2021).

The section elaborated initially on the technical issues of recycling technology, followed by the social challenge. It supports Marshall and Farahbakhsh (2013) argument, stating that E-waste management is multifacet in technical, social, and even institutional cross-cutting different stakeholders at the local and national level. The formulation refers to the concept of the framework and studies of Gunarathne et al. (2020) and Henzler et al. (2017). Apisitpuvakul (2007) mentioned that for ELCA to be informative for policymakers, the results should be complemented with the characteristic of local E-waste management regulation and the existing practices, which become the basis for these enabling factors formulation.

4.5.1 The monitoring and modification of the recycling technology

ELCA results informed that SFL recycling improved protection to human health, ecosystem damage, and resource depletion. The major contributor to these impacts was electricity. Coal-based energy dominates Thailand's energy source and reported various health impacts (Boyland, 2018; Energy, 2015; IRENA, 2017). Therefore the target in MPSWM (2016-2021) should consider the future energy transition in the country. Welz et al. (2011) reported that potential global warming was reducing consistently with the more renewable electricity mix used in the lighting, not how energy-efficient the lights are. Multidialogue with the Ministry of Energy shall be in place regarding the impacts of renewable energy on human health through the SFL recycling process.

Recycling of SFL also influenced the local community and worker's health, and the ecosystem through mercury exposure. Bulb Eater used for recycling has a high performance of mercury capture (Air Cycle Foundation, 2013; Environmental Protection, 2021). However, lamps sometimes are broken before feeding or during transportation and storage (US EPA, 2016; Wongsoonthornchai et al., 2016; Zimmermann et al., 2014). This condition caused the operators shall adjust the position for the lamps to feed into the Bulb Eater (US EPA, 2016).

The workers in the studied plant have implemented good PPE enforcement during the operation, including safety glasses, air-purifying, face shields, negative pressure respiratory, and hearing protection. However, lamp breakage can happen anytime; thus, operators and transporters shall also wear respiratory protection outside the treatment facility. Tracing of mercury resides outside treatment facility shall also be put in place. (Erica Wilson & Meiman, 2018; US EPA, 2016)

Based on Figure 20, there is only one person conducting recycling with Bulb Eater. EPA recommended two people in operating the treatment. One person is operating the device while the other handles the operator with the entire drum and changing the drums. This positioning reduces time when opening and closing the drum for mercury vapor to escape (US EPA, 2016).

The next thing is the design of the plant. Since mercury vapor is volatile at room temperature, it is easy to escape (Budnik & Casteleyn, 2019). The recycling room shall have a ventilation system that prevents the air from entering the main office, and the Bulb Eater provides fume hoods that vent fumes through carbon filters. Since the Bulb Eater is difficult to maintain mercury vapor under safety limits, some modifications to the design were suggested (Environmental Protection, 2021; US EPA, 2016).

The Bulb Eater could add mercury leak detection, but this costs $15,000-22,000. As an alternative, monitoring of pressure can prevent continuous device monitoring. Moreover, Bulb Eater could add sulfide-agent injectors in the drum to solidifying mercury vapor released during the crushing. Mercuric-sulfide is easier to control than mercury vapor and can settle down in the drum. Such modifications help mercury release to the ecosystem as well and protect the local community (US EPA, 2016).

4.5.2 Creation of informal-formal partnership under EPR scheme

The creation of the partnership, on the first hand, was to tackle the low material supply of the formal business. The higher recycling rate reduces electricity consumption, which is consistent with the target. However, this performance shall have sustained material supply.

EPR is a policy approach proposed to manage E-waste from the upstream (e.g., product design) to the downstream (e.g., collection and treatment) stage whose responsibility is a product's producers and consumers. The EPR principle has been in multiple policies in Thailand, such as Thailand's Strategy 4 of National Integrated WEEE Management Phase II, 2017 draft Act on the Management of the Waste Electrical Products and Electronic Equipment, and 3R policy. Economic instruments are present to complement the implementation. The EPR has been proposed to manage E-waste for a long time; however, the funding mechanism and product classification is now causing the pending of the E-waste bill in Thailand.

The informal sector dominates E-waste collection and treatment in Thailand since they have higher competitiveness to buy E-waste from the customers. In addition, such competitiveness of informal sectors exists by the absence of health and environmental compliance fee, low wage, and appropriate technology in practice. A short supply disables formal sectors to operate fully and participate in E-waste management (Kamuang & Siriratpiriya, 2017; Neitzel, Nambunmee, & Sanphoti, n.d.)

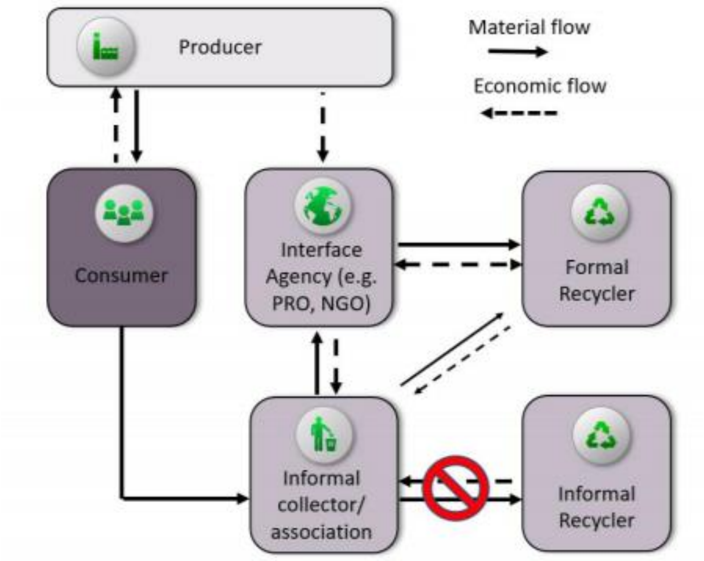

Figure 22 Partnership mechanism between informal-formal in E-waste recycling

Source: (Hinchlife et al., 2020)

The formal recycler requested implementing EPR to enhance their business; however, this approach must control informal sectors. Trying to dismiss informal sectors had not been successful here. Therefore, an alternative to connect informal sectors to the formal business aimed to fill the lack of material supply. This practice has been implemented in other developing countries (Henzler et al., 2017).

The proposed partnership between the sectors referred to India's lessons learned in plastic and household E-waste waste management (Hande, 2019; Henzler et al., 2017; Hinchlife et al., 2020). The study focused on two steps: 1) organizing smaller E-waste pickers and aggregators and 2) formalizing more prominent aggregators (segregation and processor/trader). Figures 22 and 23 channeled informal sectors to the formal business through interface agencies, e.g., producers and producer's responsibility organizations (PRO) and non-governmental organizations (NGO). These agencies directly purchased the informal collectors' waste and tunneled them to the formal recyclers. The interface agency is vital as the contact point between authorities, formal recyclers, and producers (Hinchlife et al., 2020).

To succeed and sustain the partnership, trust-building with the informal sectors is significant and requires a local intermediate organization that directly engages with them. Such action was to bridge the gap between upstream and downstream players, which requires a long-term investment. In addition, the reliability of upstream stakeholders (i.e., producers, interface agencies, and authorities) to provide information on market price and quality of the collected waste are also important. The government and producers should be able to pay the purchasing gap and ensure financial stability to the informal sectors when the long-term partnership fails (Hinchlife et al., 2020).

Meanwhile, possible mishandling from the informal sectors might occur due to a lack of awareness and skills on the know-how of proper waste handling. Such challenges could be addressed by providing incentives if they follow and implement the capacity-building training provided and use PPE. The achievement should be supported with regular waste monitoring at the collecting facility, health check-ups, and flexible agreements to attract informal stakeholders in the program (Henzler et al., 2017). The producers, government, and interface agencies shall also have the technical knowledge and to conduct the training.

Some degree of flexibility in the agreement with informal sectors should be considered as the E-waste market is highly dynamic and partnership with informal sectors is rather based on trust. Flexibility would allow all stakeholders to adapt to the dynamic conditions and respect their heterogeneous socio-economic backgrounds. In addition to this point, non-financial incentives could make the program more appealing to follow. An example in Chintan, Indian E-waste case study, the interface agency gave access to the joint informal workers to larger generators, which increased their income. Moreover, they were actively campaigning labor rights and education for the informal workers' children that were significantly attractive to the informal sectors (Henzler et al., 2017). In conclusion, non-financial incentives could fulfill the purchasing gap.

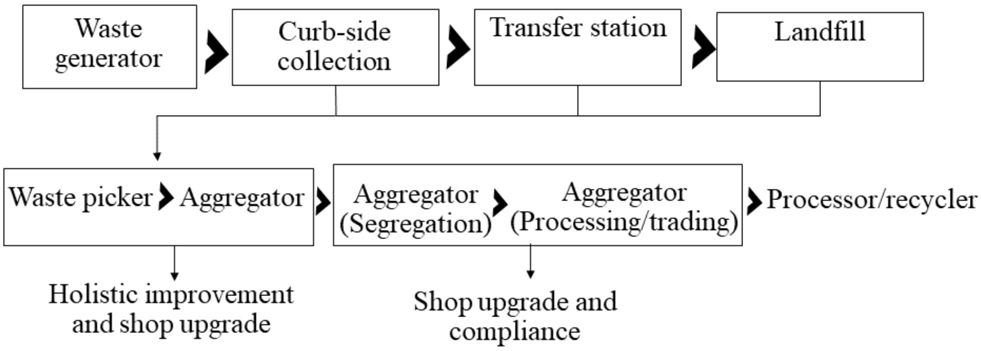

Figure 23 Scope and flow activities of informal E-waste recyclers

Source: (Hande, 2019)

Figure 23 specifically showed the order of E-waste management before landfills and actors act upon it. In this EPR mechanism, waste pickers and smaller aggregators who collect waste require knowledge and skills improvement without licensing their activities. On the contrary, larger aggregators who act as segregator/processors/traders need formalization to put their large activity under health and safety compliance and generate more revenue for the country.

Considering the Indian plastic waste management case study and Figure 22, the interface agency will establish local collection facilities to purchase waste from the informal pickers and sign them up to a digital database to track the amount of waste collected and their payment. The digital record will also notify the formal recyclers when to pick up the material. This case study succeeded in engaging 5,000 collectors and collected 3,000 tonnes of waste. This mechanism will have a better volume and quality waste traceability and reporting, improve collection and transfer logistics, and reduce cost production, as illustrated in detail in Figure 24 (Hande, 2019).

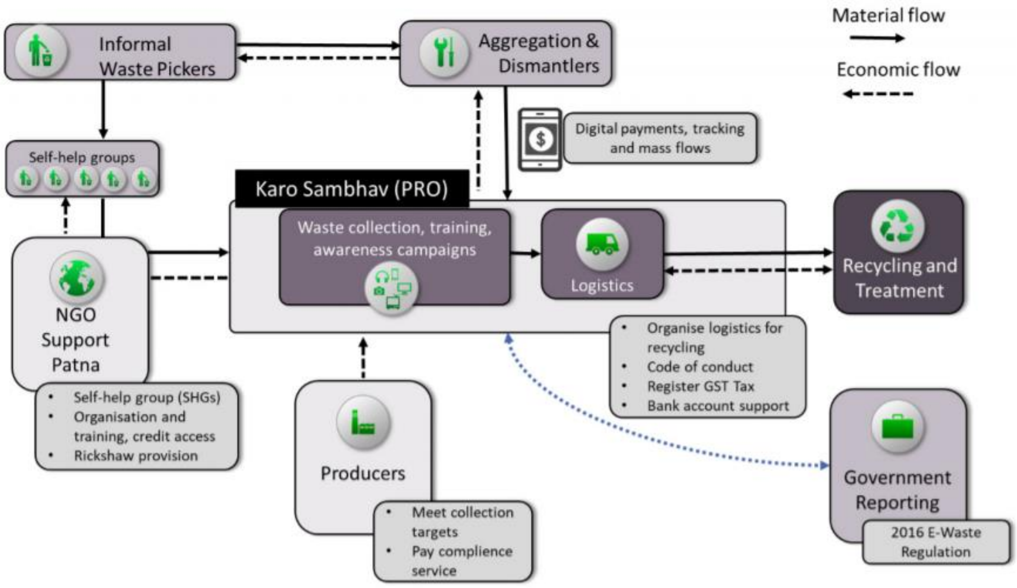

Figure 24 Example of PRO role collaborating with the informal sectors in India

Source: (Hinchlife et al., 2020)

Based on the waste generation assessment, collection activity was critical to support recycling in the formal business. Data of waste generation should be controlled to track the waste flow between formal and informal stakeholders. The partnership between the informal and formal recyclers would benefit the data record of waste flow and help the country estimate the closer possible potential impact of the recycling of SFL. Such benefits could reduce the overall environmental impacts resulting from recycling emissions (Apisitpuvakul, 2007).

Points that this scheme addressed:

- Barriers (Low supply and competition with informal sectors in Appendix D, Question Part 2, no. 1, 3, and 5) experienced by the formal business to achieve and evaluate a higher E-waste recycling rate goal proposed by the government in MPSWM (2016-2021).

- Integration of informal actors makes them more accessible to producers to carry out EPR through informal sectors, unlike before and links it to formal business to source from it.
- The established recycling facility facilitates proper waste inventory and traceability.
- Promotion of fair price, environmental and health protection is essential to the actors involved in recycling activities and people living nearby the facility.

4.5.3 Creation of financial support in EPR promotion

A fiscal instrument, such as product fees, has been discussed in the Act on Economic Instruments for Environmental Management to promote EPR implementation. The financial mechanism was drafted by MoF in coordination with a royal decree as a subordinate law from the MONRE.

The financial flow came from the producers to the governing board distributing to the local government for establishing take-back centers and to formal recyclers for buying the waste from generators. However, such a scheme was still insufficient to compete with informal sectors, including disposing costs, and is still under consideration. A feasibility study by PCD showed that the investment fee to establish a recycling plant required approximately 50 million Baht, which required 6 million material inputs of SFL. This would reduce the prior recycling cost (1.71 Baht/lamp) to only 1 Baht (PCD, n.d).

Thailand has a similar funding mechanism as China and Taiwan, which the scheme is top-down, determined by the government (Kamuang & Siriratpiriya, 2017; Sasaki, 2018). On the contrary, Austria imposed a financial burden on the light consumers to run the recycling process. A certain amount of the purchasing price will be refunded when they return the waste to the collection centers. While Germany has the consumers pay to run the recycling, and the process is more localized. These countries have a high recycling rate that is associated with sufficient funding mechanisms to support the collection center establishment and recycling activity.

This scheme, putting the recycling burden to the consumers, is not effective in developing countries where the willingness of the consumers are lower and geographical logistic is not sufficient (Cao et al., 2016).

Based on such analysis, the current financial scheme to support the proposed informal-formal partnership seemed to be practical only with modifications. This research recommended budget collected by the national body is used for informal sectors' compensation to join formal recycling value chains. There are three mechanisms; the first is financial incentive-based, where the government buys the waste from informal sectors based on local market conditions. In contrast, the following mechanism is done by the manufacturers, where they offer frequent and long-term buying. The manufactures set a minimum purchased price to protect the possible financial loss of the informal collectors.

The first option is most likely applicable to the existing financial mechanism in WEEE Draft Act. Since the local market condition is dynamic, the informal sectors can also be protected by setting monthly payments (Hinchlife et al., 2020). The subsidies will improve their trust, living wage, and working conditions to prevent the waste from going to illegal disposal.

The local administrative organizations have the authority and budget to establish a local collection center. By integrating into the suggestion, the local budget can fill the price gap to give incentive to interface agencies that engage with local informal waste collectors. These informal waste collectors will collect household SFL as well (Manomaivibool & Vassanadumrongdee, 2011; Pollution Control Department, 2020). Ensuring the financial distribution to the local level would increase waste collection.

Concern appeared from the decreasing production of FLs that might cause the producers and investors to hold more subsidies for increasing the collection and filling the price gaps. This challenge could be addressed by creating a microfinance mechanism and diversifying the activities to create revenues, e.g., offering waste management, consulting or recycling services, and improving recycling technology, and utilizing the recovered materials because the largest revenue for recyclers came from material recovery (Henzler et al., 2017).

When there is a higher material flow to formal sectors, investment in the recycling business will increase. More input entered will produce more recycled materials for sales. Stable revenues are significant in attracting investment for the business. It has to be supported with the existence of legal law that regulates financial schemes and controls the material flow (Henzler et al., 2017). The regulation was the most significant since it serves as the guidance for legal promotion and implementation of EPR (Xiong Zheng et al., 2017).

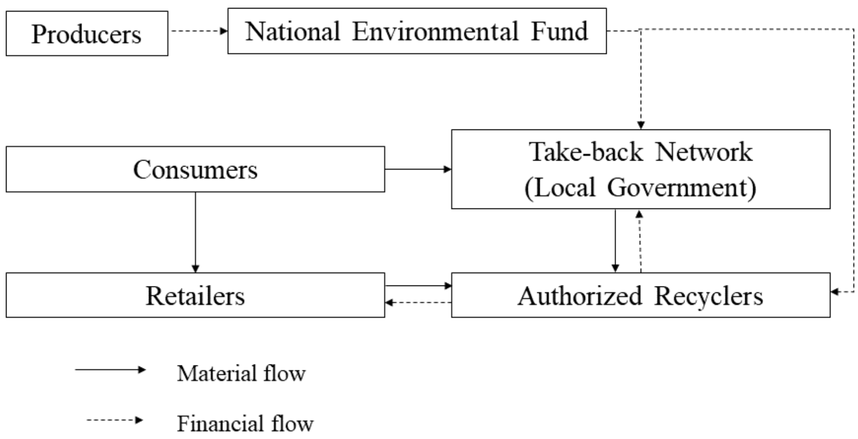

Figure 25 Proposed financial mechanism in Thai WEEE Act
Source: (Manomaivibool, 2018)

Selling recycling products is another source of income for the formal business to increase their revenue to overcome the reduced budget from the decreasing production of FL. Ideally, those products could be aluminum/other metals (Pb, Ar, and Kr) that compromised 18-30% of the total weights and mix of plastic and metals that is for 20%. These parts are from the light end caps that can be reused for the new light production. The highest percentage (45-80%) came from the glass tubes that are reused for new manufacturing. However, a common practice in Thailand only reuses the glass tube scrap for new manufacturing (Apisitpuvakul, 2007).

Increasing recovery technology and practice to generate more products to sell are potentially applicable under this partnership. The informal aggregator is the center of the informal E-waste ecosystem, which directly sells recycled materials to dismantlers, exporters, and refurbishers. By formalizing, the aggregators will support this proposed financial solution by optimizing their experience and usual business network (Hinchlife et al., 2020). Another point is that aggregating larger waste quantities will increase the bargaining power toward the buyers in the market. Moreover, governments should ensure resources (i.e., funding and human resources) allocation is in place and enforced (Henzler et al., 2017). Additionally, financial support must also be supported with other non-material incentives that suit all involved actors' diverse socio-economic conditions, such as education and capacity building training, knowledge transfer between all involved stakeholders to ensure project adaptability (Hande, 2019; Henzler et al., 2017; Johnso; & Trang, 2019).

4.5.4 Coordinated institutional arrangements

Previously, the business representative stated that the fragmented coordination in the government affecting their efficient performance. Gunarathne et al. (2020) found that fragmented governance responsibility in handling E-waste was one of the management barriers in developing countries, including Thailand (Chanathip Pharino, 2017). In Thailand, NEB is responsible to oversee environmental quality. While SFL recycling requires coordination with the energy sector as well.

Besides, Henzler et al. (2017) mentioned the structured partnership between formal and informal in E-waste management require coordinative governance. Such governance will assist in the financial flow and facilitate knowledge transfer between the stakeholders. Governance also became one of the key factors to implement effective regulation and enforcement and provide capacity building (Appendix D, Question Part 2, no.4, 6, and 7).

Improving the performance of SFL recycling requires more comprehensive coordination between governmental bodies because the SFL recycling process's environmental impacts intersect with health, safety, and energy areas. Coordinative governance requires much willingness due to conflict of interest. CatalySD framework provides a guideline to create high-quality stakeholder engagement and communication (Hemmati; & Rogers, 2015).

This framework identified four dimensions for collaborative engagement and communication: individuals, relationships, institutions, and culture. It suggests: 1) Governance strategy should include multi-level and multi-dimensional in the reflection and communication to result in a fruitful interaction between policymakers and practitioners, 2) Policymakers, private, public, local communities shall share the success story, failure, and interest to prevent further mistakes. In this open and mutual learning process, the discussion may likely encourage institutional change that is a challenge in Thailand. Such multidisciplinary governance is critical to pursue human and environmental protection in increasing the recycling rate (UNDP, 2017).

A success story of implementing the above principles was when Thailand took part in OECD Urban Green Growth in Dynamic Asia and Thailand. The multisectoral discussion highlighted essential key points in developing sustainable urban resilience in financial and institutional mechanisms, economic, social policies, and building capacities, which meet local conditions and community. If the same principles were applied for the SFL recycling mechanism, it would result in an inclusive policy made by governments, the local community, and stakeholders in the business at the local and national levels.

Currently, a unique national sub-committee under NEB functioned to coordinate and track the WEEE Strategy's progress and was overseen by the Ministry of Interior to implement up to the local level. However, site-level implementation often underestimates local civic organizations' role in accommodating informal sectors within a region. While they understand the local condition that smoothens the interaction between government staff and informal sectors and delivers the capacity building. Informal sectors work individually and see themselves as entrepreneurs and may show disagreement under the government's strict hierarchy.

4.6 Data Confirmations and Potential for Future Studies

The term sustainability considers multidimensions such as ecological, political-institutional/social, and economic as a whole (Ruggerio, 2021). The social dimension in the Master Plan goal for industrial waste management was overlooked. To propose sustainable E-waste management, other dimensions such as technical and cultural have to include according to the sustainable E-waste management framework (Marshall & Farahbakhsh, 2013). This research has a limited scope of social analysis and others to support sustainable SFL recycling. Therefore, future research has an opportunity to explore these aspects to include in this topic. Multi-disciplinary analysis such in the framework had advantages to disseminate recommendations to policymakers (Gunarathne et al., 2020).

This study provided a multi-criteria evaluation of SFL recycling practices in Thailand from the environmental and social impact analysis, which is limited in the literature. The latest research in Thailand on the formal SFL recyclers was found in 2016, which this study provided an updated perspective of the practice. Moreover, it laid out information on the challenges experienced by the formal business directly. Despite the gaps, this study could become initial research and future potential studies.

Potential areas for future research in detail were described per section. In the ELCA, data of mercury concentration in the lamp scrap and indoor mercury emission in the recycling plant were not based on actual data in 2019. Hence, the estimation of environmental impacts required confirmation and comparison with other national and international studies. The input data for mercury concentration emission was only collected from the laboratory result of the lamp scraps in a month in 2019, and data for indoor mercury concentration was unavailable.

The mercury contained in the indoor ambient air ranges according to the Bulb Eater operation. Mercury release from a total of 185 air samples showed 35.1% of samples contained mercury concentration below the safe limit ACGIH TLV (0.025 mg/m^3) and OSHA PEL (0.1 mg/m^3), 45.4% were equal to above TLV and below PEL, and 19.5% greater than or equal to PEL value (US EPA, 2016). Meanwhile, in a study in Thailand, the mercury emission was in the number of 4.38E-08 kg/SFL with wet absorption technology (Apisitpuvakul, 2007). Wet absorption technology applied water, cement, and sodium sulfide as absorbing, stabilizing, and solidifying agents and had lower mercury recovery than Bulb Eater (91.40%).

Besides releasing mercury, Zimmermann et al. (2014) with a similar lamp crusher found that SFL recycling also released dust containing barium (0.2 – 109.9 µg/m^3), yttrium (0.1–1010.2 µg/m^3), and lead (0.1–85.6 µg/m^3) below and above the France national safety standards for barium OELs France 500 µg/m3, yttrium 1000 µg/m^3, and lead 50 µg/m^3.

According to the above emissions data, it was recommended to include emissions information in the SimaPro input data, such as mercury concentration in the lamp scrap for the possible land contamination and mercury, barium, yttrium, and lead concentration in the air samples with the range value as above mentioned. Moreover, in the emission section, incineration should be excluded

The incineration process because is inapplicable and considered hazardous. The plant transported the waste to Japan in the case of incineration. Incineration to this type of waste caused deposition in the fly and bottom ash, polluting the environment significantly and triggering health risks. (Muenhor et al., 2009). However, Japan applied bag filters and activated carbon adsorption in the incinerators to reduce dioxin emissions and increase mercury removal up to 97% from 22%. Mercury and mercury compound has been a top priority pollutant under the Air Pollution Control Law (Asaria, Fukuib, & Shin-ichiSakaia, 2008).

In addition, future research should add components in the FL in the input inventory of SimaPro. FL consists of other elements such as glass (0.192 kg), aluminum (0.021 kg), copper (0.00028 kg), phosphor (0.00032 kg), filament (0.000028 kg), zinc (0.00000425 kg), mercury (0.00000425 kg), argon (0.00000118 kg), krypton (0.00000472 kg), steel (0.851 kg), nylon (0.0015 kg), polyester (0.001 kg), and paper (0.001 kg), that showed significant impacts to the analysis (Thavornvong, 2016).

ReCiPe impact analysis showed that the recycling process resulted in glass and aluminum contributed to health impacts with the score 0.0036 Pt and -0.214 Pt, while steel 0.000331 Pt. Moreover, these elements gave a score to ecosystem quality as 0.000572 Pt, -0.00327 Pt, and 0.00169 Pt respectively, and resource depletion as 0.00393 Pt, -0.0622 Pt, and-0.000302 Pt. The negative sign illustrated that the impacts had been avoided (Thavornvong, 2016).

The above alternatives for SimaPro input were considered to assist in building this research results to be more accurate. However, the pandemic situation altered the closure of buildings and access to SimaPro software to prove the recommendations. Therefore, future research should consider alternatives.

The next point for future research is social analysis. SIA required extensive judgment and confirmation from experts or studied stakeholders to confirm the reliability and credibility of the results before being disseminated. Expert's judgment from multi sectors and disciplines could be obtained from a governmental body such as DIW on the low material supply facing by formal recyclers over the years, the amount of SFL generated, and contributions of formal recyclers to the national economy, and other aspects.

Moreover, the PCD statements on the occurrences of improper disposal over the years, possible health complaints from SFL recycling, and current SFL management at the local level. In addition, the government's support and challenges to improve the formal business will be conducted. After the results and challenges identified in the study were confirmed, a discussion of the proposed solutions will take place. Such confirmation is significant since the SIA process is complex integrating a variety of values of interests. The complex analysis makes hardly a complete and accurate assessment. Besides relying on experts' judgment, the results should have documentations along the process to help the information dissemination.

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CHAPTER V

CONCLUSION

SFL as one of the intensive lighting sources in Thailand is classified as hazardous waste by the national industrial regulation, particularly when it is generated by the industrial sector. One of the reasons is the light contains mercury for lighting purposes. The management of the end-of-light requires special treatment before disposal. Recycling is most preferred to conduct for waste treatment. Due to the potential hazards of the waste, the government was serious to increase the treatment rate (100%) including recycling as mentioned in the Master Plan on Solid Waste Management (2016-2021).

However, the target achievement measures were only based on the environmental benefit settings such as a higher collection facility, awareness-raising, separation, storage, transportation, recycling, and treatment/disposal without tracing the stakeholders' social challenges. These overlooked social hurdles might encounter the environmental and social benefits of the recycling process. Formal recycler is the key player in industrial SFL management. If their concerns and challenges were not considered, the target unlikely would be achieved.

It is vital to evaluate the barriers when the policymakers want to increase the recycling rate. Therefore, an evaluation of the challenges experienced by the formal stakeholder was carried out to complement the analysis of the environmental and social impact to highlight the importance of the recycling process, and identify the enabling factors. To answer such research objectives, three research stages were taken place.

The first stage was the SFL generation estimation using the supply method model. The second was the assessment of the environmental and social impacts using a life cycle approach. The results from the previous stage were to formulate the enabling factors. The assessment was following the framework of Integrated E-waste management by Marshall and Farahbakhsh (2013). It explained that multiple aspects, layers, and stakeholders shall be considered in E-waste management.

FL waste was primarily generated by industries and treated by a formal SFL recycling business. The waste, SFL, has remained a concern because it was estimated that 17,371,960 pieces of SFL would be generated in 2025, and the production would diminish in 2030. Although the production number has been decreasing, the country has to deal with waste. The information helped monitor the material flow especially when the domestic 90% of E-waste entered the informal recyclers. This stage highlighted the importance of a collection system and how the collaboration between the formal and informal recyclers helps track the waste flow and boost the entry of material to the formal recyclers.

The environmental impact of proper recycling of SFL through LCA SimaPro 8 and ReCiPe and IMPACT 2002+ impact assessment showed that the recycling activity contributed to the overall impact categories. The results of ReCiPe showed that the current recycling activity contributed the most to human health risk (14.96 µPt), followed by ecosystem damage (0.74 µPt) and resource depletion (0.0086 µPt). The ReCiPe results were consistent with IMPACT 2002+ results showing human health was the most affected in a 38.47 nPt impact score, followed by resource depletion (21.80 nPt), ecosystem quality (17.91 nPt), and climate change (17.36 nPt).

The most contributing material to the impacts was electricity consumption. A higher recycling rate would be beneficial to the protection of human health and the ecosystem through the reduction of electricity consumption. Based on midpoint assessment electricity consumption altered human health through different pathway mechanisms such as the effects of global warming, ozone depletion, ionizing radiation, a human carcinogen, and non-carcinogen, and fine particulate of fossil-fuels based energy. However, the source of electricity influenced the impacts. A transition from coal-based energy to more renewable is important to identify.

Another concern points in the operation were the design of the Bulb Eater and ventilation system in the recycling plant influencing the safety of mercury exposure. Mercury emission was not presentable due to data unavailability. Meanwhile, mercury might deposit in the environmental matrix and cause a health risk. There was no actual and robust evidence to show the impacts. Potential health impacts only referred to literature studies—such limitation disadvantaged decision making. Increasing the recycling rate should be equipped with modification of Bulb Eater.

The business representative did not report Bulb Eater as an issue since it has a high degree of mercury recovery efficiency. However, it is difficult to maintain mercury exposure from the device below OSHA safety level. Improper ventilation and less stringent recycling procedures increased the exposure of mercury to the environment and the workers.

SIA is present to complement and provide an in-depth assessment from ELCA. The recycling process positively contributed to decent working conditions for the workers through fair salary and local employment (Score 4 for local employment and fair salary impact category). In contrast, workers and local community health and safety were at risk of chronic mercury exposure (Score 3 in worker and local people's health and safety). In addition, the business quoted the other challenges in SFL management were government support, unclear legal mechanism of E-waste management, and low material supply.

Based on the above descriptions, it was evident that E-waste management including SFL was multi-facets, multilayers, and involved various stakeholders as in the integrated E-waste management framework. Four enabling conditions to address the stakeholder's challenges in performing effectively and sustainably to reduce the environmental damage along with the goal of increased recycling rate were:

1. Monitoring and modification of recycling technology contributed to the improvement of protection against mercury exposure. Bulb Eater should be modified with a leakage monitoring device and sulfide agents to reduce mercury release from the crushing drum. This hall is supported with adequate PPE use, residue, and health monitoring.
2. EPR concept as the preferred mechanism to manage E-waste in the postponed draft bill should be able to accommodate informal-formal partnership and integrate informal into formal recycling value chains to

enhance and sustain material supply to the formal business and generate revenues to both sides.

3. Attractive financial flow helps integration of informal sectors to the chains and improve waste collection to tackle low material supply.
4. Good governance at the national and local level provides practical implementation, capacity building, and multi collaboration, especially in shifting the energy source. Partnership with local civic organizations was required to accommodate and facilitate the communication between the government and stakeholders at the local level.

The study provided an overview of alternative areas to address in increasing recycling rate, particularly in SFL based on environmental and social impact assessment. The exploration of the environmental and social impacts was not fully representative due to the COVID-19 situation. The situation altered the access to the SimaPro software and interaction with the study participants. The interview was only carried out to the business representatives.

A future study that could explore and confirm the impacts on the workers and local community in this study and the alternative input data for the ELCA. Health risk assessment could be the critical confirmation tool to raise mercury deposition awareness from the recycling process.

Appendix A

Inventory Data of the Studied Recycling Plant in 2019

Month	Waste name	Quantitiy (Kg)	Quantity (Tube)	Process	Disposal Location				Calculation factor	Number	Unit
					Landfill (Kg)	Other disposal (Kg)	Filter (?)	Package	Electrcity input characteristics	220	VAC
Jan	Lamp	3,730	6,000	Bulb eater			3.5			4.25	A
Feb	Lamp	6,164	13,800	Bulb eater	9,002		9			50	Hz
March	Lamp	5,549	7,200	Bulb eater			4.97		Power= I * V	935	Watt
Apr	Lamp	2,821	18,600	Bulb eater	8,520		17.49		1 unit	1000	Watt
May	Lamp	4,581	7,200	Bulb eater	6,629	4,280	3.55		1 Watt	0.935	unit
Jun	Lamp	4,893	7,200	Bulb eater			3.90		1 hour running of bulb eater needs	935	Watt
Jul	Lamp	3,811	12,000	Bulb eater			7.42		1 hour processes	938	Tubes
Aug	Lamp	4,724	12,000	Bulb eater			10.41		935 Watt	938	Tubes
Sep	Lamp	3,670	12,000	Bulb eater		5,030	17				
Oct	Lamp	2,906	6,000	Bulb eater			6.06		1 tube	0.216	kg
Nov	Lamp	3,905	12,000	Bulb eater			12.49		0.996801706		Watt/tube
Dec	Lamp	4,187	6,000	Bulb eater			3.47	6,383	4.62962963		Tube/kg
Total		**50,941**	**120,000**		**24,151**	**9,310**	**98.83**	**6,383**	4.614822712		Watt/kg
Average		**4,245**	**10,000**		**8,050**	**4,655**	**8.2358**	**6,383**	0.004614823		KWH/kg

Cost from 1 day or 6,000 tuber 5 drums				
Filter cost	**Unit**	**Price B**	**Price (USD)**	**Baht**
1st filter	10	31.56	3.5	1104.6
2nd filter	0	31.56	160	0
Spinner	1	31.56	64	2019.84
Drum	5	400		2000
Human cost	1	441		441
Forklift cost	1	1000	33.33	1000
Electrict cost	6.3	3.57		21.03
Total				6586.47
SG&A 20%				1317.294
G. total				7903.764

Cost from 2 days or 12,000 tuber 10 drums				
Filter cost	**Unit**	**Price B**	**Price (USD)**	**Baht**
1st filter	10	31.56	3.5	1104.6
2nd filter	1	31.56	160	5049.6
Spinner	2	31.56	64	4039.68
Drum	10	400		4000
Human cost	2	441		882
Forklift cost	2	1000	33.33	2000
Electrict cost	13	3.57		43.39
Total				17119.27
SG&A 20%				3423.854
G. total				20543.124

Operational cost about 1.71 baht per tube	
Disposal fee/tuber (120,000 tube x 1.71 Baht)	205,200
Disposal fee/ton (Landfill + other disposal)	106,106
Transport fee/trip	21,200
Total disposal cost	332,506

Volume of a drum
400 tube per drum
230-250 kg/drum (After process)
1,200 tube/drum (can dispose)
Spinner 1 unit per 5 drums

Figure A1 Inventory data analysis from the studied recycling plant in 2019

Appendix B

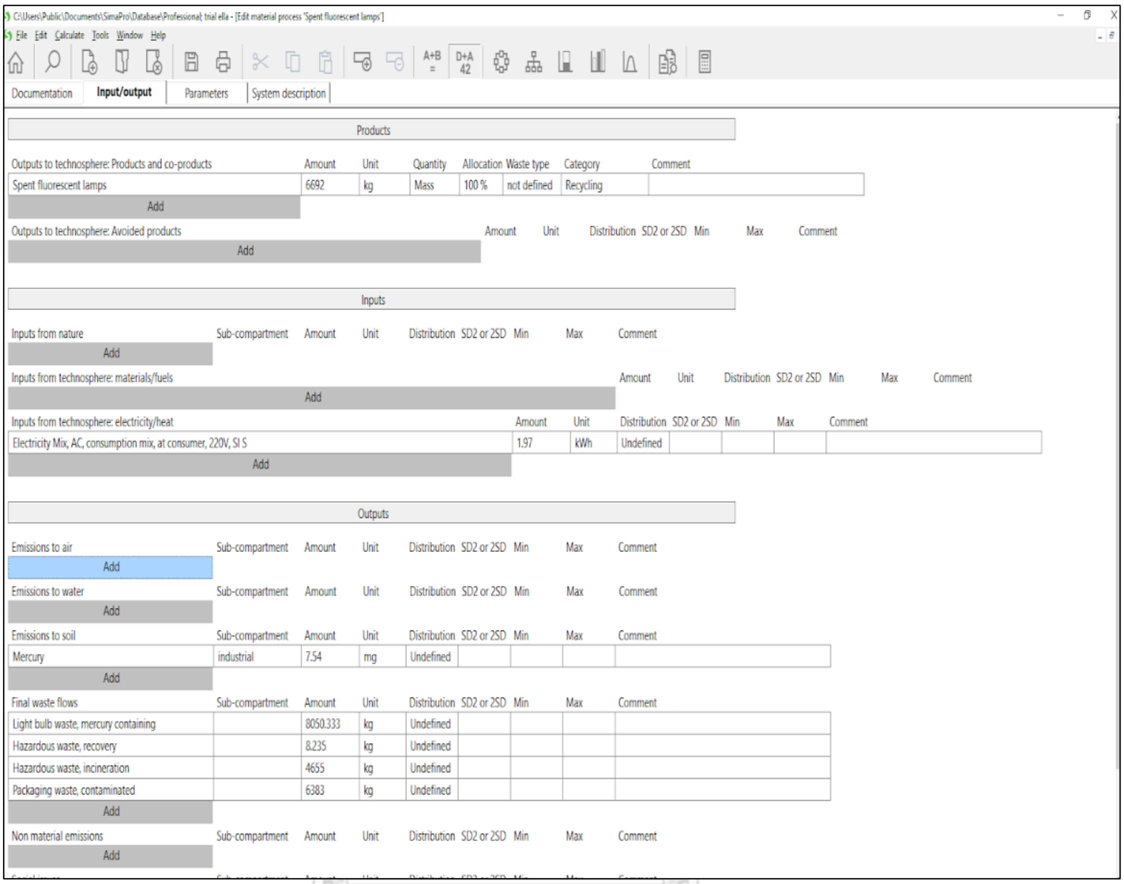

Figure B1 Inputs details to SimaPro 8 based on inventory data of the studied recycling plant

Appendix C

Life Cycle Assessment Results

Table C1 Impact values based on ReCiPe endpoint damage assessment score

Damage category	Unit	Total	Spent fluorescent lamps	Electricity Mix, AC, consumption mix, at consumer, 220V, SI S
Human health	DALY	0.0000000008886716509	0	0.0000000008885420783
Ecosystems	species.yr	0	0	0
Resources	USD2013	0.000001206484993	0	0.000001206484993

Table C2 Impact values based on ReCiPe endpoint normalization score

Damage category	Total	Spent fluorescent lamps	Electricity Mix, AC, consumption mix, at consumer, 220V, SI S
Human health	0.0000000374130765	0	0.0000000374076215
Ecosystems	0.000000001841437189	0	0.000000001841436849
Resources	0	0	0

Table C3 Impact values based on ReciPe endpoint single score

Damage category	Unit	Total	Spent fluorescent lamps	Electricity Mix, AC, consumption mix, at consumer, 220V, SI S
Total	µPt	15.71041978	0.002182138824	15.70823764
Human health	µPt	X114.9652306	0.002182002989	14.9630486
Ecosystems	µPt	0.7365748755	0.0000001358355562	0.7365747396
Resources	µPt	0.008614302847	0	0.008614302847

Table C4 Impact values based on ReCiPe midpoint normalization score

Impact category	Total	Spent fluorescent lamps	Electricity Mix, AC, consumption mix, at consumer, 220V, SI S
Global warming	0.00000002303176281	0	0.00000002303176281
Stratospheric ozone depletion	0.0000000009231776187	0	0.0000000009231776187
Ionizing radiation	0.00000005800602036	0	0.00000005800602036
Ozone formation, Human health	0	0	0
Fine particulate matter formation	0.00000004460012203	0	0.00000004460012203
Ozone formation, Terrestrial ecosystems	0	0	0

Impact category	Total	Spent fluorescent lamps	Electricity Mix, AC, consumption mix, at consumer, 220V, SI S
Terrestrial acidification	0.00000009178529953	0	0.00000009178529953
Freshwater eutrophication	0	0	0
Marine eutrophication	0	0	0
Terrestrial ecotoxicity	0.00000006193240447	0	0.00000006193240447
Freshwater ecotoxicity	0.000000006266399246	0.0000000002626268081	0.000000006003772438
Marine ecotoxicity	0.00000004046336814	0.0000000001757782218	0.00000004028758992
Human carcinogenic toxicity	0.00000001238883079	0.0000000004921618948	0.0000000118966689
Human non-carcinogenic toxicity	0.00000001886547556	0.000000003696977376	0.00000001516849819
Land use	0	0	0
Mineral resource scarcity	0	0	0
Fossil resource scarcity	0.000000005410170172	0	0.000000005410170172
Water consumption	0.00000000154444665	0	0.00000000154444665

Table C5 Impact values based on IMPACT 2002+ single score

Damage category	Unit	Total	Spent fluorescent lamps	Electricity Mix, AC, consumption mix, at consumer, 220V, SI S
Total	nPt	95.54917806	17.73508561	77.81409245
Human health	nPt	38.47164606	0.3999098956	38.07173616
Ecosystem quality	nPt	17.91520701	17.33517571	0.5800312987
Climate change	nPt	17.36240561	0	17.36240561
Resources	nPt	21.79991939	0	21.79991939

Table C6 Impact values based on IMPACT 2002+ normalization score

Damage category	Total	Spent fluorescent lamps	Electricity Mix, AC, consumption mix, at consumer, 220V, SI S
Human health	0.00000003847164606	0.0000000003999098956	0.00000003807173616
Ecosystem quality	0.00000001791520701	0.00000001733517571	0.0000000005800312987
Climate change	0.00000001736240561	0	0.00000001736240561
Resources	0.00000002179991939	0	0.00000002179991939

Table C7 Impact values based on IMPACT 2002+ characterization score

Impact category	Unit	Total	Spent fluorescent lamps	Electricity Mix, AC, consumption mix, at consumer, 220V, SI S
Carcinogens	kg C2H3Cl eq	0.00000004333477091	0	0.00000004333477091
Non-carcinogens	kg C2H3Cl eq	0.000001255830852	0.000001012942998	0.000000242887854
Respiratory inorganics	kg PM2.5 eq	0.0000003828336276	0	0.0000003828336276
Ionizing radiation	Bq C-14 eq	0.005464857526	0	0.005464857526
Ozone layer depletion	kg CFC-11 eq	0	0	0
Respiratory organics	kg C2H4 eq	0.00000001290329177	0	0.00000001290329177
Aquatic ecotoxicity	kg TEG water	0.02487438749	0.01779350534	0.007080882148
Terrestrial ecotoxicity	kg TEG soil	0.03011039967	0.02990833457	0.0002020651011
Terrestrial acid/nutri	kg SO2 eq	0.00000576138365	0	0.00000576138365
Land occupation	m2org.arable	0	0	0
Aquatic acidification	kg SO2 eq	0.00000395457184	0	0.00000395457184
Aquatic eutrophication	kg PO4 P-lim	0.0000000009210697633	0	0.0000000009210697633
Global warming	kg CO2 eq	0.000171905006	0	0.000171905006
Non-renewable energy	MJ primary	0.003313047951	0	0.003313047951
Mineral extraction	MJ surplus	0.000000009706742985	0	0.000000009706742985

Appendix D
Research Questionnaires

No. ....

Research Questionnaire on
Potential Environmental and Social Impacts of
Fluorescent Lamp Recycling Process in Thailand

Explanation:

This questionnaire is subjected to the thesis research of Ms. Ella Nanda Sari, a master's student in the Hazardous Substance and Environmental Management Program, Graduate School of Chulalongkorn University, Bangkok, Thailand.

The purpose of this questionnaire is to collect data related to the research titled "Potential Environmental and Social Impacts of Fluorescent Lamp Recycling Process in Thailand".

The questionnaire consists of 2 sections including:
General information of respondents consists of 4 questions.
Section 1. Assigned to plant management
Section 2. Assigned to business management

All information will be exclusively used for the research purpose and the informant will be anonymous.

To conduct this research, I would kindly request your permission to take note and recording the interview.

Your cooperation in this research is greatly appreciated.
Yours sincerely, Ms. Ella Nanda Sari

Questionnaire for the representative(s) in the recycling plant:

General Information

Explanation: Please mark your response with an 'X' in the blank space.

1. Gender

   (.....) Male (.....) Female

2. Age

   (.....) 18 – 30 years
   (.....) 31 – 40 years
   (.....) 41 – 50 years
   (.....) 51 – 60 years
   (.....) over 61 years

3. The current position in the management ......
4. How many people do you supervise? ....

Questions

1. How many workers are approximately in the recycling process and transportation?
2. How many of them (or percentage) coming from the local community?
3. How many of them are approximately in the management and recycling process?
4. Do you have prerequisites for hiring an employee? Do you prefer to hire a local community? Why?
5. Are there any incentives along with the salary?
6. Do you have overtime compensation? How to regulate it?
7. What kind of personal protective equipment (PPE) do you provide?
8. Do you think the workers use them? If yes, how do you encourage/enforce it?
9. Is there any measure to control and monitor mercury indoor and outdoor emissions? If yes, how do you monitor it?
10. Do workers or people living nearby have a concern about mercury emission?
11. Do you have a third party to monitor the mercury emission? What are the benefits (e.g., finance)?
12. Who are your major customers (e.g., food industry, electronic industry, etc.)?
13. What options do customers choose after the waste is recycled?
14. Do you have any resources information I have not asked that can help me? Or suggestions from other resources?

Questionnaire for the representative(s) in the business management:

General Information

Explanation: Please mark your response with an 'X' in the blank space.

1. Gender

   (.....) Male (.....) Female

2. Age

   (.....) 18 – 30 years
   (.....) 31 – 40 years
   (.....) 41 – 50 years
   (.....) 51 – 60 years
   (.....) over 61 years

3. The current position in the management......
4. How many people do you supervise? ....

Questions for business management

1. What do you think about the formal E-waste recycling business in Thailand (e.g. the potential and challenges)?
2. How do you see the role of formal E-waste recycling in E-waste management?
3. How do policy instruments (e.g., 3R concept in Master Plan on Solid Waste Management 2016-2021) support formal recycling? Could you give an example?
4. What could facilitate the private sector to the improvement of the recycling rate?
5. How do you see the concept of Extended Producer Responsibility in Thailand as beneficial to formal E-waste recycling?
6. What would be the enabling factors for EPR to engage the private sector?
7. What would be the private sector's concern?
8. Do you have any resources information I have not asked that can help me? Or suggestions from other resources?

Appendix E

Scoring system to the questionnaire answers

Table E1 Scoring of given answers by the recycling representative to the questionnaires

Stakeholder categories	Indicators	Measurement	Score		References	Question part & number	Details scoring
The local community	Safe and healthy living condition	Health and safety effects caused by the recycling plant	1	There are no initiatives to protect the community and cause health issues among the people.	(Padilla-Rivera, Morgan-Sagastume, Noyola, & Güereca, 2016) with modifications	Pt. 1, no. 9-11.	
			2	Complains from the community that does not cause severe health impacts like odors			
			3	Meet the requirement to guarantee the safe living environment surrounding the plant and no complaints from the			It is unclear if there has been any concern from people living nearby related to the recycling activities

Stakeholder categories	Indicators	Measurement	Score		References	Question part & number	Details scoring
				people			
			4	There are health emergency initiatives from the plant for the community			
	Local (provincial) employment and contribution to the local economy	People hired from the local community at significant locations in the plant	1	There are no local people as workers	(Padilla-Rivera et al., 2016) with modifications	Pt. 1, no. 1-4.	
			2	Few local people employed			
			3	Number of local people employed but there is no promoting initiative to engage locals			
			4	There are initiatives to engage local workers			30-40% out of 120 people in the recycling and transportation process and preference to engaging local community and 25 of them present

Stakeholder categories	Indicators	Measurement	Score		References	Question part & number	Details scoring
							in the management team
Workers	Fair salary	Staff salary	1	No wage	(MSNA Group, 2016)	Pt. 1, no. 5	
			2	Below the minimum wage			
			3	Reach the minimum wage 325 THB/day for 8 hours working time and 48 hours in a week			
			4	More than the minimum wage with other social benefits			Yes, there is another incentive along with the basic salary
	Working hours	The average number of working hours a week	1	More than 48 hours and more than additional 36 hours a week without compensation	(MSNA Group, 2016)	Pt. 1, no. 6	
			2	More than 48 hours but less than additional 36 hours a week			

Stakeholder categories	Indicators	Measurement	Score		References	Question part & number	Details scoring
				with compensation higher than 1.5 to 3 times of normal average hourly wage rate			
			3	Maximum 48 hours a week with compensation			Every department has set working hours, assuming that the company follows the national guideline and provide compensation
			4	Less than 48 hours a week with compensation			
	Health & safety	The concentration of mercury in indoor air and enforcement to use personal protective equipment (PPE)	1	More than OSHA PEL limit, no PPE enforcement + amount of work injuries/year	(Erica Wilson & Meiman, 2018) (United States Department of Labor, 2012b)	Pt. 1, no. 7-9	
			2	More than OSHA PEL limit + PPE			Need a detailed answer as

Stakeholder categories	Indicators	Measurement	Score		References	Question part & number	Details scoring
				enforcement + several work injuries/year			they mentioned there are mercury monitoring installment and a third party who monitor it every year but unclear if it applies to indoor and outdoor monitoring and what standard they follow, but the staff has regular health check-up every year, but it is also not detailed if it includes mercury concentration in the body
			3	OSHA PEL limit 0.1 mg/m3 air for an 8 hour/day			

Stakeholder categories	Indicators	Measurement	Score		References	Question part & number	Details scoring
				workday + PPE enforcement + very few work injuries/year			
			4	Less than OSHA PEL limit + regular monitoring + PPE enforcement + no work injuries/year			
	Management performance monitoring program	The presence of programs undertaken by institutions to improve	1	Lack of proper actions aimed at monitoring the plant management operation by authorities. Standards are not in compliance with the government's standards	(Padilla-Rivera et al., 2016)	Pt. 1, no. 9-10	
			2	Do not comply with the government standards and			

Stakeholder categories	Indicators	Measurement	Score		References	Question part & number	Details scoring
				actions/plans to achieve the standards			
			3	Comply with the government standards			Yes, there is a monitoring inspection for mercury emission even though it is not clear, but the benefit from this monitoring is staff in the plant become supervised and trained to maintain the compliance
			4	Comply with the government standards and plans of improvement			

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