University of Southern Queensland

Faculty of Health, Engineering and Sciences

Re-purposing LED Light bulbs

A dissertation submitted by

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Abstract

Lightbulbs have experienced a natural evolution over recent years, with LED bulbs becoming the primary bulb in use, partly due to obsolescence of incandescent bulb technology, as well as bans such as that introduced by the EU in 2009 of incandescent bulbs due to their inefficiency and decreased life span compared to new LED bulbs. Despite LED bulbs being the primary lighting option around the world, there is currently a lack of sufficient infrastructure supporting the recycling of these bulbs in Australia. It is estimated that 48.5M tonnes of e-waste is generated each year globally, contributed to by the disposal of LED bulbs reaching the end of their life, and only 20% of such e-waste is recycled in some form. Where e-waste is not responsibly managed and disposed of, contamination of soil and waterways by heavy metals and other toxic substances is possible. Additionally, disposal of LED bulbs to landfill is irresponsible management of scarce finite resources such as rare earth elements (REE), which can be recycled and repurposed, reducing reliance on and impact of mining virgin ore.

This research therefore seeks to evaluate current LED light bulb recycling practices and schemes, including in the private sector and local government, as well as processing technologies used in the recycling of e-waste that may be adopted in the recycling of LED bulbs. Additionally, current LED bulb design and manufacture processes are investigated to identify any constraints that may inhibit the recycling process and recommend improvements in their design to facilitate a circular life cycle and economy.

Through investigation of the design and assembly of LED bulbs, it was identified that some factors may hamper the recycling process, including an all-in-one, sealed, glued style of bulb assembly, which may restrict the ability to automate disassembly. Additionally, as the designs are not standardised, a range of disassembly techniques may be required to dismantle various types of bulb housing. Improvements to LED bulb design were therefore recommended to facilitate the end of life recycling process, including a modular design such as snap on clip style housing or threaded screw on design such as those used in other products including LED torches.

Material processing technologies currently being utilised in e-waste recycling streams were investigated to identify their suitability to LED bulb recycling. E-waste recycling processes for products such as mobile phones and fluorescent lighting were also investigated to provide a better understanding of how other e-waste products are currently being recycled, and what recycling approach can be applied and adopted for the LED light bulbs recycling. Hydrometallurgical and pyrometallurgical processing methods were both assessed, with pyrometallurgical processing selected as the preferred technology due to its ability to be expanded to large scale operations, the ability to extract a wider range of metals,

and the existing infrastructure currently established which can be expanded to include provision for waste LED bulbs.

Review of existing legislation and policy in Australia identified that current product stewardship schemes and various other legislation do not currently provide provision for the recycling of LED bulbs. Furthermore, LED bulbs are classed as general domestic waste and are permitted to be disposed of to landfill despite containing heavy metals and other potentially hazardous materials. While the Product Stewardship Act includes provision for e-waste, the legislation is lacking in making provision for a range of products, including LED bulbs. Three types of product stewardship schemes were developed based on the principals of the Product Stewardship Act and existing schemes for other products, with a Consumer Product Refund Scheme ultimately being proposed as the best outcome for recycling of LED bulbs due to the incentivising of recycling through cash refunds. Evidence of success in existing schemes of similar nature demonstrates the opportunity for improved recycling of other products, including e-waste such as LED bulbs.

The framework set out for development of a product stewardship scheme requires engagement of various stakeholders including government, industry, and the community, to seek feedback on scheme design prior to implementation of pilot schemes. While outside the scope of this research, this would be the next step in development and implementation of a product stewardship scheme for the recycling of LED light bulbs.

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Date:14/10/2020

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Table of Contents

List of Figures

List of Tables

Nomenclature

AC	-	Alternating current
DC	-	Direct current
LED	-	Light emitting diodes
SMD	-	Surface mount devices
US	-	United States of America
EU	-	European union
REE	-	Rare Earth element
IC	-	Integrated circuitry
EPA	-	United States Environmental Protection Agency
PPE	-	Personnel protective equipment
RCD	-	Residual current devices.
G12	-	Goal 12
WEEE	-	Waste Electrical and electronic products
CFL	-	Compact Florescent Light
NSW	-	New South Wales
VIC	-	Victoria
QLD	-	Queensland
UN	-	United Nations
PCB	-	Printed Circuit Board

Chapter 1. Introduction

1.1 Project Background

Popularity of LED bulbs has increased in the developed world over recent years and a surge in uptake of LED technology was especially evident between 2010 – 2019 (Australian Government 2011). Increased usage of LED bulbs in many parts of the developed world can be partially attributed to changes in legislation which banned the use of incandescent bulbs (Frondel & Lohmann 2011). Other factors contributing to the increased use of LED bulbs include improved energy efficiency, advancement in and automation of technology manufacturing applications, affordability and cost effectiveness due to their long life compared to other traditional bulb types (Frondel & Lohmann 2011). While the lifespan of and LED bulb can vary from 30,000 to 50,000 hours (De Almeida et al. 2014), the typical lifespan of an average LED bulb is approximately 30,000 hours, which corresponds to roughly 15 years of use in a household environment. Due to the increased use of LED bulbs over the past ten to twenty years, an increasing quantity of LED bulbs are now reaching the end of their life.

As new LED bulbs are designed to allow retrofitting of older legacy light fittings, demand for bulbs with poor energy efficiency, including fluorescent, halogen and incandescent light bulbs, is decreasing significantly. LED bulbs are increasingly becoming the preferred globe in a wide range of applications, leading to the phasing out of obsolete bulb technology and an increased demand for LED light bulbs. According to studies conducted by the US Strategies Unlimited (Smallwood 2016), it is estimated that the demand for LED light bulbs will increase at an annual growth rate of 4.5% (Fang et al. 2018).

Many parts of the world, including India, China, South Africa, the European Union and the United States of America are in the process of developing legislation that encourages the use of LED light bulbs and phasing out of old light bulbs such as incandescent light bulbs (Fang et al. 2018). As the use of LED bulbs continues to increase, the end of life disposal of such bulbs is also expected to increase. It is therefore important to consider what happens to LED light bulbs that have reached the end of their life, whether they are being recycled and if so, which recycling measures are being implemented. Where recycling initiatives are implemented, it is similarly important to consider whether these are sufficient to contribute to a sustainable production model.

In Australia, there are currently a range of recycling initiatives in place for electronic waste, also known as e-waste, however, these predominantly target small household appliances such as computers, televisions, toasters, pedestal fans, electronic tools, phones and other electronic devices such as some children’s toys (Queensland Government 2019). Such initiatives vary in scope between councils, however one thing common to these initiatives is that they do not facilitate the repurposing or recycling of LED light bulbs (Queensland Government 2019).

While legislation in several Australian states currently allows provision for the recycling of many electronic goods, there is no specific state legislation pertaining to recycling of LED light bulbs (Australian Government 2020). The LED light bulb can be classified as municipal solid waste and is therefore commonly disposed of in general waste and ultimately goes to landfill (Queensland Government 2019). Inclusion in the general waste category indicates that LED light bulbs are considered low risk waste such as that would commonly be found in household waste from domestic premises (Queensland Government 2019).

While legislation, policy and product stewardship schemes currently exist for some forms of e-waste, including mobile phones, televisions, computers, and compact fluorescent lamps, there is currently no legislation or product stewardship schemes for LED bulbs in Australia. There is potential for existing legislation and product stewardship schemes to be expanded to include provisions for the repurposing of LED lightbulbs.

This research therefore seeks to examine the viability of recycling LED bulbs and the implementation of product stewardship schemes and legislation specific to repurposing of LED bulbs, through the evaluation of existing waste processing practices and legislation, bulb disassembly techniques, and metallurgical processing of rare-earth metals. Further investigations will also be conducted in relation to current state and federal legislation surrounding e-waste recycling in Australia, together with legislation currently in use in other countries that may be applicable to the recycling of LED light bulbs. Where appropriate, recommendations will be made to inform legislation and implementation of recycling methods to facilitate the sustainability of LED bulb manufacture and end of life disposal.

1.2 Research Aim and Objectives

The aim of this dissertation is to review the end of life of the LED light bulbs and to identify opportunities to repurpose waste from LED light bulbs. The benefit of the proposed solution will result in reduced quantity of LED light bulbs to landfill and environmentally more sustainable outcomes as stated in the project specification (Appendix A – Project Specification).

The above aim will be achieved through an investigation and analysis of the following;

1. The current legislations in both Australia and overseas regarding recycling and repurposing of LED light bulbs and other forms of e-waste,

2. Current repurposing methods being applied in Australia and overseas in terms of the recycling of LED light bulbs and its components including chemical processing of materials,
3. Constraint and parameters during disassembly and abstraction processing for recycling and repurposing of LED light bulbs and e-waste,
4. Sustainability of current recycling methods.

Further to the above objectives, recommendations will be made on potential improvements of the current practices and legislation surrounding recycling and repurposing of LED light bulbs.

1.3 Project Scope, Constraints and Limitations

As undergraduate research, the full scope of this project is limited to investigations and analysis related directly to the recycling of LED bulbs. Despite there being many manufacturers, manufacturing techniques and variation in products currently available on the market, the physical investigation and disassembly of bulbs will be limited to a range of three LED light bulbs commonly found at local Australian retailers. It is not possible to perform and investigate many disassembling process techniques that may provide the best disassembling outcome in the time provided, therefore a basic approach has been adopted where possible. Similarly, due to limited available budget, it is not possible to purchase many of the variations of LED light bulbs currently available from all the manufactures of the LED light bulbs that exist on the consumer market.

Due to lack of specialist tools and equipment, basic manual handling, manual disassembly methods and basic hand tools will be utilised for disassembly and investigative purposes. Any automated disassembling techniques are outside of the scope of what is being considered for the purpose of this project. Additionally, evaluation of legislation will be limited to policies surrounding e-waste in general in Australia, and policies specifically relating to LED bulbs in the rest of the world, or as time permits. Recommendations will be made pertaining to improvement of recycling practices and legislation.

1.4 Project Implications and Consequences

While recycling of LED bulbs does occur in Australia, the total volume of bulbs that are recycled is approximately 10% of the total number of bulbs that are disposed of each year (Ecocycle 2019). This is largely due to the absence of product stewardship schemes and legislation throughout Australia that would incentivise the recycling of LED bulbs. This has resulted in the disposal of the majority of LED bulbs through general waste, which further contributes to the increasing quantity of e-waste and composite material products that are disposed of in landfill each year. While LED bulbs are considered low risk to the environment in small quantities, larger quantities of waste LED bulbs could be considered regulated hazardous waste. (Fang et al. 2018). This is due to the presence of hazardous materials including heavy metals such as lead, copper, nickel, tin and molybdenum (Tuenge et al. 2013). Despite responsible disposal to landfill, such hazardous waste may result in contamination of soil and groundwater through the production of leachate in landfills, further contributing to pollution (Tuenge et al. 2013). Implementation of recycling practices has the opportunity to limit the quantity of LED bulbs that contribute to e-waste, thus reducing the total volume of e-waste disposed of in landfills throughout Australia.

In addition to the negative environmental impact of e-waste disposed of in landfill as outlined above, the lack of recycling and repurposing of LED bulbs presents another concern. Many resources, particularly rare earth metals, which are used in electronics such as LED bulbs, are becoming increasingly scarce due to the increasing production of electronics globally and REEs being finite in nature (European Commission 2014). Continued mining of global reserves of such metals will eventually result in their depletion if recycling programs are not introduced. Additionally, as global reserves of rare earth metals are depleted, the cost of mining them is expected to increase significantly (Fang et al. 2018).

The above evidence demonstrates that existing practices involving the mining of finite resources and their subsequent disposal in landfill is not sustainable. It is therefore prudent to consider opportunities to repurpose or recycle LED bulbs at the end of their life, to assist in recovery of rare earth metals and to mitigate against the negative environmental impacts caused by their disposal in landfill.

1.5 Research Outline

The following chapters of this dissertation will be organised as follows.

Chapter 2 consists of a review of the background information and relevant literature for this research topic including end of life LED light bulb re-purposing, current legislation and product stewardship schemes in Australia and internationally surrounding LED light bulb recycling, e-waste recycling methods, environmental outcomes and sustainability of electronic production cycles.

Chapter 3 outlines the resources, process design methodology and disassembly procedures for LED bulbs used as part of this research in order to propose optimum solutions for the recycling of LED bulbs and implementation of appropriate legislation and / or product stewardship schemes.

Chapter 4 contains the results of the investigation and experimental component of the research in the context of the Australian recycling industry.

Chapter 5 discusses the application of the results, potential implementation of recycling methods for LED light bulbs in Australia, and the required support from public and / or private sectors in relation to legislation, policy and product stewardship.

Chapter 6 concludes with recommendations and conceptual design alternatives for improvement of current practices pertaining to recycling and repurposing LED light bulbs and development of legislation incentivising LED bulb recycling, improving environmental and sustainability outcomes.

Chapter 2. Literature Review

2.1 Chapter Overview

This chapter reviews the existing literature relevant to the recycling and repurposing of LED light bulbs at the end of their life. The topics of specific interest include current e-waste disposal systems and the challenges surrounding recycling of LED bulbs, the environmental implications of continued disposal of e-waste to landfill, waste and resource recovery policies, including local and international regulations and legislation, together with product stewardship schemes that incentivise the recycling and responsible disposal of various types of e-waste. Additionally, barriers to implementation of recycling practices together with the application of other e-waste recycling methods to LED light bulbs will be investigated. On completion of the review of the existing literature, relevant research gaps will be identified, and the application of the literature to this dissertation will be explained. Opportunities for improvement in current legislation and recycling practices will be identified and developed further.

2.2 Technological Advancement in Lightbulbs

Over recent years, improvement of technology has led to advancement in the design and manufacture of light bulbs. This has resulted in improvements to their energy efficiency, life expectancy and performance. Developments in manufacturing processes have assisted in the mass production of light bulbs, contributing to a significant increase in use, such that light bulbs are now commonplace in every household. Development in design has further resulted in changes to the types of lightbulbs that are available, from the first light bulb invented, the incandescent bulb, to the LED bulbs that are used today. Mass production has similarly contributed to a significant decrease in cost, making light bulbs widely available for a range of uses.

2.2.1 Incandescent bulbs

The incandescent light bulb was invented in 1879 by Thomas A. Edison. In 1880, Joseph Swan created the first commercial incandescent bulb, which used a filament made from a cellulose material, attached to a spring-clip which held the driver and lamp together. This was superseded by Thomas Edison's bamboo filament with a screw based driver, which then became the standard as we know today as the Edison screw light bulb (DiLaura 2008). The modern incandescent light bulb we know today is constructed with an inert gas and filament made of Tungsten, which is enclosed within a vacuum glass tube (Finolex 2018). The incandescent bulb became the standard and due to its affordability, remained in use in homes for many years. Due to their inefficiency, incandescent light bulbs are being phased out in many parts of the world. In 2009 the European union (EU) introduced a new policy which saw the use of incandescent light bulbs prohibited (Frondel & Lohmann 2011).

The incandescent light bulb is still manufactured today and is widely available for purchase from many lighting stores. It is mostly used in Australia for ambient purposes due to its warm light output, although development in LED light bulb manufacture technology has meant that LED bulbs can now offer the same warm light effect as that of the incandescent bulb, with greater efficiency and a longer life span.

One of the drawbacks of the incandescent lamp is that it produces and dissipates a high amount of heat energy during its operation, causing it to be a highly inefficient light source. The average life expectancy of the incandescent light bulb is approximately 1,000 hours, which is very short when compared to other light bulbs currently available on the market such as LED light bulbs, with life expectancies as low as 25,000 hours and up to 56,000 hours in some of the newer LED bulb designs (Scholand & Dillon 2012).

2.2.2 Halogen bulbs

Halogen bulbs were developed by the GE development team in 1952. While working on the development of the bulbs, the team experimented using iodine within the heat lamp (Furfari 2001). Seeing its potential, a chemist was assigned to investigate the iodine lamp and assist with its development. By 1955, further personnel were assigned to work on the project, contributing to the development of an engineering production line that began production of iodine lamps in 1957 (Furfari 2001). By the end of 1957, GE announce the quartz iodine lamp in collaboration with Phillips, who successfully further developed the lamp using Hydrogen Bromine (HBr) which was released in 1966 as the HBR lamp (Furfari 2001). The halogen bulb known as the Tungsten Halogen lamp gained popularity in the market during the 1970s for its long life and increased efficiency, along with the decrease in electricity pricing at that time. With various changes in design, low voltage halogen bulbs were developed, such as the MR-16 bulb, one of the design styles as it is known today which became the preferred bulb by 1980s within the consumer sector (Furfari 2001).

As with incandescent bulbs, one major drawback of halogen lamps is that they produce and dissipate a very high amount of heat energy during their operation. Lamp temperatures can reach over 250°C with extended use (Furfari 2001). This is of concern as it can cause risk of fire and results in high energy usage when assessed with respect to modern day standards. Due to their legacy, Halogen lamps are still in use today throughout the world including in Australia in many old homes and offices. Careful disposal is needed at the end of life of Halogen bulbs to ensure that they do not contribute excessively to the generation of harmful pollution.

2.2.3 Fluorescent bulbs

Fluorescent tubes first appeared in 1976 and were developed by Edward Hammer. The Fluorescent tubes used in the domestic market are known as Compact Fluorescent Lights (CFL) and are 25% more energy efficient when compared to their counterparts such as Incandescent lamps and Halogen lamps (Finolex 2018). Fluorescent bulbs consist of vacuum tubes which contain mercury, argon gas and a phosphor coating of the internal tube. An electric current is applied which excites the gasses and produces ultraviolet light which excites the phosphor coating producing a white light (Finolex 2018). The average life span of a fluorescent light is approximately 8,500 hours (Scholand & Dillon 2012).

Progression in design of Fluorescent bulbs over the years has resulted in improvements to fitment styles which allow for the integration of older legacy fitting types that can be found throughout many older homes and buildings around the world. The Fluorescent light bulbs are still in current production and are readily available throughout many lighting stores, department stores and local supermarkets.

Fluorescent light tubes, especially CFLs, are still popular due to their low price and energy efficiency, which make them direct competitors to the LED light bulbs sector. However, Fluorescent light bulbs are slowly being phased out around the world due to containing Mercury, which is classified as toxic material and is harmful to the environment if disposed of within landfills as it can leach into groundwater and cause contamination and significant damage to ecosystems. Careful disposal is therefore especially necessary at the end of life of Fluorescent bulbs.

2.2.4 LED bulbs

The light emitting diode, widely known as the LED light, is one of the most popular transducers found in electronic circuitry (Rodney et al. 1993). As a semiconductor, the light emitting diode acts as a one-way switch which allows current to flow through it in one direction. The combination of various chemical compounds causes the LED to emit a range of colours of light as current is passed through the device (LED Magazine 2004).

LEDs require low operating power and are extremely efficient due to their low current requirement and low operating voltage. LED bulbs also have a very long life-expectancy when compared to other types of light bulbs. Figure 2.1 demonstrates the number of incandescent bulbs or CFL bulbs required to meet the life-expectancy of one LED bulb when standardised based on the equivalent of 20 million lumen-hours. Because of the compact nature of LEDs and excellent energy efficiency, they are highly useful in a range of applications. Such uses include LED light bulbs for use in buildings such as homes and offices, LED display panels in televisions, computers and handheld devices, as well as other household and consumer appliances that require lighting output (Rodney et al. 1993).

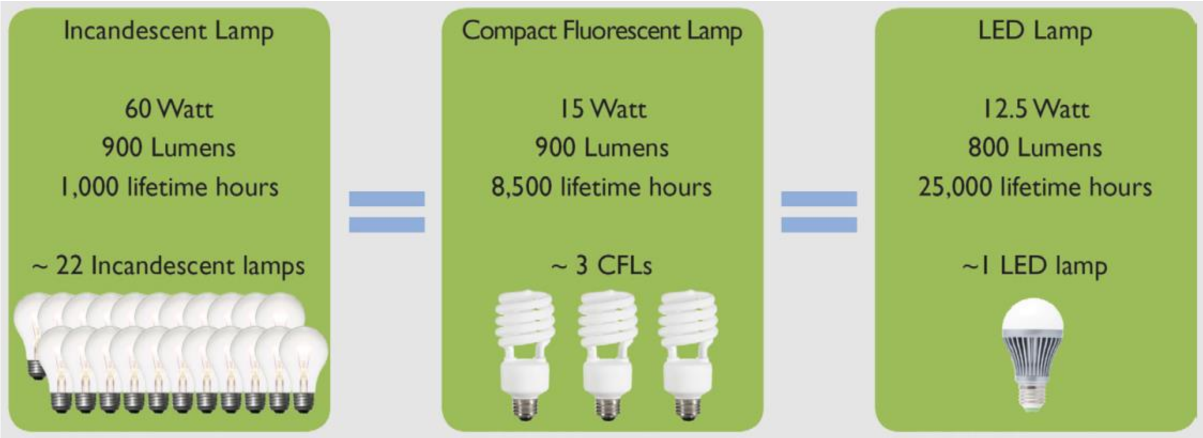

Figure 2.1 Bulb comparison showing number of lamps required to reach equivalence of 20 million lumen-hours (Scholand & Dillon 2012).

In recent years, the demand for LED light bulbs has increased steadily, with growth in global production of LED bulbs of 4.5% per annum (Fang et al. 2018). Additionally, Figure 2.2 shows LEDs are increasingly becoming the preferred bulb, with over 60% of total market share in 2020 (Kumar et al. 2019). This is due to a range of factors including affordability, extended life expectancy along with government legislation incentivising the use of LED bulbs and disincentivising the use of obsolete bulb technology (Kumar et al. 2019). Further development in LED light bulb technology has also contributed to increased life expectancy of up to 56,000 hours, further improving on the already excellent life span of LED bulbs (Maxlite 2020).

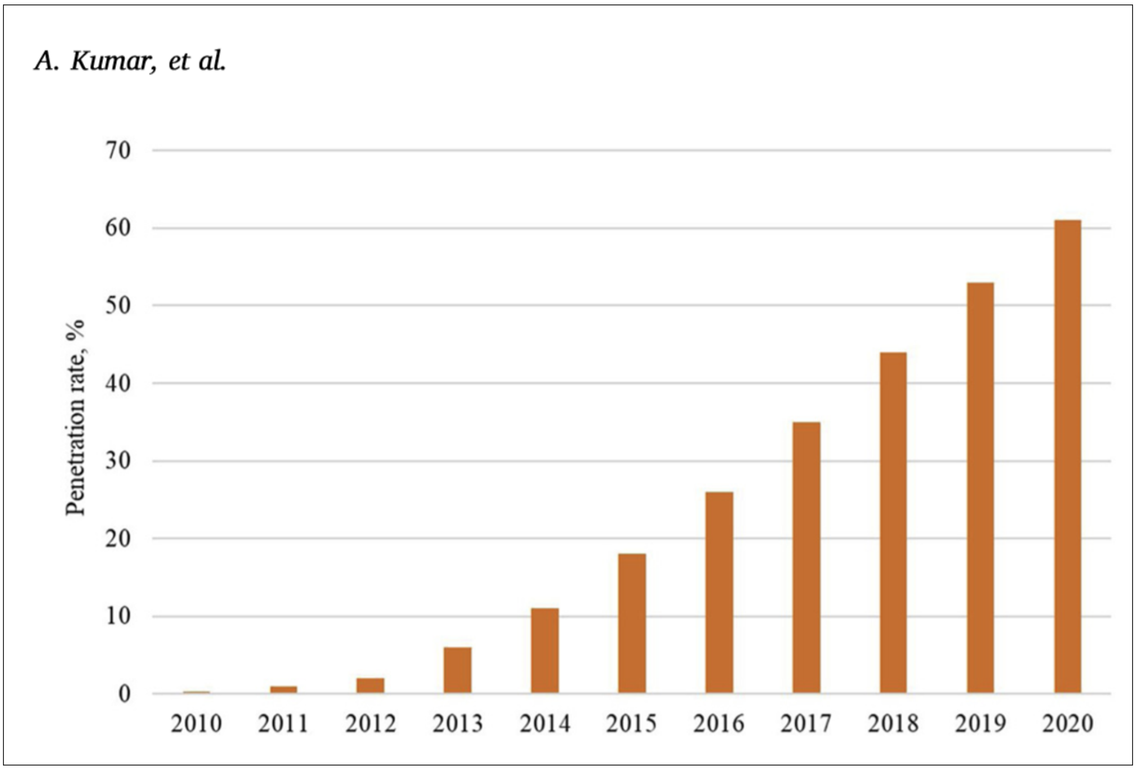

Figure 2.2 Increasing use of LED bulbs as a percentage of total bulbs produced annually (Kumar et al. 2019).

Figure 2.3 shows the various legacy style light fitments that have been integrated within the LED light bulbs. This is to allows direct replacement and integration of the LED light bulbs into any of the older light bulb's fittings. GU5.3 and GU10 fitment come from the old halogen legacy fitting, while the E27, Edison screw cap fitment comes from the old incandescent legacy light fitting. The G3 are the new modern style ceiling down light that are in use within the modern home.

Figure 2.3 Philips 12V and 240V various LED lights available (Philips Lighting Australia 2020).

The life span of an LED bulb is dependent on a range of factors including its design, construction, and quality of components, which are often reflected in the purchase price. More affordable LED bulbs available on the market have a typical life span of 15,000 to 30,000 hours, however LED light bulbs designed and manufactured using the latest technology have an increased life expectancy of up to 56,000 hours. While CFL light bulbs are slightly cheaper than LED bulbs to purchase, when considering the life expectancy of obsolete bulb technology, even the more expensive LED bulb alternatives are cheaper on a per hour use basis than other bulbs due to the reduced frequency of replacement (Scholand & Dillon 2012).

2.3 Composition of LED Lightbulbs

The most common types of LED bulbs are the GU5.3 pin type, B22 bayonet style, E27 Edison screw and the ceiling down light style (Reduction Revolution 2020). While the application of the different types of bulbs varies, the manufacture process and physical composition of the bulbs is generally similar. LED bulbs are produced using a variety of materials and components which typically consist of an exterior housing to suit the intended use, together with the internal components which emit light. The exterior housing is usually made using metal, plastic, or both, with a transparent glass or plastic lens on the side of the bulb that produces light. The lens and housing materials ensure the internal components are protected and provide an aesthetically pleasing exterior product appearance. The LED operating colour is determined by the chemical material composition used within the core chip, while the total brightness output is dependent on the operating voltage.

2.3.1 Physical Composition

An LED light bulb consists of several LED chip cores, electronic circuitry, lens / reflector, the casing which houses the LED electronics, printed circuit board (PCB) and the mounting / fitting of its base unit. Current manufacturing processes utilise surface mount device (SMD) components including the LED chip core, resistors, capacitors, inductors, voltage regulators and other components. The use of PCBs and SMDs reduces the overall cost and manual assembly, allowing for automation of the manufacture process. The quantity of LED chip cores per bulb is dependent on the LED wattage required, and the design style of the housing and fitting.

The physical composition of the GU5.3 series bulb is illustrated in Figure 2.4, separated into each of its components, from the outer shell, which is typically made from aluminium material, through to the inner components and integrated circuitry. In addition to the housing and the SMDs and PCBs as described above, the physical composition also consists of a collimator, which narrows and directs the beam of light in the desired direction. This helps to achieve the required light distribution of the bulb, which may vary depending on its intended use (Reuter & Van Schaik 2015).

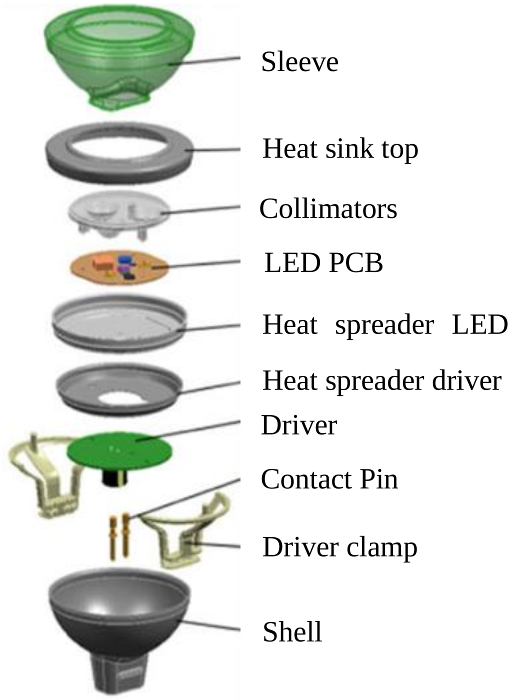

Figure 2.4 (inset): Physical composition of a GU5.3 Series LED light bulb (Reuter & Van Schaik 2015).

2.3.2 LED Core and Chemical Composition

The LED chip is manufactured using a range of materials including plastic, glass, solder, and metals such as copper, tin, silver and aluminium (Pradhan & Kumar 2014). LED cores are composed of smaller quantities of valuable materials including rare earth elements, such as Gallium (Ga), Arsenic (As), and Indium (In), which make up chemical compounds known as phosphors that exhibit the phenomenon of luminescence when energised (Bessho & Shimizu 2012). The chemical composition of an LED bulb is dependent on the desired light colour to be produced (Fang et al. 2018). Combinations of different chemical compounds produce a range of colours. For example, Gallium and Arsenic Phosphide will produce orange and red light while Gallium Nitride (GaN) produces white light, such as is commonly found in household LED light bulbs (Rodney et al. 1993). Combinations of chemical compounds are used to transform high frequency UV light into a range of wavelengths, producing light in all colours of the visible light spectrum, as illustrated in Figure 2.5 (Buchert et al. 2012).

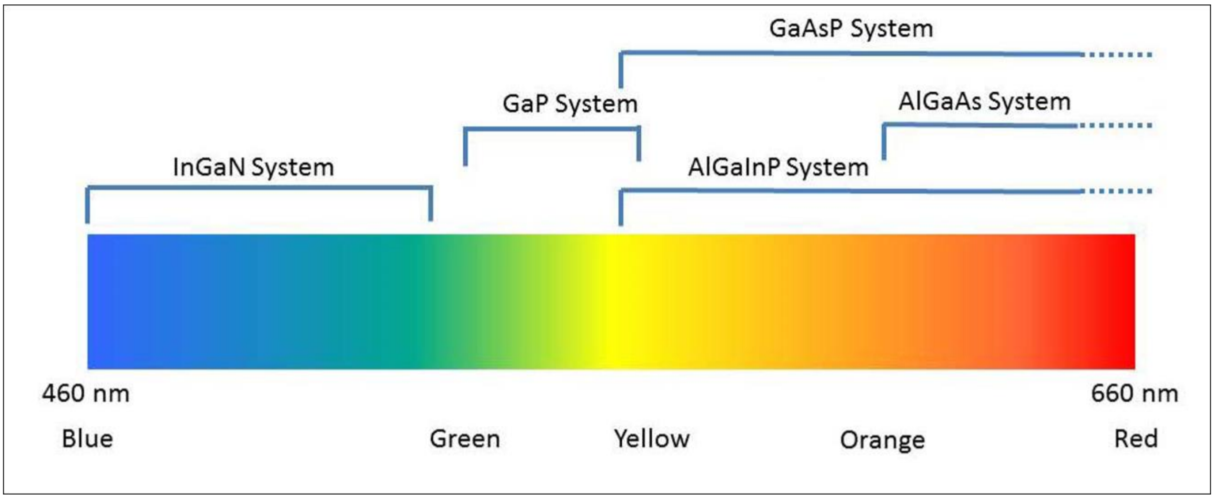

Figure 2.5: Effect of the semiconductor material on the colour of the LED light (Buchert et al. 2012). Environmental Impact of LED Disposal

Due to the ever-increasing use of digital technology, e-waste continues to be the fastest-growing component of household waste disposed of in landfill each year in Australia. One 2018 estimate put the total quantity of e-waste generated globally at 44.7 million tonnes per annum, and this is expected to increase by a further 8% each year, (Balde et al. 2017). Such a volume of e-waste is expected to contain up to $90 billion Australian dollars' worth of raw materials, including precious metals such as gold, silver and platinum as well as other rare metals. While efforts are increasing to facilitate the recycling of e-waste in Australia, most of the 590,000 tonnes of e-waste produced each year is still currently being disposed of in landfill facilities (World Economic Forum 2019). With the increasing use of LED bulbs around the world, LEDs are a growing contributor to the e-waste waste stream.

Adequate recycling facilities will need to be implemented to provide for future demand for the re-purposing of LED light bulbs. Currently, the method predominantly used for LED recycling is the process of crushing the bulbs, extracting the glass, followed by melting to extract the gold, copper, aluminium and other metals (Ecocycle 2019). Whilst this is the most cost-effective method, it is not an environmentally friendly process due to the production of hazardous by-products (United States Environmental Protection Agency 2015). This method is also ineffective for extracting some of the valuable metals that occur in very small quantities in e-waste, including in LED bulbs.

2.3.3 Toxicity of E-Waste

While e-waste typically represents 2% of solid waste streams, it makes up approximately 70% of hazardous waste that ultimately is disposed of in landfill (Balde et al. 2017). Many countries such as Australia, EU, and the USA have classified LED light bulbs as hazardous waste, meaning an accumulation of these bulbs within our landfill is expected to have a significant negative impact over time to the environment and inevitably, human health (Fang et al. 2018). Such negative environmental and health impacts can be due to several factors, many of which stem from leachate production in landfill environments. Leachate that is not effectively managed can contaminate groundwater and surface water, leaching into, local streams, rivers, and water reservoirs, affecting plant and aquatic life, as well as animals and humans who rely on the water for drinking purposes (Fang et al. 2018). With the increased demand for LED bulbs, there is a clear need for a robust recycling process for LED bulbs at the end of their life. Plastics from e-waste contributes 20% cooperatively to landfill (Hashmi & Varma 2019).

2.3.4 Depletion of Natural Resources

Increase in consumer demand for electronics over recent years has further increased demand for natural resources as many of the electronics components and products are made from natural metals and minerals such as precious metals and rare earth elements, including LEDs (Fang et al. 2018). As easily accessible metal and mineral deposits are exhausted, exploration and mining continue in other regions. To meet expanding demand, additional mining in many parts of the world has resulted in damage to the natural environment, together with many toxic by-products from the extraction and manufacturing process itself which further contributes to pollution (Bessho & Shimizu 2012). Additionally, many of mining process also requires vast amounts of water which are then required to be disposed of. Often such wastewater is disposed of in rivers, lakes or underground which further pollutes water systems and ecosystem (Helios Rybicka 1996).

Following the increase in mining, several countries and regions have restricted the mining practices that contributed to the damage to the environment by implementing export quotas and other restrictions (Fang et al. 2018). The restrictions to mining and export of precious metals and REEs, together with increased demand and depletion of natural resource deposits, has limited the availability of natural resources and driven up their price. This has further contributed to the need to recover metals and minerals from secondary sources, including from the recycling of LED bulbs and other e-waste (Fang et al. 2018).

2.4 International Environmental Standards

Environmental management standards are a set of standards and guidelines aimed at environmental impact minimisation, waste reduction and working towards sustainability (International Organisation for Standardisation 2015). The standards provide a framework for the design of environmental management systems, infrastructure, assist governments and organisations to accurately measure environmental impacts, improve resource efficiency and consistently manage environmental obligations. While the standards themselves do not prescribe specific environmental regulations, they can assist in the development of systems that implement and adhere to local legislation.

2.4.1 ISO14001:2015 Requirements and Guidelines

The ISO 14001:2015, revised in 2015 set out the standards and guideline requirement for within the environmental management system (International Organisation for Standardisation 2015) to improve an organisation performance. It sets out guidelines on how to manage environmental obligations with a methodical approach that supports an integral part of environmental sustainability (International Organisation for Standardisation 2015). Part of the environmental system consists of improvement of performance, implementation of obligations, compliance, and guidelines on how to meet environmental objectives (International Organisation for Standardisation 2015).

2.4.2 ISO14004:2016 Guidelines for Implementation

The ISO 14004:2016 revised in 2016 forms part of the ISO 14001:2015 family and sets out general guidelines to enable and the tools for organisation and businesses to implement processes within the environmental management framework (International Organisation for Standardisation 2015).

2.4.3 ISO14009 Guidelines for Incorporating Material Circulation in Design

The ISO14009 environmental management standard provides a set of guidelines and standards for incorporating material circulation within product design (International Organisation for Standardisation 2015). It gives specific guidelines regarding material distribution and flow to allow efficiency of material uses within design considerations and reduce the demand of natural resources, extending the end of life of the product through careful design process. The overall intent of the process is to enable the product to be designed in such a way to facilitate the repair, upgrade, and repurposing or recycling at the end of the products' life (International Organisation for Standardisation 2015).

2.4.4 ISO14044 Life Cycle Assessment

The ISO 14044 is designed to bring awareness to both the consumers and manufacturers in regards to the significance of environmental impact of products and develop processes to better mitigate environmental impacts associated with these products by applying and developing life cycle assessment (LCA) processes (International Organisation for Standardisation 2015). The LCA identifies environmental impacts and consequences through a product life cycle from birth, such as from raw material through it manufacturing, uses and to its end of life re-purposing, recycling and disposal (International Organisation for Standardisation 2015).

The LCA involves identifying ways to improve and reduce environmental impact of different products through its life cycle and to notify various decision makers within various industries, governments and organisations the importance of strategic planning, products and process designs to mitigate against negative environmental impacts (International Organisation for Standardisation 2015).

2.5 Waste and Resource Recovery Legislation

Through a range of international agreements, many countries around the world have committed to improving their collective efforts in the management of environmental and sustainability issues, including working towards the minimisation of waste through the increase of resource recovery. It is the role of each country's respective government to implement strategies to meet their targets and obligations under such agreements. This is generally coordinated through the introduction of waste policy initiatives, targeted legislation and industry regulation that promotes recovery of waste materials and valuable resources, and manages the impact of products and waste on human health and the environment (Australian Government 2020).

2.5.1 E-Waste Policy in EU, Japan & USA

E-waste management policy in the EU is among the most developed in the world. This is reflected in the higher levels of recycling of e-waste in member countries of the EU, in comparison with other countries around the world. Recently, the EU has set targets to increase energy efficiency and minimise waste by 20% over five years (Machacek et al. 2015). To achieve these goals, strict policies in relation to energy consumption have been introduced to phase out inefficient technology including bulbs such as the incandescent bulb, which has now been banned throughout the EU (Machacek et al. 2015). Furthermore, LED light bulbs are required to be recycled under the e-waste recycling scheme implemented following enactment of Commission Regulation 244/2009 on the eco-design requirements of household lamps (Franz & Wenzl 2017).

Much of the EU environmental legislation adopts the producer-pays principle, which ensures that all parties involved including manufacturers, suppliers and customers contribute to the end of life recycling cost (Izatt 2016). Under the producer-pays principle, manufactures are responsible for the cost of collection, end of life recycling and recovery of products while ensuring it is done in a manner that minimises environmental impact (Izatt 2016). LED light bulbs are classified as lamps under the e-waste category, which has nominated target recovery rates of 50 – 80% under the EU recycling legislation (Izatt 2016). To further reduce hazardous substances produced as by-products e-waste, the EU has additionally introduced the Restriction of Hazardous Substance (RoHS) which is a regulatory piece of legislation banning of the use of mercury, lead and cadmium in electronics products particularly within the consumer sector (Izatt 2016). Many parts of the world have now introduced the RoHS policy for all consumer electronics products in an effort to reduce the use of harmful substances in product manufacture.

In Japanese legislation, manufacturers and importers are responsible for e-waste and recycling under what is commonly known as a take back scheme. Under such schemes, consumers contribute to the cost of recycling of a product at the time of purchase, as the cost of recycling is incorporated into the up-front purchase price of the electronic goods. This can increase the cost of an electronic product by up to 20% (Silveira & Chang 2010). Consumers can then return the product in exchange for a small rebate of the purchase price, thus incentivising the return of electronic goods for recycling.

Similarly, in the United States, mobile phones that have reached the end of their life are collected through private companies which provide drop off bin facilities and prepaid envelopes to consumers (Geyer & Blass 2010). It is estimated that end of life recycling value per mobile phone is estimated to be USD0.68 to USD0.90 (Bollinger & Blass 2012). Similar approaches to those considered above can be implemented for the collection of LED light bulbs, further assisting in reduction of landfill volumes and re-purposing of the materials used in the manufacture of these bulbs.

2.5.2 Australian E-Waste Policy

The National Waste Policy was established in 2009 which forms part of the Australian Government legislation framework for waste and resource recovery throughout Australia (Australian Government 2018). The legislation is a result of collaboration between the Australian Government, states and territories and is designed to provide guidance and outline the shared responsibilities for government agencies, business as well as individuals in regards to waste and recycling (Australian Government 2018). Some of the key aims of the National Waste Policy are to avoid waste, improve waste recovery, and improve management of materials to benefit human health, the environment, and the economy. It also endeavours to provide information to support future innovation, investment, decision making and better informed consumers (Australian Government 2018).

In 2015, the United Nations (UN) formed a new policy aimed towards setting goals to end poverty, protect the planet, and encourage prosperity for everyone under the sustainable development agenda known as Goal 12 (Australian Government 2018). Australia has adopted Goal 12 and integrated it into its national waste policy through development of national plans that encourage sustainable business practices and consumer behaviour as well as management of hazardous chemicals and waste (Australian Government 2018).

2.5.3 Queensland State-Specific Legislation

The Queensland environmental waste policy Environmental Protection Act 1994 (EP Act), together with the supplementary legislation, the Environmental Protection Regulation 2019 (EP Regulation) provide guidelines for the management of waste in Queensland (Queensland Government 2019). They provide definitions of waste, including categories of waste which are dependent on the risk associated with the respective waste products. They further set out how waste management activities, including disposal to landfill and recycling activities are regulated.

Waste is defined in Section 13 of the EP Act as "anything other than an end of waste resource, that is –

(a) Left over, or an unwanted by-product, from an industrial, commercial, domestic or other activity; or
(b) Surplus to the industrial, commercial, domestic or other activity generating the waste."

Waste is further identified as "gas, liquid, solid, or energy, or a combination of any of them" (Queensland Government 2019).

The categories which are used to determine how a waste product is classified are provided under Schedule 9 of the EP Act as follows:

- Category 1 Regulated waste (highest risk). This category classifies waste that presents a high risk to the environment, health, and safety.
- Category 2 Regulated waste (moderate risk). Waste in this category also presents risk to the environment, health, and safety, however the risk is considered moderate.
- Non-regulated waste / General waste (lowest risk). This category presents low risk to the environment, health, and safety. It includes waste such as municipal solid waste (MSW) from domestic households, and low risk industrial and commercial waste, such as paper, plastics, building material, metal, untreated wood, bricks etc (Queensland Government 2019)

Under the definitions and categories set out in the legislation, LED light bulbs are classified as waste since they are unwanted or left-over waste from both domestic and industrial sectors and can be further classified as general waste or municipal solid waste when disposed of by consumers. If mass collection and processing of LED bulbs was carried out, this would likely result in a change in classification due to the increased quantity of hazardous materials contained in a large amount of bulbs (Queensland Government 2019). According to Queensland Government Department of Environment and Science however, the EP Act and EP Regulation do not regulate the subsequent processing of the extracted components into new recycled products.

2.6 Product Stewardship Scheme

Product stewardship takes many forms, for example when people recycle packaging or when companies re-design their product to reduce hazardous substances, they are being good product stewards. The Act provides a framework for mandatory, co-regulatory and voluntary product stewardship. Co-regulatory approaches involve a combination of government regulation and industry action, whereby government makes regulations that set the outcomes to be met, while industry funds and implements the scheme and has flexibility in determining how those outcomes are achieved.

The Product Stewardship Scheme supplements the Australian National Waste Policy. It became legislation in 2011, under the Product Stewardship Act 2011. The Product Stewardship Act consist of two pieces of legislation, the Product Stewardship Act 2011 and the Product Stewardship (oil) Act 2000 (Australian Government 2011). Its purpose is to mitigate the impact of various waste product within the environment through the product stewardship program. Its core principle is that everyone including manufacturers, suppliers, distributors and consumers share the responsibility to ensure that waste product is managed and disposed of responsibly within the products' life cycle to reduce impact on both the environment and human health and safety (Australian Government 2011).

Furthermore, the Product Stewardship Act provides the structure and guidance to mitigate the impact of these waste products on the environment, human health and safety in regards to end of life of the waste products (Australian Government 2011). Product Stewardship now includes a wide variety of products, including batteries, child car seats, electrical and electronic products, plastic oil containers, plastic microbeads, and photovoltaic systems. The product stewardship also extends its e-waste category to include mobile phone, batteries, compact fluorescent lamps (CFLs) and high intensity discharge (HID) lamps but excludes LED light bulbs recycling under this scheme (Australian Government 2011). While plastic and packaging are also included under this Product Stewardship Scheme, it is targeted towards certain selective plastics such as plastic bags, plastic packaging, plastic marine debris, microbeads plastics, plastic bottles and it containers. This aims to reduce environmental impact caused by plastics and bring awareness and education through the Product Stewardship scheme umbrella (Australian Government 2011).

The Product Stewardship scheme for waste electrical and electronic products (WEEE) was introduced in 2016 and covers a wide range of electrical and electronics products such as hi-fi equipment and home appliances. To further distinguish between the e-waste categories, the National Television and

Computer Recycling Scheme was introduced under Product Stewardship scheme to facilitate the recycling of printers, computer parts and peripherals for end of life collection which is industry funded for the repurposing and recycling of these products (Australian Government 2011).

Several Australian states including New South Wales (NSW), Victoria (VIC) and Queensland (QLD), among others, have incorporated both the National Waste Policy and Product Stewardship Act 2011 in their respective state legislation. In Queensland and many of the other states throughout Australia, the Product Stewardship scheme forms part of local council's e-waste recycling facilities, which include designated collection points for certain e-waste product categories.

2.6.1 Regulation and Accreditation

Recycling organisations form a crucial role in managing and e-waste reduction. Under product stewardship schemes, only accredited agencies and local government councils are permitted to recycle e-waste. Voluntary product stewardship schemes allow many industries to participate in implementing processes to aid towards reduction of negative environmental, health and safety impacts of their products, further encouraging improvement towards sustainability. Under such scheme industries receives funding from the government to encourage innovations towards sustainability, environment, health and safety (Australian Government 2011).

To become an accredited provider under a co-regulatory Product Stewardship scheme, the provider must meet certain criteria and demonstrate its businesses can meet all appropriate requirements, such as environmental, health and safety policies. This ensures practices are up to a predetermined standard as set out by the government whereby providers must adhere to strict rules and must provide data annually to the reporting regulatory body (Australian Government 2011). Furthermore, the Government sets guidelines and operational requirements, while allowing industries the flexibility of how to meet the requirements and outcome (Australian Government 2011). To further strengthen and promote the Product Stewardship scheme, the Australian government also provides additional funding to firms and business that can demonstrate a contribution to sustainability and circular economy (Australian Government 2011)

2.6.2 Existing E-Waste Product Stewardship Schemes

Many stores and companies, such as Office Works are part of the National product stewardship scheme and they serve as a drop off centre for the public and small businesses. Mobile phone recycling has been available for many years, with options now available for the collections of old mobile phones at many mobile phone stores as shown in Figure 2.6 and Figure 2.7. Some private companies also offer to buy old phones with free pick up services such as Mazuma Mobile and Mobile Muster. Such services are becoming more accessible to the general public, with a range of companies coming on board under product stewardship schemes. Mobile Muster has 3 recycling branches in Australia: Melbourne, Sydney, and Brisbane. Once the mobile phones arrive at the recycling centres they are then distributed for disassembly and recycling.

Figure 2.6: Office works Stewardship recycling program collection point (Officeworks 2020).

Figure 2.7: Mobile Muster drop-off recycling services (Mobile Muster 2020).

2.7 Recycling Processes

2.7.1 Current Recycling of Lightbulbs in Australia

The LED light bulbs available for the domestic market are manufactured with a range of materials which can result in complex resource recovery methods. Although many of the LED light bulbs may physically look similar in appearance, manufacture processes between brands and bulb types can vary significantly. Some of the variations of LED lights constructions are now aluminium plastic-coated housing, while some higher priced designs consist of all glass housing construction. Other variations include the design of the power supplies or driver units to be built into the housing as all in one package or having separate driver unit. The complexity in various design and manufacturing techniques s show in Figure 2.8 demonstrates that several disassembling techniques may be required to allow the separation at the different recycling stages.

Figure 2.8 Power supply integrated or independent system (Reduction Revolution 2020)

Currently in Australia there are very few companies involved in the end of life recycling of LED light bulbs. One company based in Victoria, CMA Ecocycle, primarily recycles fluorescent light tubes has begun to include the recycling of LED light bulbs in their recycling systems (Ecocycle 2019). The bulbs are collected from nominated recycling depots and transported to the processing plant where a recycling process is undertaken as shown in Figure 2.9. The processing method involves crushing of the LEDs which are then melted with glass, and copper, being retrieved from the process for further recycling. This is a simple all in one process that is automated and involves little manual intervention. This recycling method of processing is one of the preferred methods that is used for the recycling of light bulbs in many parts of the world. It is not the most effective approach however, as many of the rare earth elements (REE) and valuable materials are not recovered, they are burned off resulting in harmful fumes being released as by-product.

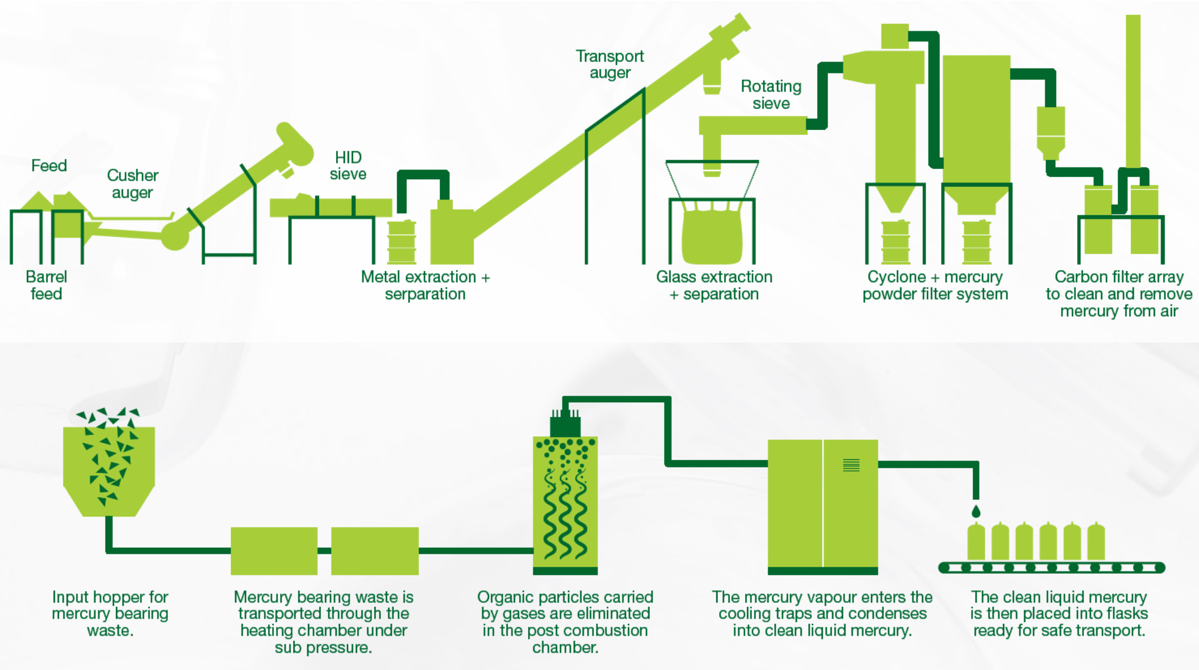

Figure 2.9 Lighting waste and continuous flow recycling processes utilised in Australia (Ecocycle 2019).

2.7.2 Mobile Phone Recycling Processes

LED light bulbs contain many of the components found in mobile phones such as printed circuit board (PCB), surface mounted devices (SMD), resistors, capacitors, glass, and plastics. LED light bulbs form part of the e-waste category therefore recycling processes for mobile phones may be applicable to LED light bulbs. Relevant processes may then be implemented for LED light bulb re-purposing.

2.7.2.1 Mobile Phone Recycling in Australia

In Australia, part of the final processing of the electronics scraping are sent offshore to Singapore for further extraction (Soo & Doolan 2014). Mobile Muster is one of the major corporations in collaboration with the product Stewardship scheme (Australian Government 2011), which in Australia is responsible for mobile phone recycling services. The company has also extended their services to recycling smartwatches, fitness trackers, chargers, and other mobile accessories (Mobile Muster 2020). Once the mobile phones arrive at the recycling facility, they are then manually sorted and dismantled by hand, where each component has separated by its category and recycling process, as shown in the flow charts in Figure 2.10 and Figure 2.11 (Mobile Muster 2020).

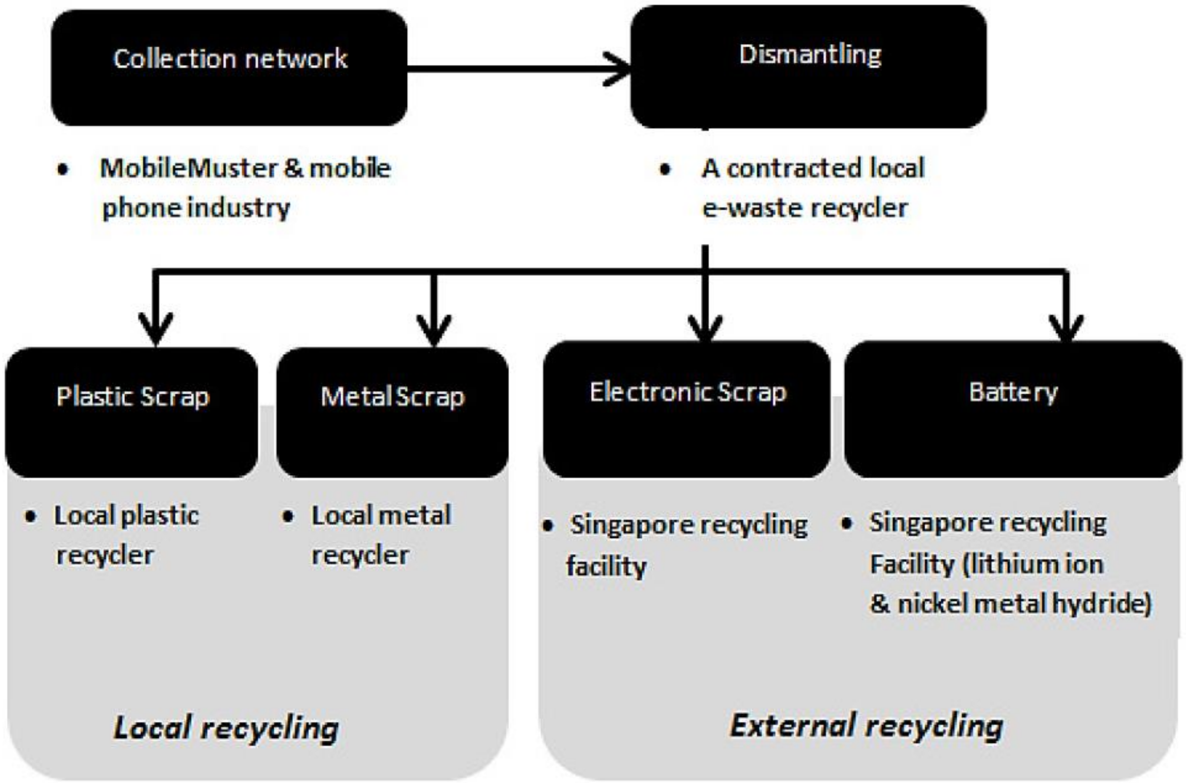

Figure 2.10: Australia Mobile phone recycling process flow diagram.(Soo & Doolan 2014).

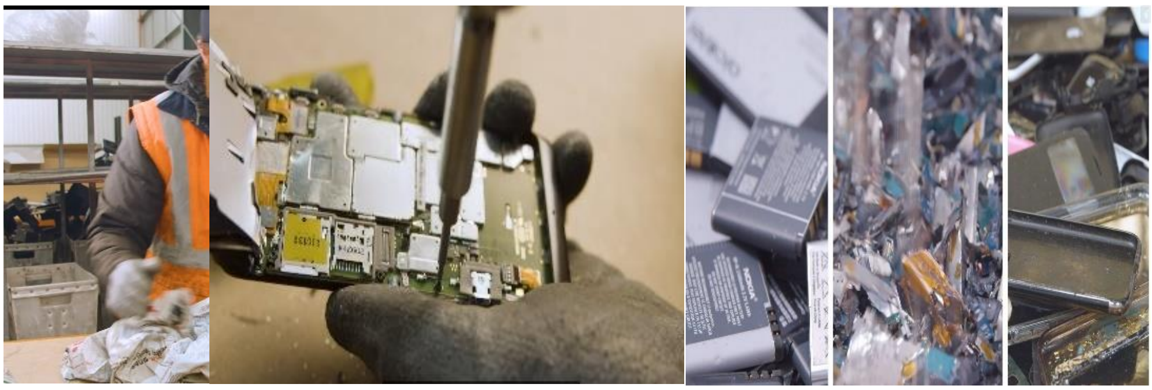

Figure 2.11: Various stages of recycling, sorting, dismantling, categorisation (Mobile Muster 2020).

2.7.2.2 Mobile Phone Recycling in Malaysia

As with most e-waste, LED light bulbs contain toxic materials and form hazardous waste. To combat e-waste pollution, Malaysia introduced take back incentives, law enforcement policies, public awareness and joint partnerships with mobile phone manufacturers to minimise e-waste disposal (Soo & Doolan 2014). Figure 2.12 shows the current recycling process flow currently used in Malaysia for mobile phones (Soo & Doolan 2014). The PCB is further processed using hydrometallurgy, a wet chemical process (Soo & Doolan 2014). This method is used for the retrieval of metals, such as gold instead of the conventional smelting process which involves chemical leaching (Gupta & Mukherjee 2017).

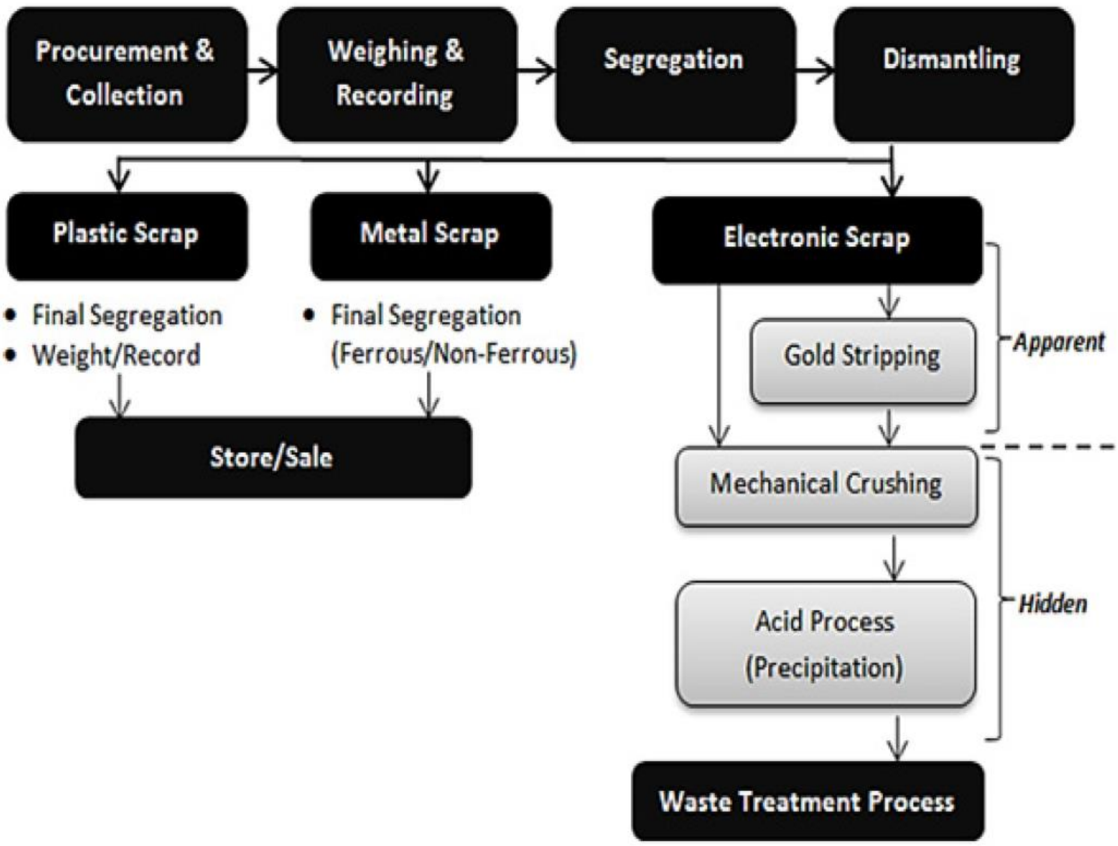

Figure 2.12: Flow chart of the Malaysian recycling process of e-waste (Soo & Doolan 2014)

The circuit boards are crushed and shredded via a shredding machine. In this step, everything is destroyed from the circuit board, including personal data information within the phone's electronic memory chips. Once shredded, the circuit boards are smelted as shown in Figure 2.13 for the retrieval of metals such as copper, gold, silver which is then recycled again for uses as new products, including new mobile phones. The batteries are then processed by crushing and shredding methods for the separation of the compound such as lithium, nickel and cobalt, where it is recovered for reuse to make new batteries as shown in Figure 2.14.

Figure 2.13: Electronic scrap shredded and melted for metal recovery (Mobile Muster 2020).

The glass is crushed, smelted and reused for use in new products while the batteries and PCB scraps are exported for further refinement (Soo & Doolan 2014). As shown in Figure 2.15, the plastics are shredded prior to being crushed then injection moulded in new plastic which can be used to create new products such as pallets, part bench tops as well as new phone cases (Mobile Muster 2020).

Figure 2.14 (left): Batteries are fed via conveyor belt for crushing

Figure 2.15 (right): Plastics are shredded prior to being melted and injection moulded into new products

2.7.3 Material Recovered from the Recycling of Mobile Phones

Printed circuit boards in both mobile phones and LED light bulbs contain numerous valuable materials, including precious metals and REEs (Soo & Doolan 2014). The proportions of each material can be quantified as shown in Table 1, with ferrous metals and copper among the highest quantities recovered while recovery of other metals such as gold and silver are minimal due to their limited use in mobile phones. These metals are useful in production of new electronics and other products and are worth recovering due to their valuable nature.

Table 1: Inventory output material recycled from Malaysia Recycling facility (Soo & Doolan 2014)

Material Recovered from Mobile Phone PCB	Quantity Recovered
Ferrous metals	27.9%
Copper	23.7%
Gold	0.0146%
Silver	0.104%
Platinum	0.0001%
Palladium	0.0001%
Trace Metals	0.424%
Rubber waste	5.9%

Recycling not only reduces environmental impact of disposal of e-waste but also adds additional benefits to the economy as it creates jobs, and materials extracted from e-waste are resold for profit thus adding to a country's economy. It is estimated that 95% of the materials contained in mobile phones can be recycled, while over 95% of LED light bulb content is recyclable (Kumar et al. 2019). A simulation conducted in 2016 of metal waste from LED light bulbs in Canada estimate returns from material recovery processes of up to $10 million per annum (Kumar et al. 2019). Furthermore, through the incineration process used in metal recovery, the heat energy output can further be used to generate electricity (Kumar et al. 2019).

2.7.4 Application of Mobile Phone Recycling Methods to LED Bulbs

LED light bulbs, in many ways, are very similar to mobile phones in their construction. They are constructed as modular units, made from various electronic components including capacitors, inductors, resistors, integrated circuit (IC) chips, and PCB board. PCBs are constructed with combinations of material such as fiberglass-reinforced epoxy laminate, which is a toxic material (United States Environmental Protection Agency 2015).

Due to the commonality of materials contained in mobile phones and LED light bulbs, including electronic components, recycling methods used in the processing of mobile phones may be applicable and be incorporated in the recycling of LED light bulbs. By applying similar manual disassembling process to the LED light bulbs, the plastic lens reflector can be easily separated, while the glass can be crushed, melted, and separated for further recycling into new products. Similar methods can be applied for electronic circuitry and PCB boards which can be separated or crushed for the extraction of its various metal. Many of the LED light bulbs uses an aluminium body for the purpose of heat sinks which can also be melted for aluminium extraction.

While this process is not currently being adopted in Australia for the e-waste recycling industry for both the mobile phone and the CFL, chemical extractions can be utilised to further extract the REE from the electronics components such as Integrated Circuits (IC) (Soo & Doolan 2014).

2.8 Metal Recovery Methods

A range of recovery methods can be used to extract metals from e-waste. The two favourable processes currently in use for the recycling of e-waste are Pyrometallurgical and Hydrometallurgical processing. The incineration process used for LED bulbs has been found to be an ineffective approach to the extraction of the materials inside the bulbs as many of the metals are burned off and are not recoverable. Pyrometallurgical processing has its own disadvantages due to its high set up costs, high operating costs, sizable infrastructure and incorporated smelting system, which puts it out of reach to many under-developed countries and can only be profitable in large scale production (Navazo et al. 2014). In contrast, hydrometallurgical processing requires less operating cost, however it is not suitable for large scale e-waste recycling and is limited to recycling of fewer metals at once (Navazo et al. 2014).

2.8.1 Hydrometallurgical Processing

Hydrometallurgical processing is another method used to extract precious metals and REE from e-waste. This process uses leaching, precipitation, separation, and purification to recover the various metals, which are then refined for further use and inclusion in new products as shown in Figure 2.16. Hydrometallurgy uses toxic solvents such as sulfuric acid (H_2SO_4) as leaching agents along with other aqueous solutions (Sarfo et al. 2020). In this process, the metals are separated depending on their metallurgical and chemical properties, where the precious and heavy metals are separated by the uses of various chemical solvents and application of heat (Izatt 2016). Metals can be separated individually, and the process is considered low cost and comparatively efficient. One disadvantage of hydrometallurgical processing is that many repeated processes are required to extract a wide range of metals.

Currently in Australia there are very stringent policies in relation to toxic chemical use which requires special permits and licences which are governed by The National Standards for Environmental Risk Management of Industrial Chemicals (Australian Government 2018) . Several of the private firms in Australia who are currently recycling e-waste, including mobile phones and CFL lamps favour the incineration process instead of heavy reliance of chemical leaching process.

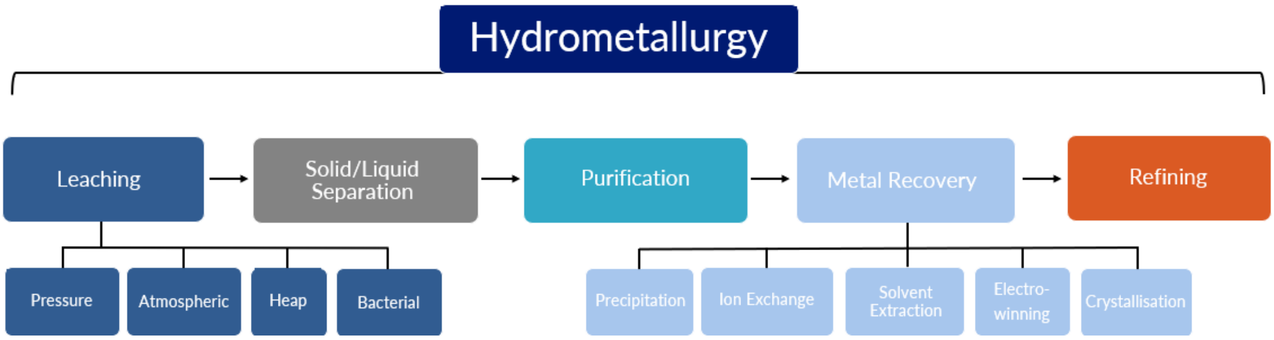

Figure 2.16 Hydrometallurgical processing methodology and techniques (CGIS 2020).

2.8.2 Pyrometallurgical Processing

Pyrometallurgical processing is used for metal extraction from a range of e-waste products and involves roasting, smelting, incinerating, and refining for the purposes of metal extraction. One of the process that separates Pyrometallurgical from other processes for the removal of metals from e-waste is the use of smelting the materials in a furnace at very high temperatures (Izatt 2016). Burnt off remains consisting of inorganic ash are processed further for the extraction of various metals. These polymeric materials are highly toxic if released into the air (International Organisation for Standardisation 2015; United States Environmental Protection Agency 2015). Some disadvantages of the pyrometallurgical process include the high energy requirement and the production of by-products including slag and toxic gases which can be difficult to manage effectively. The process is also not very versatile and can result in a significant amount of material that is difficult or impossible to recover as it is converted into various by-products (Gupta & Mukherjee 2017).

In the smelting process, once the e-waste has been separated and sorted into its various categories, both plastic and PCB boards are fed into the smelter. The plastic waste is used as fuel and reduction agent (Navazo et al. 2014). The smelter separates the copper from other precious metals such as gold, silver, and lead (Navazo et al. 2014). Approximately 80% to 90% of the materials including copper, gold, lead, tin, and gold are retrievable. During the smelting process, copper is known as black copper as it is coated and mixed with impurities which need to be further refined prior to use in new products. Table 2 demonstrates the quantities of various materials output from 1 tonne of e-waste, including precious metals and other by-products (Navazo et al. 2014).

Table 2: Material recovered form 1 tonne of mobile phone e-waste (Navazo et al. 2014).

Material	Weight recovered per tonne of e-waste
Black copper	128 kg
Lead bullion	17 kg
Actual Lead	6 kg
Tin	10 kg
Antimony	1 kg
Nickel	3.6 kg
Gold	347 g
Palladium	151 g
Platinum	5 g
Slag (consisting of plastic, aluminium oxide)	396 kg

The residue remaining (slag) consists of plastic and aluminium oxide, neither of which can be recovered through the smelting process. While the aluminium is not recoverable, the iron can be pre-treated prior to the smelting process. The smelting process can result in the loss up to 20% of valuable metals (Navazo et al. 2014). The smelting process outputs gasses which are derived from zinc oxide, copper and lead oxide. These particles can be recovered from the smelter. The next step of the process involves further extraction through the use of pyrometallurgical processes utilising anode, furnace or Hydrometallurgical processing as discussed above (Navazo et al. 2014).

2.9 Importance of Recycling and Process Efficiency

In some underdeveloped countries that process a significant quantity of e-waste, recycling practices often utilise dangerous or outdated methodology which has numerous negative impacts, including reducing the quantity and quality of recovered materials, as well as having adverse impacts on the environment and human health, through exposure to harmful chemicals and production of toxic fumes and other by-products. To be effective in minimising environmental hazards such as dangerous gas emission and heavy metal pollution, and to be economically viable, the recovery process needs to be done under controlled and standardised operations, and in accordance with relevant legislation. Currently, only 25% of the materials including gold, silver, and palladium were able to be recovered by underdeveloped countries and small backyard recycling operators when compared to 95% to 99% metals recovery rate from the industrialised world (Bollinger & Blass 2012). This demonstrates the need for rigorous processes that are developed to extract materials as efficiently as possible and maintain safe practices for staff involved in the recycling process.

Life cycle assessments comparing the energy requirements of mining ore to the energy requirements of extracting rare and precious metals through recycling of e-waste show that it is far more efficient to recycle various kinds of e-waste than to mine metal-containing ore (Navazo et al. 2014). One life cycle assessment demonstrated the significant difference in energy requirements, with extraction of gold from mining ore requiring 34,224 kJ/kg, compared to 18,765 kJ/kg required for the extraction of gold through e-waste recycling, specifically the recycling of mobile phones. This shows that recycling of e-waste could be as much as twice as efficient for some metals, in comparison to mining them directly. The further benefit of this is the reduction of e-waste sent to landfill, together with the reduction in environmental impact of mining practices.

Currently, the main metals being recycled from e-waste are precious metals such as copper, gold, silver, platinum and palladium, among others (Navazo et al. 2014). Many of the rare earth elements (REE) such as gallium, and other rare materials contained in e-waste, including mobile phones and LED light bulbs, are not being prioritised for recycling. This is due to a number of factors such as the low quantities found within electronics components, the recovery cost, economic profitability and the heavy use of pyrometallurgical processing (Buchert et al. 2012). REE recovery is not possible in pyrometallurgy, partly due to their low quantity, they become diluted and converted to oxides in slag in the incineration process (Buchert et al. 2012). Where other processes are used such as hydrometallurgy, recovery of REEs may be more feasible.

2.10 Literature Gap

The various studies discussed in this literature review of LED light bulbs and recycling processes highlight the work conducted regarding the repurposing of e-waste. Investigation of the literature demonstrated that there is not one consistent recycling approach, rather various approaches have been utilised throughout the world, with some being more effective than others. This review of the literature identified several areas where current research, legislation and recycling processes are lacking and require improvement or refinement to facilitate the recycling and repurposing of LED light bulbs that have reached the end of their life.

One significant gap identified in this literature review was the lack of appropriate e-waste recycling management for LED light bulbs in Australia and the clear need for legislation regarding e-waste recycling through local government with industry support. Currently, local councils do not facilitate the recycling of LED light bulbs and there is a need to further expand current e-waste legislation to include LED light bulbs to ensure less LED light bulbs within the landfill. This is especially critical given the increasing contribution of LED light bulbs to the e-waste waste stream and due to the presence of precious metals and REEs, which are valuable materials that can be utilised in the manufacture of new products.

Some private recycling facilities for recycling of fluorescent light tubes within Australia accommodate LED light bulbs as part of their recycling plant, however there are currently no facilities that are specifically tailored to the recycling of LEDs. Since LEDs are not the main waste stream accepted at these facilities and they are not tailored to LED light bulb waste, the processes utilised for recycling are not considered best practice as they do not fully capture the recycling potential of the materials contained within LED light bulbs. This demonstrates the need for legislation, schemes and facilities that are tailored to the recycling of various kinds of e-waste, including LED light bulbs.

From the review of the available literature, it is evident that there currently exist several issues that inhibit the uptake of recycling of LED light bulbs in Australia. This includes insufficient legislation and policy relating to e-waste and LED bulbs specifically, and the design of LED bulbs which restrict the use of certain recycling techniques and processes. The following chapter will consider a range of ways to address the insufficient legislation, design issues and recycling processes in order to better facilitate the recycling of LED light bulbs.

2.11 Research Questions

As a result of the above identified gaps in current literature and industry practices, the following questions have been identified for further investigation as part of this research:

- How can the design and assembly of LED light bulbs be modified to make deconstruction easier to facilitate the repurposing LED light bulbs?
- How can the metals and minerals in LED bulbs be processed in the recycling process to allow re-use in new products?
- What are the gaps in the legislation and existing product stewardship schemes that need to be resolved to allow for repurposing of LED light bulbs?

Chapter 3. Methodology

3.1 Chapter Overview

This chapter describes the methodology used to assess and recommend improvements to e-waste recycling legislation, policy and procedures. While disassembly techniques are investigated to inform the design for disassembly, the methodology for this research is primarily desktop based. It focuses on three main areas of concern, as identified in Chapter 2 Literature Review, Chapter 2as follows:

- Design for Disassembly and Recycling
- Processing of Materials
- Australian Legislation and Policy

By investigating the design and current manufacture processes of LED bulbs available on the Australian market, various factors have been identified that may hamper the recycling of LED bulbs. Identification of such constraining factors assists in recommending areas of development and improvement in the design of LED bulbs to facilitate their recycling at the end of their life.

Analysis of data specific to the contents of LED bulbs in Australia will demonstrate what materials require repurposing in the recycling process, and therefore, which recycling technologies will be most suitable for LED bulbs in Australia. Various technologies will be investigated relating to the recycling of trace metals, as well as other by-products. Assessment criteria will be defined to enable the objective analysis of these technologies.

An assessment of the implementation of current legislation in Australia will be conducted to ascertain whether the legislation is fit for purpose and provides sufficient guidance surrounding the recycling of LED bulbs.

3.2 Design for Disassembly and Recycling

As identified in the literature review, the complexity of LED light bulb design and manufacture is prohibitive to their disassembly, recycling and ultimate repurposing into new products (Reuter & Van Schaik 2015). To facilitate improved recycling outcomes, alternative design and manufacture processes may be recommended to simplify the disassembly process. The purpose of this methodology is to assess the difficulty of disassembling various existing LED light bulb designs currently available for the domestic market. Doing so will provide valuable feedback and information regarding its recycling, repurposing capability of the various LED lightbulbs chosen for this research and enable recommendations to be made for the improvement of design processes.

3.2.1 Criteria for Disassembly Assessment

The following outlines the criteria's regarding the disassembly assessment:

1. The ease of dismantling for gauging their complexity of LED light bulb structures. How easy can it be dismantled and break apart/separated?
2. Ease of separations of various material compositions. Example, lens/reflector, PCB board, LED board, heat sinks materials, glass, plastics, wires and LED bulb housing.
3. Requirements for specialist tooling
4. What construction method is used?
5. How many different materials are used in the product?
6. Can the disassembly be conducted automatically?
7. How many disassembly stages are required in the entire process?

The criteria for each bulb will be based on a rating approach by uses of a numbering system from 1 to 5. Where 1 is extremely difficult, 5 easy. The number system approach is used for its simplicity and easy to get a gauge the results which can be used for decision making of the outcomes and recommendations. This approach will also apply to decision making where the answer would normally be 'yes' or 'no'.

Further breakdown of each criteria will be individually explained in detail during the review stage for each bulb once the experiment has been executed.

3.2.2 Disassembly Procedure for LED Bulbs

These main types of light fitments are primarily. (Noting that all the legacy light fitments have been integrated with LED bulbs for easy integrations).

- GU5.3 series downlight light bulb which are from the old legacy 12 DC volts operating system from the halogen bulbs. Theses bulbs have two pins for connection
- E27 screw cap, also known as the Edison Screw fitment is from the incandescent light bulb legacy which are still in existence and widely found in many old homes today. The has the diameter of E27mm and is known as screw cap style fitting
- G3 LED ceiling downlight modern design.

The aim is to also select a representative sample available by not only choosing the various common light fitment style, but to also select various construction materials such as glass constructions, plastic and sub-part containing metal such as aluminium body construction. The experiment will be performed on various LED light bulbs by dismantling process.

The experiments are to evaluate the different disassembling stages of the various LED light bulbs used for this experiment. This will provide useful information which will be used towards the final proposal solution. The following disassembling methods below were chosen because of its simplicity, minimal equipment, tools requirement and safe approach. Other methods such as hitting or cutting of the Lens/diffuser and main housing unit for the separation of the bulb proposed additional safety risk to injury as well as additional efforts and may be deemed to be unsafe under the University of Southern Queensland (USQ) Safety Risk Management guidelines. The outcome of this experiment is to also preserve most of the LED light bulbs electronics components including it printed circuit boards (PCB). While other methods used by large recycling firm such as CMA Ecocycle simply crush the complete unit (Ecocycle 2019). Therefore, this is the best practice approach for this experiment. This experiment will only require a few hand tools and minimal equipment which are outlined under Appendix B – Risk Assessment.

3.2.2.1 LED Light Bulb Samples

The Olsent brand of LED light bulb shown in Figure 3.2 has an Edison screw cap style fitment, 9W, Olsent LED downlight 12V globe, model GU5.3 fitment style and Philips LED down light, GU5.3 fitment style.

The LED bulbs were purchased at the supermarket as they are commonly available on the shelves to the public. Woolworths supermarket and Beacon Lighting were chosen as well-known suppliers of light fittings and bulbs. With such a large variety of models, price ranges, suppliers and manufacturers of the LED light bulbs, it is not possible to test every LED light bulb variation available in Australia coupled with time constraint and set budget limits. Therefore 4 LED light bulbs were chosen due to the pricing from the two suppliers which would suit most consumers.

From the samples of the GU5.3 LED light bulbs, two variations were purchased due to its material constructions as they would represent the disassembling issues during testing. The Philips body shown in Figure 3.4, including its housing, were all glass construction with plastic lens, costing much more due to the material used and manufacturing process required. The Olsent light bulbs shown in Figure 3.3 are all plastic for the housing and lens construction, which is also reflected in its lower purchase price.

3.2.2.2 Dismantling Process of LED Downlight

Dismantling of the LED downlight shown in Figure 3.1 is conducted in two phases, the first being the disassembly of the housing and removal of wires and other miscellaneous items, the second being the disassembly of the driver unit.

Figure 3.1: GE Ceiling LED down light.

1. Place the LED light bulb into the vice, position the bulb into the vice just below the lens and the housing.
2. Slowly tighten by the turning vice handle, this will increase pressure causing the bulb lens/ diffuser to separate from its housing.
3. Remove the bulb from the vice by unwinding the vice handle.
4. Remove the lens/ diffuser cap if it is not already fallen off.
5. Once the lens/ diffuser come off, the led PCB board is exposed.
6. Remove the plastic film reflector. Note the reflector film is held by silicon material.
7. Using small Philips screwdriver remove the 3X Philips screw.
8. Using a flat head screwdriver pop out the LED PCB board. Underneath the LED PCB board contains heat transfer material paste.
9. To allow complete removal of the LED board cut off the conducting wires.
10. Using pair of pliers cut the wires/cables at both ends of the Driver unit

The disassembly of the driver unit is completed as follows:

1. Cut off the power lead to the LED PCB board base of the housing unit.
2. To remove the cable retainer cap, use a triangle tipped screwdriver and remove the 4X triangle screw (consist 2X each side) base corner of the driver unit.
3. Use a flat blade Screwdriver to separate the top cover from the base of the unit. This will expose the electronic PCB board and its components.

3.2.2.3 Dismantling Process of Edison Screw Cap Style LED

Figure 3.2: Olsent Edison Screw Cap.

1. Place the LED light bulb into the vice, position the bulb into the vice just below the lens and the housing.
2. Slowly tighten by the turning vice handle, this will increase pressure causing the bulb lens/ diffuser to separate from its housing. Simply remove the lens/ diffuser from its housing, exposing the LED PCB board.
3. To separate the LED board from the housing further tighten the vice, forcing the LED PCB board to further separate from the housing.
4. Remove the bulb from the vice by unwinding the vice handle.
5. To remove the screw base from the housing, simply place screw housing into the vice and repeat process step 2 and 3 above. This will separate the base from the bulb housing.
6. Cut off the connection wires to separate the LED PCB board.

3.2.2.4 Dismantling Process of GU5.3 LED

Figure 3.3: Olsent GU5.3, 6W LED bulb.

1. Place the LED light bulb into the vice, position the bulb into the vice just below the lens and the housing.
2. Slowly tighten by the turning vice handle, this will increase pressure causing the bulb lens/ diffuser to separate from its housing.

3. Remove the bulb from the vice by unwinding the vice handle.
4. Remove the lens/ diffuser cap if it is not already fallen off
5. Using small Philips screwdriver remove the 2X Philips screw from the LED board.
6. Either by hand or uses of a pair of pliers, pull out the LED board and the electronic PCB board unit form the housing.
7. Cut off the wires from the electronic PCB board unit.
8. By hand, simply remove the silicon material from the electronic PCB board unit.

3.2.2.5 Dismantling Process of GU5.3 All Glass LED

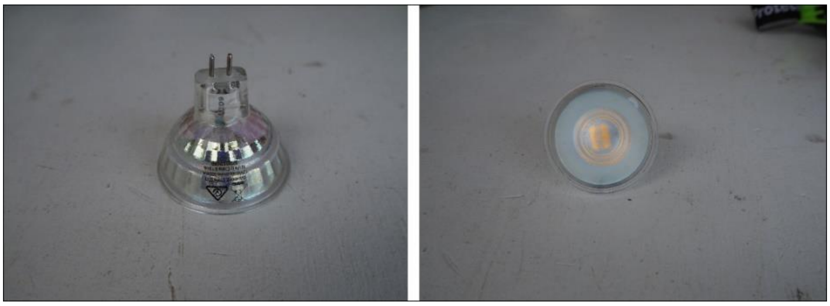

Figure 3.4: Phillips GU5.3, 5W LED bulb.

1. Place the vice into safety plastic container. Ensure correct safety procedures is used.
2. Repeat step 1-2 as above process. Careful about broken glass and possible flying glass fragments as the LED bulbs are all glass construction.
3. Remove the remaining unit from the vice.
4. Remove the lens/ diffuser cap if it is not already fallen off
5. Simply remove any remaining glass material held to the electronic PCB board by silicon material.
6. Separate the LED board form the electronic PCB board.
7. Remove any silicon material from the electronic PCB board.

3.2.2.6 Dismantling Process of Circuit Board

1. Using a pair of plier or Vice grip secure the LED PCB board.
2. Using the heat gun (setting at max temperature) place heat gun approximately 5cm to 10 cm away from the board. Apply heat to the board.
3. Once the solder starts to melt, shake, or tap the LED PCB board to remove the components. (component should fall off the circuit board).
4. Repeat step 1-3 process for the electronic PCB board.

3.3 Processing of Materials

Review of the existing literature surrounding technological processing of materials identified two technologies predominantly used in the recycling of e-waste such as LED bulbs, hydrometallurgical and pyrometallurgical processing (Navazo et al. 2014; Soo & Doolan 2014). Various technologies are used in a range of applications and differ by geographic location. While the processes employed for other waste products such as mobile phones may share similarities with LED bulbs, it is necessary to evaluate the processing methods available to determine which technology is better suited to the recycling of LED bulbs as one technology may not suit all applications. The ultimate purpose of such an assessment is to identify whether technologies being used for other waste streams are suitable for integration of LED bulbs, or if alternative technologies provide an improved approach. This methodology follows a similar assessment method used by other researchers of developing a set of assessment criteria and ensuring assessment is conducted across a range of relevant categories to enable a holistic assessment from a range of perspectives (Soo & Doolan 2014).

The following section develops criteria for the assessment of recycling technologies and processing techniques currently in use, to determine which technological processes are best suited to Australia for the recycling of the LED light bulbs.

A set of criteria was developed to aid towards determining which methods are best, identifying their strengths and weakness and their benefits regarding environmental, social, economic and technical aspects. Two technological processes were identified in the literature review which are currently being implemented in various countries around the world in the recycling of e-waste. These two processes include Hydrometallurgical and Pyrometallurgical processing. The assessment criteria for these two processes will be developed and split into the following categories:

- **Environmental** – Criteria that assesses the process with respect to environmental outcomes and consequences including output materials, pollution etc
- **Social** – Criteria that assesses the social impact of the process including local community, external social factors, social acceptability of the process and sustainability
- **Economic** – Criteria that assesses the economic impact including benefits and potential consequences, such as added value of output materials and job creation.
- **Technical** – Criteria that assesses the technical value of the process including quantitative and qualitative value of the process and output materials.

Qualitative criteria will be assessed and given a rating to ensure that both processes can be compared objectively following completion of each assessment. Closed ended (yes/no) criteria will similarly be assigned a numeric rating for comparison purposes.

The environmental assessment criteria for the technological processes are as follows:

1. What waste products are produced as a result of this process and are they considered hazardous?
2. Are any waste by-products appropriately contained in the process?
3. Does the process produce toxic gas as a by-product and if so in what quantity?
4. Does the process produce toxic liquid waste by-products and if so in what quantity?
5. Does the process produce toxic solid waste by-products and if so in what quantity?

The social assessment criteria for the technological processes are as follows:

1. Can any waste by-products from the process be disposed of responsibly or recycled in a follow-up process?
2. Does the process have any negative health consequences for the public or those involved in the process?
3. Is the process deemed socially acceptable and if not, can public education contribute to the acceptance of the process?

The economic assessment criteria for the technological processes are as follows:

1. How much does the recycling process cost compared to the value of the recovered materials?
2. Is the process scalable for large scale recycling purposes?
3. In what way does the process contribute to job creation and ongoing employment?

The technical assessment criteria for the technological processes are as follows:

1. What materials are recovered from this process?
2. How much of the original materials are recovered in this process?
3. How does the recovered material quality differ to the virgin material?
4. Is the quality of the resulting materials adequate for inclusion in new product manufacture?

3.4 Australian Legislation and Policy

As identified in the literature review, a legislative gap outlined the need to include LED light bulbs recycling within e-waste legislation and polices. Therefore an assessment frame work was produced to assist the development of the various stages of the legislation and policies from the analysis to the final design proposal of the legislation scheme (SLR Consulting NZ 2015).

Part of this methodology will cover the assessment of Australian Legislations and Policy, the purpose of this is to assess current legislations and policies regarding the E-Waste recycling only. Development of assessment criteria will assist in the review of current legislation, in identifying opportunities for improvement to legislation and provide a framework for the development of further legislation and policy as shown in Figure 3.5.

3.4.1 Framework for Assessment and Development of Legislation and Policy

An analysis of the current legislation and policies is required to assist in the development of additional policies and legislation tailored to the recycling of LED bulbs.

1. Legislation and Policy Analysis (Stage 1): Analyse and compare current E-Waste Legislation and Policy, identifying parts of the legislation and policy that are relevant to the recycling of LEDs
2. Identification of Gap in Legislation and Policy (Stage 2): Further identify what is missing within the current legislation and policies which have been identified from stage 1 and clearly outlines these gaps and weaknesses.
3. Preliminary Scheme Design (Stage 3): Develop draft documentation, processes and proposed amendments to existing policy where necessary for the recycling of LEDs.
4. Industry Consultation and Stakeholder Engagement (Stage 4): Consult with industry and key stakeholders on legislation and policy to identify areas for improvement in the legislation / policy.
5. Refinement of Scheme Design (Stage 5): Amend documentation according to feedback from industry representatives and key stakeholders.
6. Scheme implementation: (Stage 6): Implementation of the process and monitoring of its performance for a predetermined trial period. which is then reviewed after this period to ensure any issues are amended which is done at scheme evaluations stage.
7. Scheme Evaluation (Stage 7): Feedback is sought from industry and key stakeholders on scheme performance and a review is conducted to evaluate the effectiveness of the scheme. Any issues in the implementation of the scheme are identified.
8. Recommendation of Improvements (Stage 8). Following detailed evaluation of the implemented scheme, fine tuning of the framework and policy can be conducted. Amendments to the scheme will be proposed and influenced by scheme performance and industry and key stakeholder feedback.

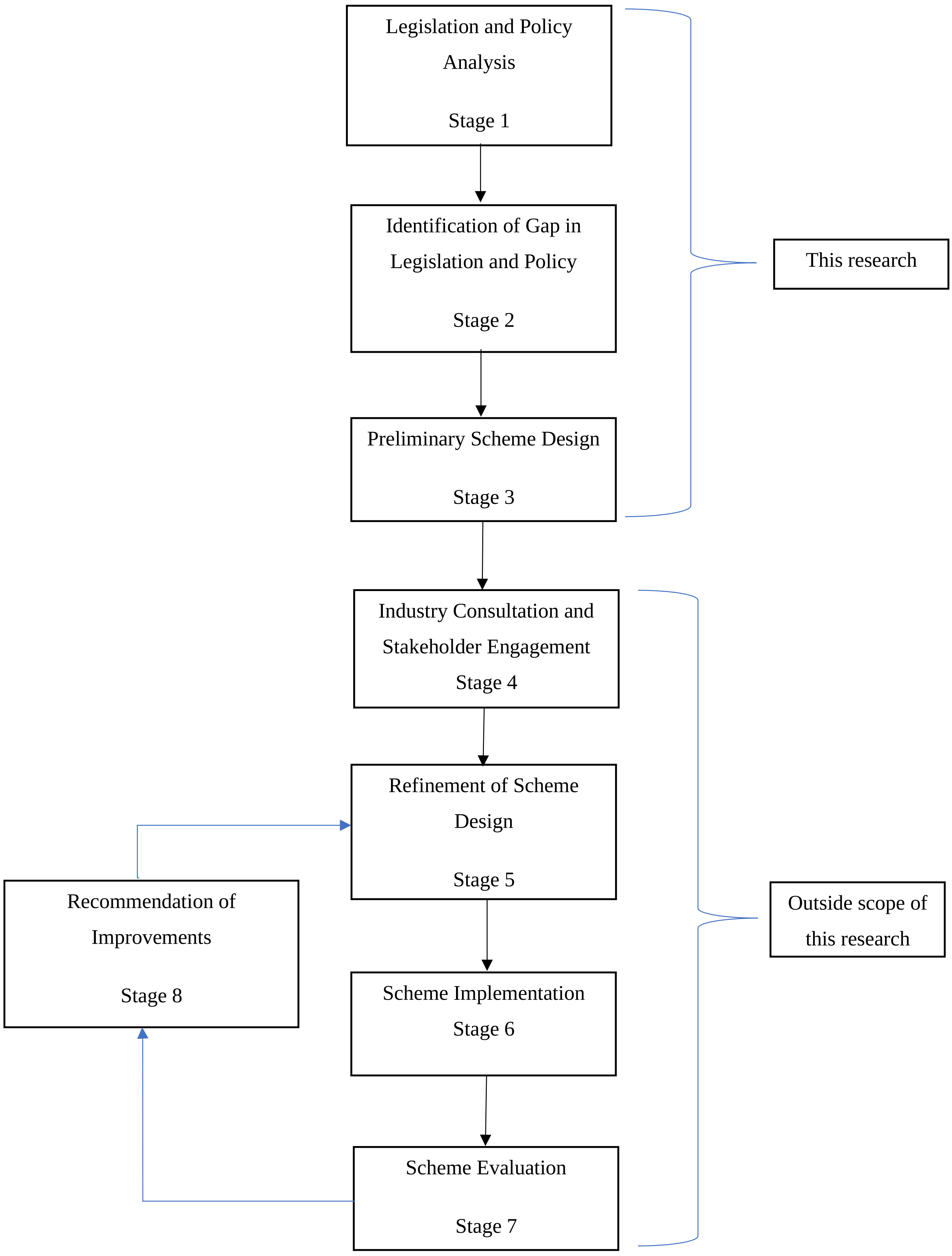

Figure 3.5: Framework for value optimisation for resource recovery of LED light bulb recycling

3.4.2 Criteria for Legislation and Policy Assessment and Gap Identification

Currently there are E-Waste legislations already implemented within Australia wide, this also extends to local councils' authorities. The main legislation surrounding E-Waste in Australia is known as the Product Stewardship Act 2011. The Product Stewardship Act 2011 is integrated and forms part of all the states and local councils' policies:

Currently the Product Stewardship scheme has a wide range of e-waste products listed under this scheme. Product lines are categories into its family types and its recyclers. Under the current Product Stewardship Scheme, for E-Waste the following categories are:

- Product Stewardship of Mobile Phone. A voluntary scheme operated by Mobile Muster that facilitates the recycling of all types of mobile phones (Mobile Muster 2020).
- Product Stewardship for National Scheme for Television and Computers (Australian Government 2011). A co-regulatory scheme which facilitates the recycling of a wide range of e-waste products such as TV, PC, laptop, printers, peripherals, electronics toys, blenders, toasters, electric jugs, and other household electronics products
- Product Stewardship Disposal of Mercury-containing Lamps. A voluntary stewardship scheme operated by EcoCycle that facilitates the recycling of compact fluorescent light bulbs and other lamps that contain mercury. EcoCycle current recycles a small volume of LED light bulbs within its facility (Ecocycle 2019).

The assessment of legislation and policy will consist of an analysis of existing product stewardship schemes in Australia. The literature review identified three schemes that may be relevant to the recycling of LED bulbs. Three of these product stewardship schemes will be assessed against a set of criteria to determine what aspects of the scheme are useful and applicable to LEDs, and to determine what further guidelines may be required for the inclusion of LEDs in either one of these schemes or a new scheme. Assessment will include a qualitative description of the scheme performance against each criterion and will be assigned a rating accordingly. Each scheme will be assessed against the following criteria:

1. What are the existing e-waste categories of products that are included within the Product Stewardship Scheme?
2. Does the scheme currently include provision for recycling of LED bulbs?
3. Where products currently included in the scheme consist of similar materials and composition to LED bulbs, how may the existing provisions, guidelines and restrictions apply to the recycling of LEDs?

4. What additional provisions, guidelines and restrictions would be necessary for inclusion of LEDs in the scheme?
5. What aspects of the scheme could be adopted in a new scheme tailored specifically to LEDs?

3.4.3 Preliminary Scheme Design

Following the assessment of the existing legislation against the criteria developed above, a range of preliminary options will be identified and evaluated further. Upon evaluation, one option will be selected and developed further to provide provision for LED recycling in existing and / or new legislation and policy.

3.4.4 Industry Consultation and Stakeholder Engagement

During Stage 4 of the assessment and development of policy and legislation, relevant stakeholders will be contacted in order to acquire additional information regarding legislation, policies, manufacturing processing and material outputs. Initial communications will be done by phone calls or email as appropriate and depending on availability of stakeholder contact details. The following stakeholders have been identified as possible sources of pertinent information:

- Phillips Australia. retrieve information regarding Phillips LED light bulbs material compositions, quantities its various material makeup.
- Woolworths Australia. obtain information to LED suppliers and brands
- City of Gold coast (city council). For information regarding local council recycling shames of LED light bulbs.
- Queensland Government, Department of Environment and Science. For information regarding local council recycling shames of LED light bulbs.
- Victoria Government. For information regarding local council recycling shames of LED light bulbs.
- NSW Government, EPA Department: For information regarding local council recycling shames of LED light bulbs.
- Australian Government, Department of Agriculture, Water, and the Environment. For information regarding local council recycling shames of LED light bulbs.
- CMA Ecocycle (Processing & Recycling Mercury Waste Australia). For information regarding materials being extracted within their facility and types of recycling processes being utilised.
- Mobile Muster, Australia. For information regarding materials being extracted within its current facility, type of recycling processes being utilised within the company.

Chapter 4. Analysis and Results

This chapter presents the results of the various assessments against the criteria and methodology outlined in Chapter 3. Primarily this includes assessment of the following core topics of this research:

1. Design for disassembly and recycling
2. Processing of materials
3. Australian legislation and policy

4.1 Disassembly Procedure Analysis

The experimental stages, which involved the disassembly process of the 4 LED types light bulbs. The disassembly procedure was carried in accordance with the process outlined in Chapter 3.2.2 Disassembly Procedure for LED Bulbs and Appendix B - Risk Assessment and Safety Procedures.

Throughout the experiment there were several difficulties found, with various methods being used, many issues were found during the disassembly of the 4 LED bulbs. These issues will be further discussed below.

4.1.1 LED Housing Disassembly

4.1.1.1 Ceiling LED down light

This ceiling LED down lights shown in Figure 4.1 show construction makeup consists of two separate units. The main LED light unit is attached to the electronic driver by cord between the two units, the dismantling of the units is needed to be done by two separate processes. The use of the vice is a simple process which easily separates the lens/reflector from the main LED housing unit. This method approach was used for all the 4 bulbs used for this experiment.

Figure 4.1: Downlight Diffuser Separation

In order to separate the LED PCB board, 3 screws are required to be removed manually using a Philips head screwdriver. Once the PCB board is removed, underneath is an all-aluminium cast housing as shown in Figure 4.2 and Figure 4.3. The outside of the housing is all plastic material coated onto the all-aluminium cast body. The all-aluminium body also acts as a heat sink for dissipation of heat. The internal reflector is simply thin plastic material held by small amount of silicon material. The metal spring, which is use for ceiling mounting of the bulb unit is made of plated metal material.

Figure 4.2: Downlight LED Board removal process

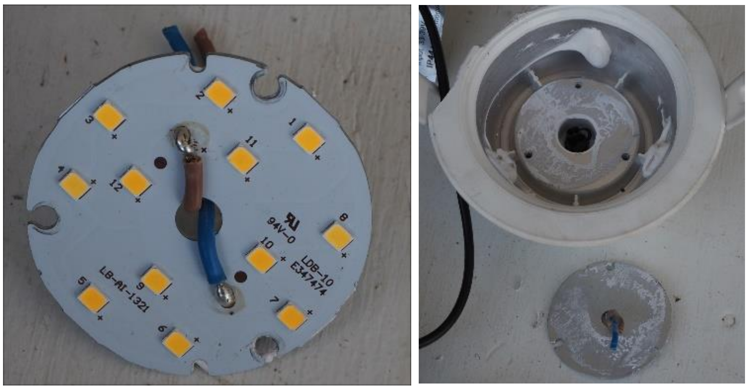

Figure 4.3: Fully disassembled ceiling downlight

The LED light units are all SMD components which are soldered onto a PCB board. The PCB board is then glued onto an aluminium plate, for heat dissipation purposes. Disassembly of the power supply requires manual intervention. The power supply consists of PCB board, which is constructed of a mixture of SMD components and through-hole components as seen in Figure 4.4. The PCB board is enclosed in a plastic box which can be accessed by the removal of 4 specialised triangle screws.

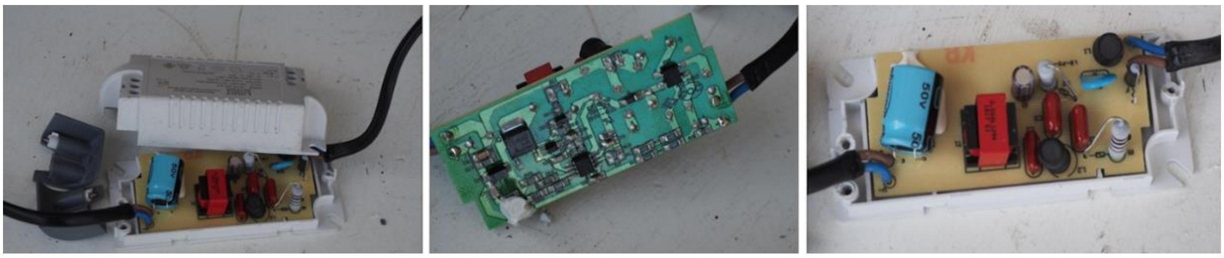

Figure 4.4: Disassembly of driver unit

4.1.1.2 GU5.3 and Edison Screw Cap style LED bulb

The same approach of separation of the lens and main body for both GU5.3 and the Edison screw cap were utilised by the use of the vice to crush the bulbs housing as shown in Figure 4.5 to separate the lens from its housing.

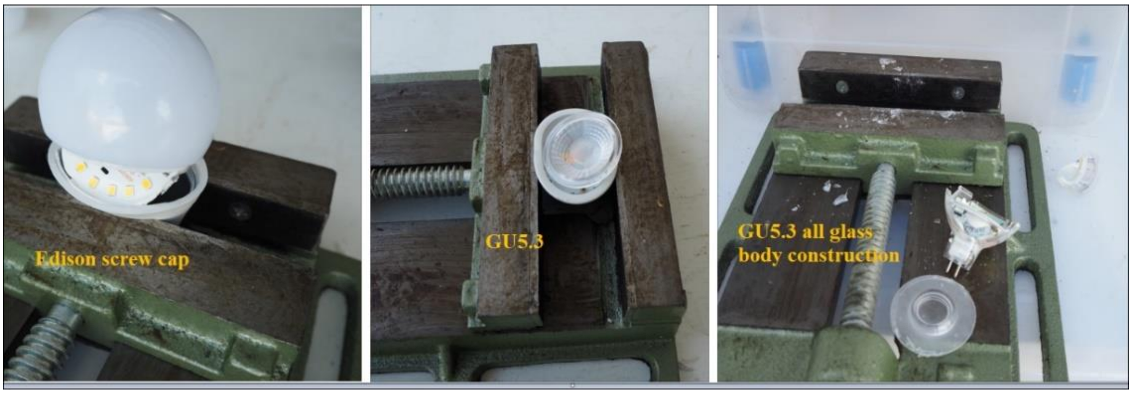

Figure 4.5: Uses of vice for separation of housing and lens

Once the lens has been separated, the next stage is the removal of the electronics circuit PCB board. All 3 LED bulbs required different approaches for the removal of the electronics circuit PCB board due to the different assembly methods utilised by the different manufacturers.

For the LED GU5.3 (non-glass construction), removal of the LED PCB board requires 2 small Philips screws to be removed as the LED PCB board is held secured by the screws as shown in Figure 4.6. Once the screws are out, the complete unit which includes LED PCB board and the electronics circuit board are easily removed. The LED PCB board is further attached by two wires which requires removal by cutting off the connection wires.

Figure 4.6: GU5.3 PCB separation

The electronics PCB circuit board () is coated by a silicon type material. To expose the electronics PCB circuit board, simply pull off the silicon type material, which is easily broken off as shown in Figure 4.7.

Figure 4.7: PCB disassembly.

4.1.1.3 GU5.3 All glass material LED bulb

The GU5.3 LED bulb all glass housing construction required a different approach. While previous LED light bulbs required several stages to remove the electronics PCB board, the all glass construction was placed into the vice, where the glass housing was simply crushed, releasing the lens/diffuser.

Figure 4.8: GU5.3 all glass disassembly.

Once the lens / diffuser is removed, the electronic PCB circuit board shown in Figure 4.8 is held within the glass body via silicon material, the broken glass body can easily be pulled apart to exposing the electronics PCB circuit the LED PCB board, the two PCB boards are held together by two contact pins and silicon material. The LED PCB board is easily separated by disconnecting the LED board from the two contact pins of the electronics PCB board. The PCB circuit board is isolated by a small heat shrink type material which is easily pulled or cut off as show in Figure 4.8.

4.1.1.4 Edison Screw cap style LED bulb

Figure 4.9: Edison bulb dismantled

After removal of the lens/diffuser, the LED PCB board is held secure by small amount of silicon material, it can be easily be separated by a small screwdriver and cut off the conducting wires with plier as shown in Figure 4.9. The housing unit is aluminium construction with plastic coating. While the 'screw mounting' unit is of aluminium construction with ceramic insulation between the 'screw base' and the positive/live contact terminal. The positive/live terminal has a resister in series between the terminal and the conduction wire.

4.1.2 PCB Disassembly

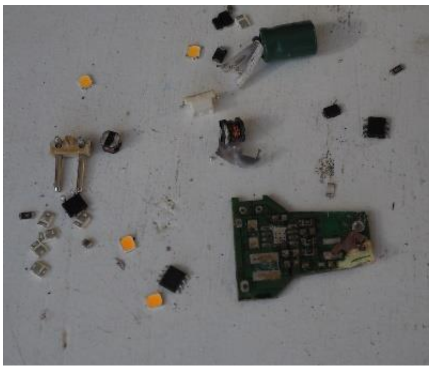

Figure 4.10: PCB board component removal

Evenly applying the hot air gun over the circuit boards at 400°C, once the solder has reached temperature and starts to melt, the components on the board can be easily removed by simple vibration of the PCB circuit board. Majority of the component will be easily shaken off the board as shown in Figure 4.10 with exception of few discrete components through-hole components.

The following 4 LED bulbs were used during the dismantling process. During the experiment, each step was assessed and analysed for its ease of dismantling and the separation of various parts of the light bulb. Each bulb was rated against the criteria set out from Table 3: Disassembly assessment criteria, assessment steps 1 to 7. The outcomes and rating are set out in Table 4: Rating of disassembly

The following outlines the criteria's regarding the disassembly assessment:

Table 3: Disassembly assessment criteria

Category	Criteria
A	Very little effort and manual intervention required, can be separated with few steps.
B	Requires additional manual intervention and process.
C	Labour intensive, requires significant intervention, cannot be separated in few steps.
Y	Defines the outcome as Yes.
N	Defines the outcome as No.

Criteria	**GU5.3 Bulb**	**GU5.3 All Glass Bulb**	**Ceiling Down Light**	**Edison Screw Style Bulb**
The ease of dismantling for gauging their complexity of LED light bulb structures. How easy can it be dismantled and break apart/separated?	C	A	C	B
Ease of separations of various material compositions. Example, lens/reflector, PCB board, LED board, heat sinks materials, glass, plastics, wires, and LED bulb housing.	B	A	C	B
Requirements for specialist tooling?	Y	Y	Y	Y
What construction method is used?	All in one unit.	All in one	All in one Clip/Driver unit	All in one
Can the disassembly be conducted automatically?	Y	Y	Y	Y
How many disassembly stages are required in the entire process?	5	5	5	6

Table 4: Rating of disassembly

KEY	
Category	**Ease of Disassembly**
A	Very little effort can be separated with few steps. Requires less manual intervention.
B	Requires additional manual intervention and process.
C	Labour intensive. Cannot be separated in one step. Requires additional intervention and process.

LED bulb types	Bulb Sections	Material Composition	Ease of disassembly	Disassembly comment
GU5.3	Lens/reflector	Clear hard plastic/Perspex	**C**	Requires some effort, additional steps and manual intervention where required for the removal of the 2 'Philips' screws.
	Housing body material	Aluminium construction with plastic coating		
	LED PCB board	PCB circuit board made of fiberglass composition and glued onto aluminium plate, solder.		
	Electronics PCB circuit board	PCB circuit board made of fiberglass composition. Copper track materials, Glue, Polymetric materials, epoxy resin, SMD LED components.		
	Contact Pin	Solder, metal plated		
GU5.3 All Glass	Lens/reflector	Clear hard plastic/Perspex	**A**	Requires little effort, there were no additional screws to be removed. The all construction unit where easily crushed and exposed all its components. Some of the glass particle needed to be manually removed from the silicon materials.
	Housing body material	All glass		
	LED PCB board	PCB circuit board made of fiberglass composition and glued onto aluminium plate, solder.		
	Electronics PCB circuit board	PCB circuit board made of fibre glass composition, coper tracks, solder material, glue, polymetric malarias, epoxy resin, SMD LED.		
		Nonconductive silicon material, Heat sink paste material.		
	Contact Pin	Solder, metal plated		
Celling Down Light	Lens/reflector	Frosted Plastic	**C**	Consisting of two stage unit. The LED light unit and the driver are separate units. This required additional effort and much more manual interventions for separation/disassembly of both units.
	Housing body material	Aluminium construction with plastic coating		
	LED PCB board	PCB circuit board glued onto aluminium plate. Heat sink paste, solder.		
	Power supply/driver unit box	Plastic box construction and material		
	Plug/Connection	Nonconductive PVC material. Solder, metal plated, Copper.		
	Power supply/driver Electronic PCB circuit board	PCB circuit board part fibre glass construction, coper tracks, solder, glue, polymetric materials, epoxy resin, various SMD components. Nonconductive silicon material.		
Edison Style Bulb	Lens/reflector	Frosted Plastic	**B**	Requires some effort, additional steps and manual intervention where required for the separation of the LED board.
	Housing body material	Aluminium construction.		
	LED PCB board and Electronics PCB circuit board are one unit.	PCB circuit board made of fiberglass composition and glued onto aluminium plate, coper tracks, solder, glue, polymetric materials, epoxy resin, various SMD components. Nonconductive silicon material.		
	Contact Pin/screw mount	Solder, metal plated contact		

4.2 Development of LED Bulb Specific Policy / Schemes

To address the insufficiencies in existing policies surrounding the product stewardship schemes and recycling of LED lightbulbs, new schemes will be developed that adapt and build upon existing legislation and framework. A range of solutions will be developed, and each proposal will then be evaluated for its strengths and weaknesses, before one proposal is ultimately recommended for implementation. Each proposal is intended to be executed under the framework of the existing Product Stewardship Act (Australian Government 2011), with expansion of the provisions of the Act where necessary to enable implementation of the scheme. Additionally, all parties involved in the collection, transportation and storage of waste products are required to be certified under AS5377 standards, to ensure compliance under the relevant health, safety and environmental regulations and policies.

4.2.1 Industry Funded Recycling Scheme

The Industry Funded Recycling Scheme is developed under the Product Stewardship Act 2011 which is currently being utilised for similar schemes such as the Television and Computer e-waste recycling scheme (Australian Government 2011). Under an industry funded recycling scheme, importers and local manufacturers of LED light bulbs become directly responsible for funding the recycling of bulbs through a co-regulatory arrangement. Importers of LED light bulbs would be required to register and contribute to a co-regulatory fund to facilitate the recycling of the products sold by each retailer at the end of the products' life.

An industry funded scheme would be managed under Government legislation, which would ensure that importers and retailers participate in the scheme in accordance with legislative requirements. The government would further be responsible for the regulation and compliance assessment of liable parties including importers and retailers, and monitoring of co-regulators and administrators to ensure outcomes are being achieved in accordance with scheme targets.

Legislation would require retailers to join and contribute to the accredited fund of their choice, the required amount correlating with the quantity of bulbs imported by the retailer each year, once they had reached a pre-determined annual import threshold or quota. The co-regulators or administrators are then responsible for managing these funds appropriately in order to achieve the objectives or target recycling rates of the scheme, on behalf of the retailers. Their responsibilities include providing information and education to the public regarding collection facilities for waste LED bulbs, and delivery of the scheme on behalf of retailers. They are additionally responsible for contracting the collection of LED light bulbs waste to an approved e-waste recycler processing plant, which is to be done by means of competitive market share. Their responsibilities could be further expanded to include elements such as marketing and branding to support the scheme and promote its use to the public, capturing data on recycling efficiency and effectiveness and reporting outcomes under Government legislation.

Once contractual agreements are established between the two parties (administrator and the recycling facilities), the LED waste will be collected and transported by the recyclers to the approved recycling facilities for processing, material recovery, and repurposing by the recycler.

Co-regulators would additionally be required to provide reporting to the regulator, the Australian government, to demonstrate evidence of the scheme outcomes and whether the aims of the scheme are being met successfully. The government would further be responsible for auditing and monitoring of co-regulators to ensure the continued success of the scheme and to refine the scheme as appropriate. This would include the establishment of quality assurance processes and auditing of co-regulators and recyclers on an ongoing basis. Where necessary, the government would adjust legislative requirements to facilitate the ongoing effectiveness of the scheme and enable improvements in scheme outcomes.

Because funds are collected early in the life cycle of the LED bulbs, consumers, including residential households and small businesses, are able to dispose of their waste bulbs for recycling free of charge at designated and approved drop off facilities provided in their area. Typically, the cost of recycling borne by the retailer is passed on to consumers, at least partially, in the purchase cost of the product. Passing on of such fees may be regulated under legislation to ensure the objectives of the scheme are achieved. Recycling of LED bulbs is further incentivised by restricting the disposal to landfill.

4.2.2 Consumer Product Refund Scheme

The Consumer Product Refund Scheme is developed based on an existing scheme which is currently being utilised by the Containers for Change scheme which facilitates the recycling of eligible containers such as cans and bottles (Queensland Government 2019). A product refund scheme would be operated as a partnership between state government and retailers throughout Australia. In this scheme, the LED light bulb has the refund unit value included in the upfront sale price of the LED light bulb. This type of scheme provides a financial incentive to encourage the recycling of the LED light bulbs by providing consumers with a partial refund of the purchase price on return of the waste product. A product refund recovery and recycling scheme would be funded jointly by the lighting retailers and state government within Australia.

The operations of the scheme are managed by an organisation appointed or approved by the respective state government. The appointed body may be a non-profit organisation which operates the scheme on behalf of state and local government. They would be responsible for scheme management, providing recycling bins, drop off locations, vending machines, and the collection of LED waste products. They would further be responsible for providing annual reporting to local / state government on the metrics relating to the collection of waste LED products to inform the effectiveness of the scheme.

To facilitate the collection of waste LED products, a network of recycling vending machines will be established at a range of venues such as malls, shops, or community centres, together with local council return points to enable easy access for consumers to return the bulbs. LED light bulbs can be disposed through the vending machines in order for consumers to receive a refund. Consumer will be instantly refunded a predetermined amount for each bulb that is returned (an amount of 10 cents per bulb is proposed). Alternatively, donation community refund bins may also be set up within approved community centres. Any LED light bulbs returned through the community return bins are held as storage points. Funds accumulated are then distributed within the community centre once the bulbs are collected by the appointed managing organisation and passed on to the recycler.

The appointed management organisation are responsible for the collection and transportation of the waste LED bulbs to the recycling facilities for processing and material recovery. The recycling contracts are an agreement between the state councils and the recyclers. E-waste recyclers must meet and operate within state, territory and local government legislation and policies, including environmental regulation and health and safety policies.

4.2.3 Voluntary Product Recycling Scheme

Voluntary, industry-led product stewardship recycling schemes are quite common for a number of products in Australia and may similarly be implemented for the purpose of collecting and recycling LED bulbs at the end of their life. Such a scheme would be championed by the lighting industry, with minimal involvement of state or federal government. Despite the government's limited involvement, government grants, accreditation and product stewardship guidelines may assist in the successful implementation of a voluntary, industry-led recycling scheme. Under such a scheme, industry associations and companies may partner to form voluntary arrangements, in order to meet social and environmental obligations and expectations.

As a voluntary scheme, retailers of LED bulbs may become involved at their own pace, organisations are free to participate but participation is not mandatory. However, increasing pressure and lobbying by community and environmental groups, together with company values transitioning to more sustainable business models, may contribute to the increasing number of companies becoming involved in such voluntary recycling schemes. Participants under the voluntary recycling scheme may opt to apply for accreditation under the Product Stewardship Act (Australian Government 2011), providing them with funding and government resources to further facilitate the scheme objectives.

Voluntary product stewardship arrangements and accreditation is set out by the Australian Government. Accreditation has a life span for a period of five years, thereafter application requires resubmission to receive renewed accreditation and continued funding. Submission is costly and does have an application fee. This type of scheme would allow the lighting industry to participate, tailor and pioneer its own approach towards targeting specific environmental and community obligations while meeting the obligations set out within the product Stewardship Act. Accreditation gives the lighting industry the rights to display the product stewardship logo. The voluntary product recycling scheme is therefore left solely to be administered by the lighting industry. There are no recycling targets that are set out such as that of the industry funded scheme, although annual reporting to the Product Stewardship board would be required for publication and information purposes.

As with other product stewardship schemes, the voluntary product recycling scheme would be free to consumers, where they can freely drop off LED light bulbs to any of the participating organisations drop off bins specifically for LED light bulbs at no cost. This provide a convenient way for consumers to drop off LED light bulbs as collection points would be located in various stores and other locations consumers are likely to visit.

The lighting industry is responsible for the promoting, transportation, and recycling of the end of life of the product. They will set up free of charge recycling drop off points or bins at selected locations such as outside shops, supermarkets, malls, and local councils recycling depots. While many organisations may offer to participate by offering drop off bins within their store, collection and transportation of the waste products to the recycler will be provided by the lighting industry.

The lighting industry are responsible for the recycling of the end of life of its product by contracting an approved recycler facility for the repurposing and recycling. The recycler is not required to be government approved, however they must operate within state, territory and local government legislation and policies, including environmental regulation and relevant health and safety policies.

4.3 Assessment of Recycling Technologies

The following tables outline the outcome of assessment of the current recycling technologies and processing techniques in use in the recycling of electronic waste, including the recycling of LEDs. Two recycling processes, hydrometallurgical and pyrometallurgical, will be assessed against the environmental, social, economic and technical criteria as defined in the methodology. Table 5 describes the outcomes of the assessment of hydrometallurgical processing against the defined environmental assessment criteria. Similarly, Table 6 describes the outcomes of the assessment of pyrometallurgical processing against the same set of environmental assessment criteria.

Table 5: Environmental Assessment for the technological processing for Hydrometallurgy

Environmental assessment criteria	**Outcome**
What waste products are produced as a result of this process and are they considered hazardous?	The process also produces highly corrosive conditions. Depending on the process, sulfuric acids or hydrochloric acid may be used. Hydrometallurgical processing is highly reliant on chemical use throughout its process. Waste products include sulphur oxides and wastewater containing ammonium, which is difficult to treat.
Are any waste by-products appropriately contained in the process?	Waste by-products are not transmitted as pollutants into waterways; however, some is released into the air. Some by-products are difficult to treat, meaning toxic by-products may inevitably become pollutants.
Does the process produce toxic gas as a by-product and if so in what quantity?	Yes. Exact values not known and out of the scope of this research.

Table 6: Environmental Assessment for the technological processing for Pyrometallurgy

Environmental assessment criteria	**Outcome**
What waste products are produced as a result of this process and are they considered hazardous?	Residue remaining (slag). Output gasses which are derived from zinc oxide, copper and lead oxide dependent of what materials are being smelted. Carbon dioxide (Navazo et al. 2014). Result in by product including slag and toxic gases which can be difficult to manage effectively (Gupta & Mukherjee 2017)
Are any waste by-products appropriately contained in the process?	Yes
Does the process produce toxic gas as a by-product and if so in what quantity?	Yes. Exact values not known and out of the scope of this research.

Table 7 describes the outcomes of the assessment of both hydrometallurgical and pyrometallurgical processing against the defined social assessment criteria.

Table 7: Social Assessment for the Technological Processing for Hydrometallurgy and Pyrometallurgy

Social Assessment Criteria	Hydrometallurgy	Pyrometallurgy
Can any waste by-products from the process be disposed of responsibly or recycled in a follow-up process?	Yes	Yes
Does the process have any negative health consequences for the public or those involved in the process?	Yes	Yes
Is the process deemed socially acceptable and if not, can public education contribute to the acceptance of the process?	Yes	Yes

Table 8 describes the outcomes of the assessment of both hydrometallurgical and pyrometallurgical processing against the defined technical assessment criteria.

Table 8: Technical Assessment for the Technological Processing for Hydrometallurgy and Pyrometallurgy

Technical Assessment Criteria	Hydrometallurgical	Pyrometallurgical
What materials are recovered from this process? (main materials)	Copper. Gold, lead, tin.	Copper. Gold, led, tin.
How much of the original materials are recovered in this process?	95%	80-90% recovered. Aluminium not recoverable. 20% of valuable metal is lost
How does the recovered material quality differ to the virgin material?	89-99% purity with additional processing. (Rudnik & Dashbold 2017).	With further refinement to output 99.99% (Prasad & Vithanage 2019).
Is the quality of the resulting materials adequate for inclusion in new product manufacture?	Yes, quality of recovered material can be as pure as virgin materials	Yes, quality of recovered material can be as pure as virgin materials
Current industries preferred processing methods for E-Waste	No, process is not suitable for large production scale	Yes, currently being utilised by industries in Australia for E-Waste

Table 9 describes the outcomes of the assessment of hydrometallurgical processing against the defined economic assessment criteria.

Table 9: Economic Assessment for the Technological Processing for Hydrometallurgy

Economic Assessment Criteria	**Outcome**
How much does the recycling process cost compared to the value of the recovered materials?	High. Exact dollar values is not in the scope of this project, But it is still cheaper to recycling than ore mining. (Navazo et al. 2014).
Is the process scalable for large scale recycling purposes?	No. Processing requires less operating cost. Not suitable for large scale e-waste recycling (Navazo et al. 2014)
Disadvantages of this process.	Limited to e-waste recycling of fewer metals at once (Navazo et al. 2014)
In what way does the process contribute to job creation and ongoing employment?	Creating jobs at: • Recycling centres. • Transportation sector • Processing plant • Distribution sector • Suppliers end • Manufacturers end for uses in new products.

Table 10 describes the outcomes of the assessment of pyrometallurgical processing against the defined economic assessment criteria.

Table 10: Economic Assessment for the Technological Processing for Pyrometallurgy

Economic Assessment Criteria	**Outcome**
How much does the recycling process cost compared to the value of the recovered materials?	High. Exact dollar values is not in the scope of this project, But it is still cheaper to recycling than ore mining. (Navazo et al. 2014).
Disadvantages of this process.	High setup cost, high operating cost, sizable infrastructure and incorporated smelting system. (Navazo et al. 2014).
Is the process scalable for large scale recycling purposes?	Yes. It is profitable at large scale production (Navazo et al. 2014).
In what way does the process contribute to job creation and ongoing employment?	Creating jobs at: • Recycling centres. • Transportation sector • Processing plant • Distribution sector • Suppliers end • Manufacturers end for uses in new products.

4.4 Chapter Summary

Chapter 4 presented findings that were identified within the 3 sections within the methodology.

1. Design for Disassembly and Recycling
2. Processing of Materials
3. Australian Legislation and Policy

From each of the categories, the observations and results were measured against the various criteria set out throughout these 3 sections from the methodology.

The following chapter 5 will provide a more in-depth discussion and review of these results in order to provide recommendations for the improvement of recycling processes and product stewardship schemes.

Chapter 5. Discussion and Analysis

In order to recommend an optimised process for the recycling of LED bulbs, further assessment of the proposed solutions is required. This chapter discusses the advantages and disadvantages of the proposed recycling schemes, areas for improvement in LED bulb design and assembly as identified through assessment of the dismantling process and advantages and disadvantages of the two recycling technologies investigated as part of this research. This discussion will assist in feasibility assessment and ultimately providing recommendations for the implementation of a recycling scheme and processing technology, as well as improvements to the design of LED bulbs to facilitate their recycling.

5.1 Analysis of Proposed Recycling Schemes

The analysis of the proposed recycling schemes will be broken into advantages and disadvantages of the three schemes described in Chapter 4. One scheme will then be recommended based on the completed assessment. The three schemes are as follows:

1. Industry Funded Recycling Scheme
2. Consumer Product Refund Scheme
3. Voluntary Product Recycling Scheme

5.1.1 Industry Funded Recycling Scheme

Product stewardship under an industry funded recycling scheme requires suppliers and manufacturers to be responsible for the end of life management of their products by providing financial backing or take back scheme for recycling of their products. Such schemes are facilitated by compulsory federal government regulation and fall under the principals of the Product Stewardship Act. Retailers and manufacturers of LED light bulbs would be required to register and contribute to a co-regulatory fund to facilitate the recycling of LED bulbs at the end of their life.

An industry funded recycling scheme influences consumer behaviour to encourage the return of LED light bulb products at the end of their life. Inferior products typically have shorter life spans and thus require more frequent recycling which would generate a higher cost to the industry funded scheme. It is therefore expected that an industry funded scheme would facilitate the reduction of inferior products on the consumer market and an increase in higher quality products being available.

One advantage of an industry funded recycling scheme is that the cost of the recycling is incorporated into the price of the product, resulting in the provision of free recycling facilities being provided to the public. With limited options currently publicly available for the recycling of LED light bulbs, such a scheme would provide an alternative recycling option which would be widely available to consumers. This would therefore provide a means for the general public to recycle old LED light bulbs at no additional cost.

The provision of free recycling services would provide encouragement to further reduce e-waste pollution by reducing the quantity of LED bulbs sent to landfill and diverting LED lightbulb waste to recycling streams. This would additionally result in the reduction of valuable and heavy metals being disposed of as unrestricted domestic waste, ensuring a more sustainable future and the recirculation of precious metals and other materials into the production of new products, reducing the requirements for mining of virgin ore and other scarce materials. A scheme tailored to the recycling of LED bulbs such as an industry-centric recycling scheme would, however, be difficult to expand to provide provision for other forms of e-waste. An industry funded recycling scheme is therefore limited in its application.

Under an industry funded recycling scheme, designated approved drop-off facilities such as the local council recycling depot would be used for collection of waste LED bulbs. The advantage of utilising such existing facilities is through the reduced cost of not requiring entirely new infrastructure and collection points for collecting LED bulbs at the end of their life. It also ensures that the correct products are being recycled, as such facilities are actively managed. Within most local councils recycling depots consumers are guided to the correct recycling area or e-waste bins depending on product classification. This reduces contamination of recycling streams, facilitating the continued success of the scheme.

An industry funded recycling scheme would be operated under the Product Stewardship Scheme and regulated by federal government, resulting in consistent requirements and well-structured processes across the industry. Requiring industry to fund the cost of recycling would also ensure that manufacturers and retailers are all subject to the same regulations and that the cost of recycling is proportioned depending on the market share of each retailer and manufacturer, with respect to quantity of bulbs produced and sold. This would improve environmental outcomes by increasing the corporate social and environmental responsibility of the industry in general, thereby reducing the adverse impacts on wellbeing and the environment.

One of the disadvantages of an industry funded scheme is the reliance on consumers to utilise the recycling facilities available for disposing of LED bulbs at the end of their life, as the scheme does not include incentives for consumers. Additionally, where the scheme relies on existing infrastructure for collection locations, such as recycling depots, consumers may be less inclined to return LED bulbs for recycling if visiting such a facility is perceived as an inconvenience. Many consumers may continue with existing behaviours of disposing of LED bulbs in domestic waste, rather than making an effort to travel to a collection depot. This would especially be the case where the travel distance to a collection facility is significant, such as is the case for many people who do not live near recycling depots.

Under an industry funded scheme, facilities may register with the federal government under the Product Stewardship Act to become accredited recycling providers. Accreditation then provides increased brand recognition and awareness, encouraging consumers to utilise the recycling services. While accreditation provides a range of advantages, it can be costly to become accredited and applications for accreditation are not guaranteed to be successful. Applicants are required to meet a set of stringent requirements and must apply to renew their accreditation every five years. Accredited product stewardship providers are further required to provide annual reporting and data to the government demonstrating their performance against a range of targets and indicators. These targets are set by the government and reviewed as recycling technologies and initiatives improve over time, resulting in improved recycling outcomes and increasingly circular product life cycles.

Providers under the industry funded recycling scheme can apply for funding and sponsorship from the government to subsidise the cost of recycling processes. Providers who offer innovative initiatives to improve recycling outcomes may also be eligible for additional funding. Such subsidisation however is reliant on provision of grants by the government which may not always be available, depending on both political and economic climate. It is prudent therefore for such schemes to be operated effectively on their own merits without excessive reliance on government funding.

5.1.2 Consumer Product Refund Scheme

Under a consumer product refund scheme, LED light bulbs can be returned at the end of their life in exchange for a partial cash refund. This provides financial incentive to consumers to recycle LED light bulbs at the end of their life, rather than disposing of them in domestic waste bound for landfill. Such a scheme would be managed by state governments in a similar manner to refund schemes currently in place for other products. The benefit of state-operated schemes is enabling of the tailoring of the scheme to suit local recycling providers and the local population, as well as the ability to optimise the scheme more easily over time as improvements in technologies and processes are made.

Day to day operation of collection facilities can be run by a range of registered providers including non-profit organisations as well as private businesses that provide collection points to the general public. This has the two-fold benefit of providing the greatest range of drop off facilities while maintaining a consistent and streamlined recycling process from collection through to processing. In addition, it provides fundraising opportunities to community centres and non-profit organisations who can set up drop-off points for members of the public who wish to donate their used LED bulbs for recycling in lieu of receiving a refund.

The convenience provided by the increased quantity of drop off locations together with the cash incentives is expected to result in a significant buy-in from consumers due to the reduced travel time required to drop off waste LED bulbs. This would subsequently result in the greatest proportion of waste LED bulbs being diverted from landfill and recycled and therefore reduce the volumes of heavy metals and other toxic contents of LED bulbs being disposed of as domestic waste and potentially causing contamination issues.

Increased cost price will encourage consumers to make purchase decisions based on cost effectiveness, essentially incentivising the purchase of bulbs with longer life expectancy, and hence increased environmental friendliness. As high-quality bulbs are more expensive, they will be viewed less as consumable items that can be disposed of with little thought, and increasingly as long-term fixtures. This contributes to a more sustainable consumption model and discourages disposable consumer behaviour and mentality.

One disadvantage of a consumer product refund scheme is the initial set up cost and operational costs which are largely subsidised by the relevant state or territory. The initial outlay is expected to be the most significant cost however, with ongoing costs reduced once consumers are aware of the scheme and marketing requirements decrease. Additionally, as the scheme is not managed with significant input from industry and is managed by state government in conjunction with non-profit organisations, it is less likely to take advantage of innovative approaches. Instead, changes are expected incrementally as developments to technology become more well-established.

In contrast to refund style stewardship schemes for other products, as LED bulbs are longer life products, it will take significantly longer for members of the public to receive a refund than for products with shorter life span. This may make the increased up-front purchase price less palatable to consumers, who will not necessarily experience a financial incentive in the short term.

5.1.3 Voluntary Product Recycling Scheme

Organisations may choose to independently develop and operate product recycling initiatives where existing schemes do not facilitate the collection and recycling of their products. Organisations are not obliged to develop or participate in such schemes and do so at their own discretion. Where organisations recognise their responsibility to reduce the impact of their products and adopt product stewardship to mitigate against any identified adverse environmental outcomes, they may also opt-in to federal government voluntary product stewardship accreditation. Accreditation by the federal government provides several advantages to organisations aiming to build more sustainable business models. Only organisations that meet the high standards prescribed by the federal government can become accredited, ensuring that only those arrangements that adopt industry best practice in product stewardship and recycling are eligible. This provides improved marketability of the product, as the public can have increased confidence that the items they are purchasing are environmentally friendly and that the organisation has been identified as applying high standards to their product stewardship arrangement.

Additional benefits of having a voluntary product stewardship arrangement accredited by the federal government include being granted exclusive use of the product stewardship accredited logo, providing a point of difference to consumers looking to support sustainable organisations. It also provides the opportunity to collaborate with other businesses and communities with the aim of sharing knowledge and improving processes through optimisation and innovation. Accredited organisations may further be provided with resources to assist in the successful implementation of their product stewardship scheme, contributing to its efficiency and effectiveness and further facilitate scheme objectives.

Voluntary product stewardship schemes are well-placed to offer drop-off facilities at the point of purchase and other convenient locations, making return of LED bulbs at the end of their life increasingly accessible to consumers. This may include drop off locations in stores that sell LED bulbs, reverse vending machines, collection boxes in supermarkets or malls as well as facilities at recycling depots in some instances. By providing this convenience to consumers through improved accessibility to collection facilities, increased quantities of bulbs may be recycled in the long term.

While organisations are not required to become accredited as product stewardship scheme providers, they may still operate such schemes without accreditation. This enables organisations to manage the way they operate their scheme independently. While this may mean that the organisation is not required to pay the fees associated with applying to become accredited, it also means that the effective governance and responsible operation of the scheme is not guaranteed. This could result in providers advertising collection schemes for the purposes of appearing environmentally responsible, while not adhering to industry accepted best practice with regards to recycling of their product. Self-regulation and independent scheme management therefore leaves open the possibility of inadequate management and poor scheme effectiveness. Additionally, businesses are driven by financial outcomes which could result in shortcuts being taken or recycling not managed responsibly, resulting in adverse environmental outcomes. All organisations are still however subject to requirements of the Environmental Protection Act and other relevant legislation. This ensures that a minimum standard is met surrounding the collection, storage, transportation, processing, and ultimate recycling of products that have reached the end of their life.

Voluntary stewardship schemes further provide the opportunity for organisations to use their own discretion when it comes to considering emerging technology and innovative processes as part of their stewardship schemes. This is an opportunity that is less likely to be afforded to schemes operated by government, which are subject to a certain level of bureaucracy and public scrutiny that private organisations may not be subject to.

5.1.4 Scheme Selection

Based on the above analysis of the three different types of product stewardship scheme, 'Consumer Product Refund Scheme' was identified as the most appropriate scheme providing the most positive outcomes and least disadvantages for implementing a recycling scheme suitable for waste LED bulbs. Several advantages were identified that make the scheme particularly favourable, especially the ease and convenience of the scheme format to consumers. Provision for a large quantity of bulb collection facilities ensures a smooth, easy and quick process resulting in many beneficial outcomes for consumers, the community and the environment.

As supermarkets and department stores commonly sell LED light bulbs and these are typical places for consumers to purchase standard light bulbs for domestic use from, it is logical to provide vending machines and similar drop-off facilities at such locations. The added incentive of a cash refund further motivates consumers to return waste LED light bulbs at the end of their life, which can further contribute to the purchasing of replacement LED bulbs. The opportunity for community involvement and collaboration with non-profit organisations is also viewed as a significant benefit of the Consumer Product Refund Scheme, with the scheme providing social benefits in addition to the anticipated environmental benefits.

Despite an increase in purchase price potentially being perceived as a disadvantage to the Consumer Product Refund Scheme, the assessment of advantages and disadvantages has identified that any negative outcomes are outweighed by benefits provided by the scheme, including economic, social and environmental. Increased unit prices are also expected to improve consumer purchasing behaviour towards product wastage, promoting sustainable purchasing choices that further contribute to positive environmental outcomes and reduced consumption of finite resources through the extended use of longer life bulbs.

The Consumer Product Refund Scheme is a positive incentive to provide economic rewards to consumers for recycling LED light bulbs, reinforcing behaviour associated with recycling and improving overall sustainability outcomes. It further provides opportunities for non-profit and community organisations to collaborate and contribute to local social outcomes.

5.2 Analysis of Dismantling Process

By investigating the ease of dismantling of a range of LED bulb design styles, preferred bulb assembly and potential areas for improvement were identified. As a result of the assessment against the criteria set out in the research methodology, the glass style bulb designs were identified as the easiest bulbs to disassemble, following a method of crushing the glass body to access the electronic componentry and circuit board for further disassembly.

One key difficulty identified in the disassembly process was that caused by the significant differences in bulb design between styles and manufacturers. Inconsistent design and manufacture approaches led to different methods of disassembly being required for each bulb. This reduces opportunity for disassembly of waste LED light bulbs to be conducted as an automated process. Manual labour disassembly is inefficient and comes at significant cost, making it an inappropriate solution in the recycling of LED bulbs. An optimised and streamlined design and manufacture process would facilitate the streamlining of the dismantling phase of recycling.

Due to the sealed, all-in-one design of the LED bulbs, dismantling was required to be completed using a crushing process, resulting in separation of the bulb housing from the lens cover or reflector. Manual intervention was required to remove the PCB from the housing and separate the various materials, however parts of this process may be automated in industrial recycling facilities. Application of heat was further identified as a suitable method for the de-soldering of the circuit board, removing surface mounted components from the board in preparation for refinement.

The dismantling of a range of styles of LED bulbs further assisted in identifying existing barriers to the efficient recycling of waste LED bulbs and providing recommendations for the improvement of design and manufacture of bulbs. As improvements are made to the design and manufacture of LED bulbs, the opportunity to automate the recycling process is increased, improving the viability of LED bulb recycling.

While LED bulbs with entirely glass housing were identified as the easiest bulbs to dismantle, two further opportunities were identified to improve bulb design to facilitate ease of recycling. This includes the development and implementation of a snap on style attachment of the lens to the main bulb housing or screw in assembly as shown in Figure 5.1, both of which would enable simpler separation of lens from the housing. Such techniques are already implemented in existing technology such as LED torches and other electronic devices where modular assembly results in very simple dismantling process (Hendrickson et al. 2010).

Figure 5.1: LED torch threaded lens cap demonstrates possible modular design option for ease of disassembly

5.3 Analysis of Recycling Technology

Two recycling technologies, hydrometallurgical and pyrometallurgical processing, were identified as potential candidates for the recycling of LED bulbs that have reached the end of their life, due to their current use in a range of recycling applications both in Australia and internationally. These recycling technologies were assessed for their suitability for recycling of LED bulbs locally within Australia against a range of environmental, economic, and technical criteria. The advantages and disadvantages of each scheme are further discussed below and expand on the results of each criteria assessment.

5.3.1 Hydrometallurgical Processing

Hydrometallurgical processing has several advantages and disadvantages. The process can be used to extract a variety of metals. Primarily, hydrometallurgical processing is used to extract metals such as copper, gold, lead, tin and silver, however it can also be used in the extraction of other metals. These metals are those typically extracted due to the increased volume present in electronic products in comparison to other metals. One advantage of hydrometallurgical processing is the cost associated with the process. When compared with pyrometallurgical processing, the initial set up and ongoing operating costs are more economical. Additionally, the process can achieve high output recovery rates of approximately 95%. However, the process is not suitable for large scale recycling operations, making it less desirable for commercial and other large-scale recycling endeavours.

One of the key disadvantages with hydrometallurgical processing, is the limitation of the process to extracting one material at a time. In cases where several metals are to be extracted, the process is required to be repeated using altered methodology to extract the desired metal. In the case of recycling e-waste such as LED bulbs, which contain multiple materials requiring extraction, such a process may not be the most suitable. In such circumstances where waste products containing multiple materials are recycled using hydrometallurgical processing, typically the materials with the highest market value are given preference for recycling, while the by-product containing other metals is discarded due to the decreased economic viability.

Another disadvantage of hydrometallurgical processing is its reliance on highly toxic chemicals in the recycling process. For each metal extracted, several different chemical processes are typically required. This often results in hazardous waste by-products which then require management and responsible disposal. Due to these limitations, hydrometallurgical processing is currently not the preferred choice in the e-waste recycling industry.

5.3.2 Pyrometallurgical Processing

Pyrometallurgical processing is often viewed as a more versatile recycling technology, due to the ability to easily adapt the process for refining and extracting a wide range of materials. While the materials that can be extracted through pyrometallurgical processing may be similar to hydrometallurgical processing, including copper, gold, lead, tin, silver and other metals, the process for extracting several of these is more efficient when compared to hydrometallurgical processing which required repeated processing for various types of metals. Due to the simpler nature of the process, it is also suited to large scale operations for the processing of general e-waste, making it the currently preferred method for processing of PCBs and other e-waste in the recycling industry.

While hydrometallurgical processing may be more efficient with respect to recovery rates of many metals, with a recovery rate of 95%, additional refinement processes can be used to supplement pyrometallurgical processing to increase the recovery rate. Supplementary processing can assist in achieving recover rates of up to 99.99%, making the process highly efficient in extracting metals.

One of the key disadvantages of pyrometallurgical processing, however, is the high initial set up costs and high ongoing operating costs. This is largely due to the sizable infrastructure that is required to carry out the material processing, including the incorporated smelting system, which can be expensive to operate and maintain. As with hydrometallurgical processing, typically higher market value materials are prioritised for extraction. However, as pyrometallurgical processing is suited to the refinement of multiple metals at one time, it may be more suited to extracting a wider range of metals with minimal additional cost when compared to hydrometallurgical processing.

Another disadvantage of pyrometallurgical processing relates to its limitations around recovery rates. Without supplementary recovery processes, 20% of valuable metal may be lost in residue by-product. For 99% recovery rates to be achieved, the supplementary processing is required to be implemented, contributing an additional cost to the recycling process which may not always be economically viable, depending on the material being refined. Additionally, due to its chemical properties, aluminium is unable to be recovered using pyrometallurgical processing. This is a significant disadvantage when considering the recycling of e-waste products that contain high proportions of aluminium.

While pyrometallurgical processing does not rely heavily on toxic chemicals, it still results in waste by-products. These primarily consist of residue in the form of slag as well as waste gasses, derived from zinc oxide, copper and lead oxide, depending on the material being smelted and extracted. Waste by-products including both toxic gases and slag can be difficult to manage effectively and dispose of responsibly (Gupta & Mukherjee 2017). Where supplementary refinement processes are implemented, the total volume of waste by-product may be reduced as the metal recovery rate is increased.

5.3.3 Summary of Technological Assessment

Both hydrometallurgical and pyrometallurgical processing technologies can extract a range of various materials such as, copper, gold, lead, tin, silver, and others. Due to economic value based on market demand, materials such as copper, gold, lead, tin and silver have the most market value and therefore dictate and have a greater influence on the materials being recycled and recovered from e-waste recycling processing facilities.

From the analysis of both processes, pyrometallurgical processing is preferred to hydrometallurgical primarily due to the limitations of hydrometallurgical processing in large scale operations, the limitation of extracting fewer metals at one time, as well as its reliance on a range of toxic chemicals, some of which are restricted for use in Australia.

Operations of pyrometallurgical processing are more suitable for large scale recycling and high output operations. Furthermore, the material recovery from pyrometallurgical processing can achieve high output recovery of 99.99% when supplementary refinement processes are implemented. In Australia, pyrometallurgical processing is a well-established technology with a number of well-respected industry leaders utilising such technology within the e-waste recycling sector. It is therefore more economically viable to utilise the existing infrastructure when expanding systems to include allowance for the recycling of LED lightbulbs.

Chapter 6. Conclusion and Recommendations

This chapter summarises the outcomes of this research, recommends the most appropriate scheme and recycling technology to be adopted, and outlines what further research and legislation development may be necessary for the successful implementation of a product stewardship scheme to facilitate the recycling of waste LED light bulbs.

6.1 Research Conclusions

A need to implement recycling initiatives to facilitate the recycling of LED bulbs at the end of their life was identified at the outset of this research project. This was further reinforced through the literature review which demonstrated the current lack of product stewardship scheme facilitating the recycling of LED bulbs. Existing schemes were identified as being potential models for LED bulb recycling schemes, including recycling schemes for mobile phones and fluorescent lights, which were then investigated further for their suitability in application to the recycling of LED bulbs.

Three key areas were identified as a result of the literature review that became the core focus of this research. These areas were design for disassembly, technological processing of materials and Australian legislation and policy relating to the implementation of recycling schemes for waste LED bulbs.

Investigation of the design and assembly of existing LED bulbs identified that current bulb designs are not standardised so vary significantly, but all inhibit the dismantling process, primarily through being all-in-one glued units requiring crushing to dismantle. While this design is used due to its being cost effective and requiring reduced labour, the consequence is that additional complexities are added to the dismantling part of the recycling process.

Review of techniques used for other recycling processes revealed that manual disassembly processes are often used, such as for mobile phone recycling. While this is an effective approach for the disassembling and sorting of mobile phone components, this approach would not be suitable for LED bulbs due to the inherent costs associated with manual processing, together with the lower product value of LED bulbs and their contents when compared with other products such as mobile phones. Simple dismantling processes such as crushing to disassemble were identified as the most appropriate for the vast majority of LED bulb designs.

Material processing technologies were also reviewed for their suitability in the application of recycling LED bulbs together with other forms of e-waste locally in Australia. Two technologies identified for further consideration were hydrometallurgical and pyrometallurgical processing. Both processes were assessed against a range of criteria, with pyrometallurgy being identified as the technology currently preferred by the recycling industry in Australia. Pyrometallurgical processing was identified as a more suitable technology due to its ability to be adapted to large scale recycling production lines, as well as already being well-established in Australia, making it a more realistic option for the expansion of recycling facilities to include provision for LED bulb recycling. It was noted through the literature review that a small quantity of LED bulbs are already being recycled as part of a fluorescent lighting recycling scheme. Utilising such existing infrastructure for an LED light bulb recycling scheme would therefore be expected to provide the most economical as well as environmentally sustainable solution.

In order to utilise the available technology and recycling facilities effectively, the relevant legislation and policy framework is required to be developed and implemented for recycling of LED bulbs. A range of models were defined based on existing schemes, which were then assessed against criteria developed in the research methodology. The assessment enabled an objective review of the various benefits of each type of scheme, as well as the various disadvantages. The Consumer Product Refund Scheme was identified as the scheme that would provide the most benefits through a cash refund model whereby consumers are incentivised to return waste LED bulbs for recycling. Such a scheme can be easily implemented by state governments through the adaptation of existing stewardship schemes that follow a similar model.

6.2 Recommendations

Based on this research, the following proposals are recommended to be implemented to facilitate the recycling of LED bulbs that have reached the end of their life, with respect to design for disassembly, technological processing of materials and Australian legislation and product stewardship policy.

LED bulbs are recommended to be designed and manufactured with end of life recycling processes in mind. Until improvements in designs are made, it is recommended crushing of the LED bulb prior to material recovery will provides the most effective outcome. This process is adopted by the fluorescent light bulbs recycling industry. However, improvements in design would further facilitate recycling of LED bulbs through the inclusion of a modular construction such as a snap on clip style or screw in fitting such as that that is used in other existing products such as LED torches. Products with such modular design are expected to be more conducive to a circular life cycle involving the recycling and repurposing of materials used in the construction of LED bulbs.

The Consumer Product Refund Scheme was identified as the best proposed scheme for the recycling of the LED light bulbs due to the overwhelming benefits and limited disadvantages it presented, including:

- Financial incentive to consumers for recycling of old LED light bulbs,
- State and territory managed under principals of Product Stewardship Act,
- Opportunity for involvement of non-profit organisations,
- Improved job opportunities within local community,
- Most significant reduction in diversion of e-waste from landfill, improving sustainability.

In order for such a scheme and technology to be executed, supporting legislation is required surrounding e-waste polices including the Product Stewardship Act 2011 as well as increased involvement of law makers such as Australian Government, States and local councils to further develop a framework for the implementation of the scheme. This also includes engagement with industries, public sectors and any stakeholders that are involved within the e-waste industries and environmental agencies in Australia for feedback to ensure smooth implementation of the LED recycling scheme.

The pyrometallurgical processing recycling technology was identified as the best technology for the recycling of the LED light bulbs because it is currently a well-established recycling process and is being utilised by various e-waste recycling processing plants within Australia and many part of the developing world. Therefore, it is more economically viable to utilise existing processes to facilitate the recycling of LED light bulbs.

6.3 Project Evaluation

The scope of this research included evaluating existing recycling practices, chemical processing technologies and disassembly processes as identified in the project specification to provide recommendations to improve recycling practices and design alternatives for LED light bulbs.

Existing recycling schemes currently in place under the Product Stewardship Act were evaluated for their effectiveness and suitability to adoption for LED bulb recycling under a similar scheme. A range of schemes were then proposed on the basis of existing legislative infrastructure, with a consumer product refund style scheme being selected as the most appropriate for the recycling and repurposing of LED light bulbs due to the economic incentive provided to customers as well as its improved feasibility over other scheme structures which may have limited uptake or be cost prohibitive.

Throughout this research, chemical processing technologies were identified and evaluated against a set of assessment criteria for environmental, technical and social impact. Assessment of two technologies, hydrometallurgical and pyrometallurgical processing assisted in the identification of advantages and disadvantages of each chemical process and led to the recommending of pyrometallurgical processing as the preferred recycling method, primarily due to its prevalence in Australian industries for the recycling of other e-waste products and the seamless introduction of LED bulbs into this waste recycling stream.

An investigation was conducted to assess the difficulty of disassembling a range of styles of LED bulbs in order to identify which style of bulb is most conducive to being recycled, and identify any areas for improvement in the design and manufacture of LED bulbs. The evaluation identified that an all glass housing LED bulb was the simplest bulb to disassemble, therefore making it the easiest style of bulb to recycle. Glue-filled bulbs were identified as being the most difficult to disassemble and therefore recycle. This led to a recommendation of a clip style or screw lens style LED bulb housing design which is expected to be more conducive to disassembly and recycling than those bulbs assessed as part of this research.

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Appendix A - Project Specification

ENG4111/4112 Research Project

Project Specification

For: Michael Chamberlain

Title: Re-purposing LED Light bulbs

Major: Environmental engineering

Supervisors: Dr Steven Goh

Enrolment: ENG4111 – EXT S1, 2020

ENG4112 – EXT S2, 2020

Project Aim: To identify opportunities to re-purpose waste from LED light bulbs. The benefit of proposed solution will result in less LED lightbulbs to landfill and environmentally more sustainable outcomes.

Program: Version 3, 08 April 2020

1. Liaise with USQ Professional Staff for material analysis and dismantling of LED Light bulbs.
2. This project will involve initial scoping, definition, and evaluation of current LED lightbulb waste recycling practices, including local council recycling schemes and private sectors.
3. To evaluate chemical processing of plastic and heavy metals found in LED light bulbs.
4. To identify any constraints and parameters such as disassembly and abstraction processing for recycling purposes of LED lightbulbs.
5. To systematically evaluate the current recycling methods in terms of sustainability.
6. Make recommendation on improvement of the current practices for recycling and repurposing LED light bulbs.
7. To propose conceptual design alternatives that may achieve the design objectives for recycling and re-purposing of LED light bulbs.

If time and resource permit:

1. To design and test the concept.

Appendix B - Risk Assessment and Safety Procedures

B.1. Risks, Tooling and Equipment Assessment Requirement

Prior to commencing of the experiment, several criteria must be met to align with the USQ engineering department, USQ health and safety standards and authorities. Therefore, the following documents must be prepared and approved before commencement:

1. An experimental instruction needs to be written up, reviewed, and approved by University supervisors. (see chapter 3)
2. Location of the experiment needs to be determined and agreed upon. During this COVID-19 epidemic all University of Southern Queensland on campus activities were closed. Therefore, a proposal to perform the experiments at a private residential property were chosen. (students' private home).
3. Risk Assessment and Safety procedures outline and documented for review and approval by the USQ health and Safety Department, course supervisor and USQ engineering Department. (Appendix B for full details)
4. Tooling and Equipment Risk assessment documentation for review and approval USQ health and Safety Department, course supervisor and USQ engineering Department.

B.2. Risk Assessment

B.2.1. Assessment of Hazards

The disassembling of the LED light bulbs requires manual handling and uses of various hand tools including a heat gun.

It is necessary to identified potential hazards and risks that be maybe present during the disassembling process, including:

1. Face and upper body injury due to lack of personnel safety gear and possibility of flying particles during disassembling.
2. Hand injury due to improper uses of hand tools and lack of uses of gloves.
3. Burning hands or body parts due to improper uses of heat gun.
4. Fume exposures due to poor ventilation and improper use of breathing mask and PPEB1.3

B.2.2. Works Assessment Review

Due to the COVID-19 pandemic causing the closure of the University of Southern Queensland, all experiment will be performed at a private home. In the preparation of the experiment process, prior discussions and methods have been discussed with the thesis supervisor.

A working space with access to a working bench have been allocated to perform the dismantling process of the LED light bulbs. The garage is isolated via locking doors to reduce entry access of un-authorised persons during the experiment.

To reduce any possibility of tripping or falling, clear access to the working area will be provided prior to commence of the experiment.

There is no additional requirement of the uses of electrical equipment apart from the uses of the electric heat gun. A residual current devices (RCD) will be used as additional safety in the case of an electrical short circuit with the heat gun.

B.2.3. Risk Evaluation

The identified risks with the control measures in place can be categorized as unlikely to low. The overall risk rating of low for this project experiment.

B.2.4. Environmental Hazards

Part of this experiment require the removal of the SMD components. The method employed via applying heat

B.3. Safety Procedures

B.3.1. Preparing and testing procedures for the Dismantling of LED light bulbs

The following work procedures are set guidance for the dismantling of LED light bulbs. The dismantling process are done through a manual process and the use of various hand tools. There is no heavy lifting involved during this process.

This document is created with the intent of minimising the risk of injury to personnel and damages property that may be present during performing this experiment by the uses and observations of standards and work practices, QLD safety standards with conjunction of the USQ Safety Risk Management System Guidelines.

B.3.2. Emergency Procedure

In the case of emergency, such as personnel injury, there will be help readily available to assist. In the case of fire, fire extinguisher and mobile phone will be provided during the experiment to call for any emergency, as well as an exit door via the garage entrance

B.4. Health and safety support material for approval

The following documentation provide brief outlines of the working area, selection of hand tools, electrical and fire safety devices and the environment space, taken in consideration as part of the experiment in order to meet USQ health and Safety stands approval process. The photos provided below are an indication of the state and conditions of both equipment and working environment.

Since the proposed experiment is to be performed at a private property, outside of the USQ controlled environment and health and safety standards, the following experiment must be carefully reviewed by the USQ health and safety authorities and in conjunction with USQ project supervisor and course examiners to insure sufficient evidence and support materials is provided. The following document and information is collected for review and additionally forms part of the risk management process.

B.4.1. Working Bench Area

A working area is provided, including working bench space, cleared of any hazards or obstacles. The working bench is a permanent fixture with no movement of the bench top.

Figure B1.0: Working bench area provided to perform experimental work.

B.4.2. Safety Equipment

Safety is an essential core consideration of this experiment and a legal requirement to ensure safety. The following safety equipment will form part of this experiment. Access to a fire extinguisher is available during the experiment.

Figure B1.2: Fire Extinguisher in case of fire

Masks must be worn prior to starting experiment to minimise exposure to any potential smell as well as providing some lower facial protection in any event of flying materials.

To mitigate against the hazards identified above, the following personal protective gear will form part of the personnel gear required to wear during the performing the experiment.

1. Safety boots
2. Gloves
3. Safety glasses
4. Overalls
5. Safety helmet
6. Breathing mask (3M multi Gas/Vapour mask and 6059 cartridge filter system)

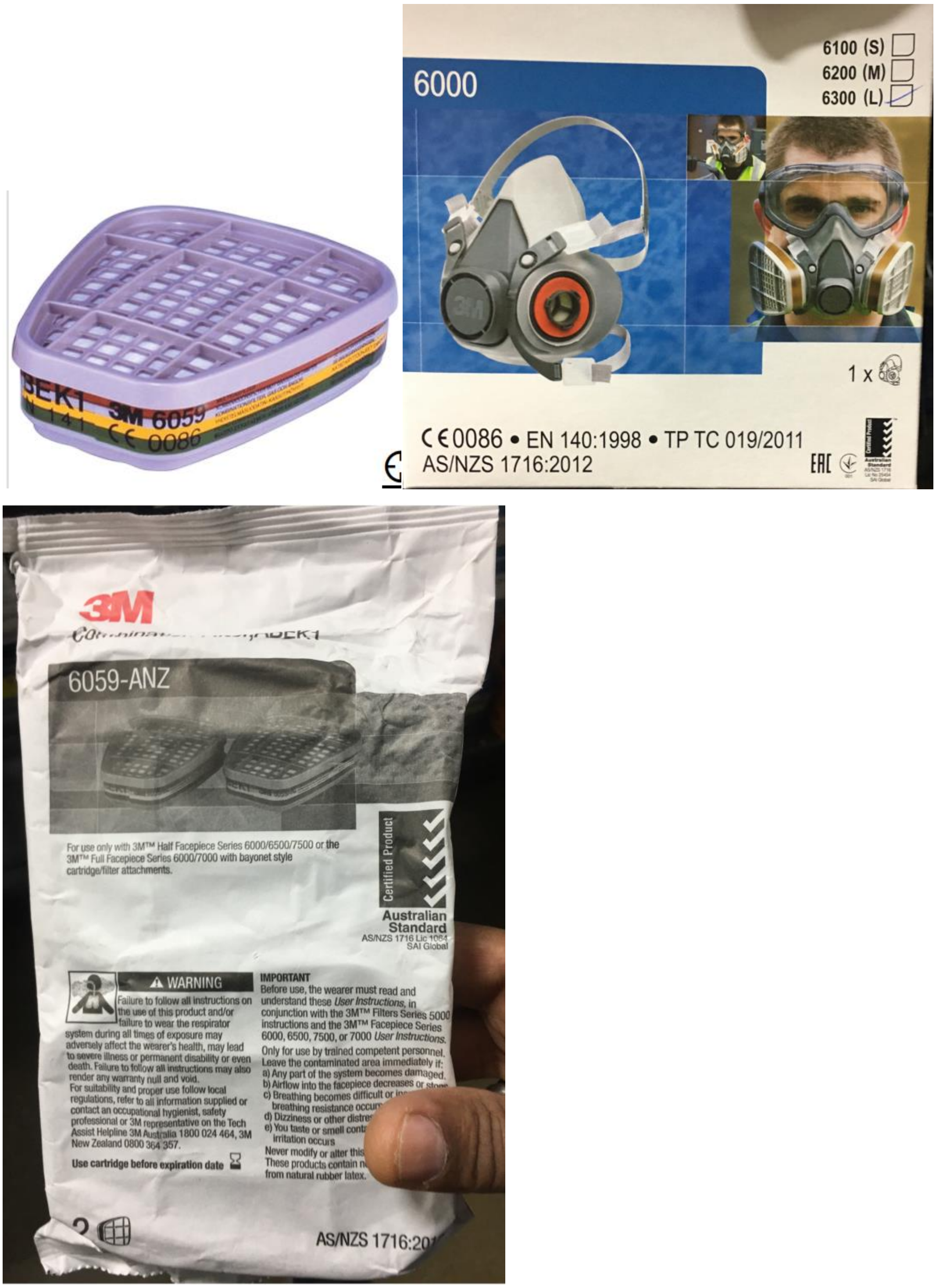

Figure B1.3: 3M multi Gas/Vapour mask and 6059 cartridge filter system.

3M™ Multi Gas/Vapour Cartridge Filter 6059, (A1B1E1K1)

Provides protection against: Organic Vapours (boiling point > 65°C) Inorganic & Acid Gases, Ammonia and Methylamine (A1B1E1K1)

- 3M™ Bayonet Connection System ensures precise and secure locking
- Low profile and well balanced twin filter design
- Suitable for use with 3M™ 6000/7500 Series Half Face Respirators and 3M™ 6000/7000 Series Full Face Respirators

Protection Factors
Note that any filtering respirator should not be used for protection at airborne concentrations of contaminants above the relevant Immediately Dangerous to Life or Health (IDLH) levels.
This cartridge/filter, when used for protection against the contaminants as specified, is capable of providing the following protection levels:

Common Applications/Hazards: For protection when working with a variety of chemicals such as organic vapours, chlorine, hydrogen chloride, sulphur dioxide, hydrogen fluoride, hydrogen sulphide, ammonia, methylamine, and formaldehyde

Specifications:

Cartridge or Filter Assigned Colour Coding: Brown/Grey/Yellow/Green

Cartridge or Filter Rating: A1B1E1K1

Cartridge or Filter Type: A1B1E1K1

Filter Type: Gas & Vapour Cartridge

Gas & Vapour Protection Type: Acid Gases, Ammonia, Inorganic vapours and acid gases, Organic Vapours bp>65 degrees°C

Product Series: 6000 Series

Compliance: Approved to AS/NZS 1716:2012

3M multi Gas/’Vapour mask and Cartridge specifications

Figure B1.4: Hand protections.

Gloves must be worn during the experiment to minimise hand injury from any sharp objects.

The uses of safety eye wear are required prior to proceeding experiment.

Figure B1.5: Safety eye wear protection

Hazardous Fumes

The following fans will be used to blow away any fumes during the use of the heat gun for the removal of the surface mount devices (SMD) component of the board.

Figure B1.6: Use of mini fans to assist with fumes

In addition of the use of fans, the front garage provides open air environment to aid with further ventilation.

Figure B1.7: Front garage provides open air environment

Tools required to perform experimental work

The following tools will be used during the dismantling of the LED lightbulbs, the following photos show the type of tools and their state of condition.

Figure B1.9: Vice for crushing LED light bulbs.

Figure B1.9.1: Various sizes of Phillip’s screwdrivers.

Figure B1.9.2: Heat gun used during component removal.

Figure B1.9.4: Selections of pliers.

Figure B1.9.5: Vice grip.

B.4.3. Environment Awareness

To minimise danger during the experiment, the working area will be locked to ensure isolation from non-authorised personnel.

Figure B1.9.6: Working area can be isolated by locking doors entry.

B.4.4. Crushing of LED light bulbs.

The following plastic box is a proposed method used for isolating any flying materials during the crushing of the LED light bulbs by the Vice. The bulbs will be placed in the vice for crushing.

Figure B1.9.7: Plastic container box is used during crushing process.

B.4.5. Electrical safety

Electrical safety is a major priority during the using any electrical equipment. The use of a residual current device (RCD) will be using as additional electrical protection when using the heat gun.

Figure B1.9.8: RCD with conjunction of the heat gun.

Additional to the uses of RCD, the main electrical switch board has advance short circuit and overload system to ensure additional safety. In the event of short circuit or overload, it will automatically shut off and isolate the circuit, thus providing protection.

Figure B1.9.9: Main switch board with incorporate advance isolation system for safety.

B.4.6. Tidying workstation

A tidy work area involves keeping working station and area safe from obstacles. A dustpan and brush are used to clean work area of broken glass, plastic and other material during the dismantling of LED light bulbs.

Figure B2.0.0: Cleaning dustpan and brush

B.5. USQ Safety Risk Management System Approval Form

University of Southern Queensland — Print View

USQ Safety Risk Management System

Version 2.0

Safety Risk Management Plan

Risk Management Plan ID:	Status:	Current User:	Author:	Supervisor:	Approver:
RMP_2020_4410	*Approval Requested*	i:0#.w|usq\u1040218	i:0#.w|usq\u1040218	i:0#.w|usq\gohs	i:0#.w|usq\kist

Assessment Title:	Dismantling of LED light bulbs end of life	Assessment Date:	3/07/2020
Workplace (Division/Faculty/Section):	204000 - Faculty of Health, Engineering and Sciences	Review Date: (5 years maximum)	

Approver: *Alexander Kist*

Supervisor: (for notification of Risk Assessment only) *Steven Goh*

Context

DESCRIPTION:

What is the task/event/purchase/project/procedure?	Dismantling of LED light bulbs
Why is it being conducted?	To investigate the dismantling process end of life of various LED light bulbs
Where is it being conducted?	Home Gargage work bench
Course code (if applicable)	ENG4111
Chemical Name (if applicable)	N/A

WHAT ARE THE NOMINAL CONDITIONS?

Personnel involved	Michael Chamberlain
Equipment	- Medium plastic box (for smashing LED light bulbs) - Phillips screwdriver - Triangle tip shape screwdriver - Pair of pliers - Rags for wipping down and cleaning - Small vice - Heat gun - Dustpan and brush - Small vacuum cleaner - Small plastic rubbish bags
Environment	Indoor at room temperature, with dry conditions
Other	- LED light bulbs: - Safety glasses - Gloves - Overalls - Safety helmet - Breathing mask (3M multi Gas/Vapour mask and 6059 cartridge filter system) - Safety boots
Briefly explain the procedure/process	1- Placing the LED light bulb into the vice Crip, position the bulb into the vice just below the lens and the housing. 2- Slowly tighten by turning vice handle, this will increase pressure, causing the bulb lens/diffuser to separate from its housing. 3- Remove the bulb from the vice by unwinding the vice handle. 4- Remove the lens/diffuser cap, if it not already fallen off. Once the lens/diffuser comes off, the LED PCB board is exposed. 5- Using a small Phillips screwdriver, remove the 3 X Phillips screws. 6- Using the flat head screwdriver pop out the LED PCB board. Underneath the LED PCB board contains heat transfer material paste. 7- To allow complete removal of the LED board cut off the conducting wires.

Assessment Team - who is conducting the assessment?

Assessor(s):	Dr. Mainul Islam, Alexander Kist
Others consulted: (eg elected health and safety representative, other personnel exposed to risks)	*Dr. Mainul Islam, Alexander Kist, Steven Goh*

Risk Matrix					
	Consequence				
Probability	Insignificant No Injury 0-$5K	Minor First Aid $5K-$50K	Moderate Med Treatment $50K-$100K	Major Serious Injury $100K-$250K	Catastrophic Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1,000	L	M	H	H	H
Unlikely 1 in 10,000	L	L	M	M	M
Rare 1 in 1,000,000	L	L	L	L	L

Recommended Action Guide

Extreme:	E= Extreme Risk – Task ***MUST NOT*** proceed
High:	H = High Risk – Special Procedures Required (Contact USQSafe) Approval by VC only
Medium:	M= Medium Risk - A Risk Management Plan/Safe Work Method Statement is required
Low:	L= Low Risk - Manage by routine procedures.

Risk Register and Analysis

	Step 1	Step 2	Step 2a	Step 2b	Step 3			Step 4					
	Hazards: From step 1 or more if identified	***The Risk:*** What can happen if exposed to the hazard without existing controls in place?	***Consequence:*** What is the harm that can be caused by the hazard without existing controls in place?	***Existing Controls:*** What are the existing controls that are already in place?	***Risk Assessment:*** Consequence x Probability = Risk Level			***Additional Controls:*** Enter additional controls if required to reduce the risk level	***Risk assessment with additional controls:*** Has the consequence or probability changed?				
					Probability	*Risk Level*	*ALARP*		*Consequence*	*Probability*	*Risk Level*	*ALARP*	
	Example												
	Working in temperatures over 35⁰ C	*Heat stress/heat stroke/exhaustion leading to serious personal injury/death*	*catastrophic*	*Regular breaks, chilled water available, loose clothing, fatigue management policy.*	*possible*	*high*	*No*	*temporary shade shelters, essential tasks only, close supervision, buddy system*	*catastrophic*	*unlikely*	*mod*	*Yes*	
1	Fyling Objects	Body face injury	Moderate	Uses of PPE (personel protective equipement) eg. safety glasses, hard hat, mask. uses of safety box while LED ligth bulb is being crushed in the vice	Rare	Low	☐	In the case of emergency, such as personnel injury, there will be help readily available to assist. In the case of fire, fire extinguisher and mobile phone will be provided during the experiment to call for any emergency as well as an exit door via the garage entrance.	Minor	Unlikely	Low	☐	!
2	Melting of s...	Burnto hand and fingers	Minor	Uses of PPE, personel protective gear, breather mask, leather gloves, long overalls. mounting PCB into vice so there is no direct body contact.	Unlikel	Low	☐		Minor	Unlikely	Low	☐	!
3	Fume	Posible Toxic fume from solder and PCB	Moderate	uses of fans to aid towards blowing fumes away from face area. uses of approved face mask. (3M multi Gas/Vapour mask and 6059 cartridge filter system).			☐	Ensure well vented work area for air flow. experiment will be performed on only one PCB board for this investigation of removal of its components.	Minor	Unlikely	Low	☐	!
4	Fire from PC...	Burning	Minor	No flame type heat being applied. only hot air from the hot air gun. Ensure type A/B extinguisher available during performing experiment.	Unlikel	Low	☐	Person carrying out this experiment has had prior 15 years work experience in the electronics industries, which envolved the removal of SMD (surface mount Devices) component from PCB boards	Minor	Unlikely	Low	☐	!
5	Disposal of e...	Environmental contamination	Minor	Dismental LED will be place in a recycling bag and placed at the E-waste section of the Gold Coast city council section at the recycling depo.	Possibl	Me...	☐	Alternatively the LED bulbs remains can be posted to ECO-recycling which is a private company for light bulb recycling.	Minor	Unlikely	Low	☐	!

Step 5 - Action Plan (for controls not already in place)

	Additional Controls:	*Exclude from Action Plan: (repeated control)*	*Resources:*	*Persons Responsible:*	*Proposed Implementation Date:*
1	In the case of emergency, such as personnel injury, there will be help readily available to assist. In the case of fire, fire extinguisher and mobile phone will be provided during the experiment to call for any emergency as well as an exit door via the garage entrance.	☐			
3	Ensure well vented work area for air flow. experiment will be performed on only one PCB board for this investigation of removal of its components.	☐			
4	Person carrying out this experiment has had prior 15 years work experience in the electronics industries, which envolved the removal of SMD (surface mount Devices) component from PCB boards	☐			
5	Alternatively the LED bulbs remains can be posted to ECO-recycling which is a private company for light bulb recycling.	☐			

Supporting Attachments

Risk Assessment and Experiment Safety Procedures-V 2.pdf
1.5 MB

Disassembling Procedure of Ceiling LED down light.pdf
13.78 KB

Step 6 – Request Approval

Drafters Name: *Michael Chamberlain* *Draft Date:* *3/07/2020*

Drafters Comments:

Assessment Approval: **There are risks not marked as ALARP**

Maximum Residual Risk Level: **Low - Manager/Supervisor Approval Required**

Document Status: *Approval Requested*

Step 6 – Approval

Approvers Name: *Alexander Kist* *Approvers Position Title:*

Approvers Comments:

I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.

Approval Decision: *Approve / Reject Date:* *Document Status:* *Approval Requested*

Appendix C - Resources

C.1. Project Resources

Project resources requirement:

- LED light bulbs.
- Safety glasses.
- Gloves.
- Breathing mask (3M multi Gas/Vapour mask and 6059 cartridge filter system)
- Miscellaneous items. personal protective equipment (PPE), full cover shoe, long shelve top and pans.
- Small box (for smashing LED light bulbs).
- Small Hammer (4-6 oz).
- Pair of pliers.
- Rags for wiping down and cleaning.
- Small Vice.
- Pen.
- Notebook.
- Computer/Laptop
- Microsoft Excel software
- Microsoft word
- Dustpan and brush.
- Small vacuum cleaner.
- Small plastic rubbish bags.
- Residual Current Devices (RCD)
- Experiment will be also carried out at home garage.

C.2. Communications

After discussion with supervisor: Steven Goh, it is agreed communication will be conducted using a mix mode communication style throughout the project's life including via face to face, email and video conferencing. Project update will be conducted every two weeks basis, unless there are some major issues that may need to be addressed urgently.

Appendix D - Project Schedule

Project Schedule 2020

Key:

- Exam
- Days Schedule
- Completed
- University holiday
- Allocation in Days

	Allocation Days	26/02/2020	**04/03/2020**	10/03/2020	**18/03/2020**	25/03/2020	29/03/2020	31/03/2020	02/04/2020	08/04/2020	09/04/2020	10/04/2020	11/04/2020	17/04/2020	20/04/2020	23/04/2020	28/04/2020	10/05/2020	**27/05/2020**	08/06/2020	19/06/2020	**09/09/2020**	16/09/2020	20/09/2020	30/09/2020	**15/10/2020**
		Semester One																				Semester two				
Project planning stage:																										
Topic allocation	8																									
Finalise scope of works	6																									
Project specification	8																									
Resource planning	7																									
Initial Literature review	28																									
Visiting local council /3rd party recycling plant	1																									
Preparation and sample stage:																										
Sample collection of various common LED light bulbs	2																									
Material analysis and dismantling of LED Light bulbs.	2																									
Material review	7																									
Results & analysis stage:																										
Disregard any irrelevant data.	1																									
Compare findings	1																									
Report findings	6																									
Evaluation and design stage																										
Evaluate chemical processing	3																									
Identify any constraints and parameters	5																									
Propose conceptual design alternatives	12																									
Report preparation stage:																										
Progress report	20																									
Draft preparation of dissertation	155																									
Preparation of project presentation	7																									
Project conference presentation	4																									
Finalise, complete and submit dissertation	16																									