Waste Electrical and Electronic Equipment (WEEE) Management in Australia and Brazil

Pablo Ribeiro Dias

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Supervised by
Prof. Dr. Andréa Moura Bernardes (UFRGS)
Prof. Dr. Nazmul Huda (Macquarie University)

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MACQUARIE UNIVERSITY

UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

Gestão de Resíduos de Equipamentos Elétricos e Eletrônicos (WEEE) na Austrália e no Brasil

Pablo Ribeiro Dias

Orientadores:

Nazmul Huda (Macquarie University)

Andréa Moura Bernardes (Universidade Federal do Rio Grande do Sul)

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Declaration

I hereby certify that the work written in this thesis entitled "Waste Electrical and Electronic Equipment (WEEE) Management in Australia and Brazil" has not been previously submitted for a degree, nor has it been submitted as part of requirements for a degree to any other university or institution other than Universidade Federal do Rio Grande do Sul and Macquarie University under the cotutelle agreement signed on 23/08/2016.

I also certify that this thesis is an original piece of research which has been written by me. Any assistance that I have received in the course of my research work and the preparation of the thesis itself has been appropriately acknowledged. Some parts of this thesis include early or revised versions of published papers:

- Pablo Dias, Arthur Machado, Nazmul Huda, Andréa Moura Bernardes. Waste electric and electronic equipment (WEEE) management: A study on the Brazilian recycling routes. Journal of Cleaner Production, Volume 174, 10 February 2018, Pages 7-16. https://doi.org/10.1016/j.jclepro.2017.10.219

- Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. Waste electrical and electronic equipment (WEEE) management: An analysis on the Australian e-waste recycling scheme. Journal of Cleaner Production, Volume 197, Part 1, 1 October 2018, Pages 750-764. https://doi.org/10.1016/j.jclepro.2018.06.161

- Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. Ensuring best E-waste recycling practices in developed countries: An Australian example. Journal of Cleaner Production, Volume 209, Part 1, 1 February 2019, Pages 846-854. https://doi.org/10.1016/j.jclepro.2018.10.306

In addition, I certify that all information sources and literature are indicated in the thesis.

The research presented in this thesis was approved by Macquarie University Ethics Review Committee (Human Research) reference number 5201700607.

Pablo Ribeiro Dias

November 2018

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List of Symbols and Abbreviations

CD – Compact disc

CRA – Co-regulatory arrangement

CRT – Cathode ray tube

DVD – Digital video disc

EEE – Electrical and electronic equipment

EoL – End of life

EPA – Environmental protection authority

EPR – Extended producer responsibility

FY – Financial Year

GDP – Gross domestic product

GPS – Global Positioning System

IT or ICT – Information (communication) technology

LCA – Life cycle assessment;

LCD – Liquid crystal display

LED – Light-emitting diode

MFA – Material flow analysis

MOUSE - Manually-operated user-select equipment

MSW – Municipal solid waste

NTCRS – National television and computer recycling scheme

OECD - Organization for Economic Co-operation and Development

PC – Personal computer

PCB – Printed circuit board

PPP - Purchasing power parity

PTV – Plasma television

RoHS - Restriction of Certain Hazardous Substances

ton – Mass unit, tonnage, metric ton, 10^6 grams

TV - Television

WEEE – Waste electrical and electronic equipment

WPCB – Waste printed circuit board

WTO - World Trade Organization

Technical and scientific outputs

The main scientific outputs of this research are listed as follows:

Journal articles:

1. Pablo Dias, Arthur Machado, Nazmul Huda, Andréa Moura Bernardes. *Waste electric and electronic equipment (WEEE) management: A study on the Brazilian recycling routes.* Journal of Cleaner Production, Volume 174, 10 February 2018, Pages 7-16. 5-year JIF 6.35, Q https://doi.org/10.1016/j.jclepro.2017.10.219

2. Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. *Waste electrical and electronic equipment (WEEE) management: An analysis on the Australian e-waste recycling scheme*. Journal of Cleaner Production, Volume 197, Part 1, 1 October 2018, Pages 750-764. 5-year JIF 6.35, Q https://doi.org/10.1016/j.jclepro.2018.06.161

3. Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. *Ensuring best E-waste recycling practices in developed countries: An Australian example*. Journal of Cleaner Production, Volume 209, Part 1, 1 February 2019, Pages 846-854. 5-year JIF 6.35, Q https://doi.org/10.1016/j.jclepro.2018.10.306

4. Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. *What Drives WEEE Recycling? An Example from Australia and Brazil*. Waste Management (Under review), 5-year JIF 5.26, Q1

5. Pablo Dias, Nazmul Huda, Andréa Moura Bernardes. *Where do WEEE go? A global review of the management of electrical and electronic waste*. Waste Management (Under review), 5-year JIF 5.26, Q1

International peer-reviewed conference papers:

6. Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. *Economic and Political Pressure on WEEE Recycling: An Example From Australia And Brazil*. 6th International Conference on Industrial and Hazardous Waste Management. September 2018. // This work was selected in the conference proceedings for the Special Issue E-Waste Mining of Waste Management Journal, which resulted in the aforementioned publication.

7. Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. *Definindo Resíduo Valioso: O Problema De Definir Massa Como Unidade De Medida De Resíduos De Equipamentos Eletroeletrônicos* (Free Translation - Defining Valuable Waste: The Problem of Defining Mass as a Measurement Unit for Waste Electrical and Electronic Equipment). 29º Encontro Técnico AESABESP, FENASAN, 2018. September 2018. // This work was selected among the top 10 papers for the award of AESABESP's young professional (*Prêmio jovem profisisonal AESABESP)*, given to young researchers who distinguish themselves in the field.

Abstract

Waste electrical and electronic equipment (e-waste) is a current global challenge due to its exponential growth, toxic potential and precious/rare materials in its composition lost when landfilled. These challenges make e-waste management crucial economically and environmentally. The ideal e-waste management approach is a matter of research given it currently varies greatly among countries and the world has not yet found an efficient and effective solution. This thesis studies two countries that share enough similarities (same territory size, similar e-waste generated per purchasing power and recent policy framework towards e-waste) and precise discrepancies to allow comparison: Australia and Brazil. Australia being a developed country that has defined the roles and responsibilities of e-waste stakeholders, and Brazil being a developing country that left most of it to free market. The thesis combines three individual manuscripts published in scientific journals: the first two characterize the current e-waste management in Brazil and Australia, respectively, showing the distribution of e-waste recyclers, the main collection channels and the processes being undertaken. They also relate specific management issues found and explain the international e-waste trade (what is exported and where to). The third paper uses quantitative information obtained in Australia to assess the international trade and explain why some WEEE are exported, while some are processed domestically. The results obtained allow to discuss the importance of regulations for e-waste management and to what extent free market can operate without compromising the environment. It is shown that collection in metropolitan areas and downstream recycling where infrastructure is available can be left to the free market, while collection in remote areas and downstream recycling where there is no infrastructure can only be achieved through regulations. First stage recycling, however, is dependable on the country's workforce cost. Where labor is cheap, it will be driven by free market and needs regulations only to prohibit environmentally damaging processes.

Keywords: Electronic waste. Extended producer responsibility. Recycling. Recycling Cost. Reverse logistics. Waste management. WEEE management.

Resumo

Resíduos de equipamentos elétricos e eletrônicos (REEE) são um desafio global atual devido ao seu crescimento exponencial, potencial tóxico e materiais preciosos/raros em sua composição, que são perdidos quando descartados em aterros. Portanto, a reciclagem de REEE é importante do ponto de vista econômico e ambiental. A necessidade de pesquisa relacionada ao gerenciamento de REEE é evidente, já que o mundo ainda não encontrou uma solução eficiente e eficaz, e, atualmente, a gestão varia muito de país para país. Esta tese estuda dois países que compartilham semelhanças suficientes (mesma área territorial, geração de REEE por poder de compra similar e recente implementação de políticas para REEE) e discrepâncias precisas para permitir comparação: Austrália e Brasil. A Austrália é um país desenvolvido que definiu os papéis e responsabilidades dos agentes envolvidos na cadeia produtiva dos REEE, e o Brasil é um país em desenvolvimento que, pela falta de lesgislação, deixou a maior parte do manejo para ser regulada pelo livre mercado. A tese foi organizada combinando três artigos individuais publicados em revistas científicas. Os dois primeiros caracterizam a atual gestão de REEE no Brasil e na Austrália, respectivamente, mostrando a distribuição de recicladores de REEE, os principais canais de coleta e os processos que são utilizados. Eles também relacionam problemas específicos de gerenciamento encontrados e explicam o comércio internacional de REEE (o que é exportado e para onde). O terceiro artigo usa informações quantitativas obtidas na Austrália para avaliar o comércio internacional e explicar porque alguns REEE são exportados, enquanto outros são processados domesticamente. Os resultados obtidos permitem discutir a importância da legislação no gerenciamento de REEE e até que ponto o livre mercado pode operar sem comprometer o meio ambiente. Os resultados mostram que a coleta em áreas metropolitanas e a reciclagem avançada (pós separação) onde há infraestrutura, pode ser deixada para o mercado livre, enquanto a coleta em áreas remotas e a reciclagem avançada onde não há infraestrutura, só podem ser alcançadas por meio de legislação. A reciclagem de estágio inicial (separação inicial), no entanto, depende do custo de mão-de-obra do país. Onde a mão-de-obra é barata, ela será incentivada pelo livre mercado

e precisa de regulamentação apenas para impedir processos prejudiciais ao meio ambiente.

Palavras-chave: Engenharia ambiental. Logística reversa. Manejo de resíduos. Manejo de REEE. Reciclagem. Resíduos de equipamentos eletroeletrônicos.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

It has been almost sixty years since Rachel Carson's Silent Spring was firstly published and a collective awareness of the environmental causes began to rise (Carson, 2002). Shortly after, Lovelock's Gaia would be published and unveil a different perspective upon planet Earth, in 1979 (Lovelock, 2000). Despite the debatable concept of Earth being a living organism, Lovelock's book was able to reach a greater audience and deliver the idea that our world is an interconnected system (Shamsudduha, 2017). These mile stones were important since they are the precursor of the vastly established environmental research fields we now see as crucial, and because they have encouraged several scientists to take a holistic approach in the study of planet Earth and its conservation. The consequences of human action on planet Earth are visible and measurable, and while politicians, economists, journalists and others may have the impression that the scientific community discords about whether mankind's activities influence on climate change or not, that impression is incorrect. There is a scientific consensus on the reality of anthropogenic climate change (Oreskes, 2004).

The Industrial Revolution that began in the nineteenth century lead to an expressive increase in the human capacity to shape and transform our resources into foods, goods and energy. Alongside, the rapid industrialization generated huge amounts of waste (Chandra, 2016). The increase in manufacturing efficiency allied to affordable prices and a capitalism paradigm resulted in an ever-increasing consumption. Perhaps the apex was the introduction of one-time-use (disposable) products that took over the market and nowadays represent the rule, instead of the exception for many products. While consumption, population and production rises, so does the amount of waste. This narrative repeated itself in recent decades with the growth of the electrical and electronic equipment sector. Goods that were rare and expensive gradually became abundant and affordable. The release of new technology become faster and faster, while the life span of products, shorter (Balde et al., 2017). This occasioned the creation of a new waste stream called e-waste or WEEE (waste electrical and electronic equipment), a waste stream particularly important due to its ever-growing pace and disposal consequences. As governments realized the hazardous potential of this waste stream, an international shift took place and the world saw large amounts of WEEE being transferred overseas from developed to developing economies (Li et al., 2013). Under the "digital inclusion" premise, old, malfunctioning and broken equipment were shipped away from their original site, into the dumps of places with minimum infrastructure and unable to safely dispose of the goods. It became such a common practice that international conventions were put into force in the attempt to stop the transboundary movement of WEEE and when these failed to an extent, the exporting countries one by one established their own set of rules banning such export. Later, when the scenario refused to change, the receiving countries ("importing countries") set their regulations prohibiting the receipt of WEEE and, in spite of all these measures, this sort of transboundary movement can still be found between several countries in negotiations that do their best to find breaches through the regulatory frameworks in place (A. Kumar et al., 2017). As the story unfolds, another particularity of the e-waste stream gained the spotlight: the precious materials it contained in concentrations significantly superior to its primary source. This realization lead to the installation of recovery plants in developed countries capable of obtaining high value materials out of what was once considered invaluable waste. The shift observed thereafter concerned the transboundary movement of e-waste, not of the whole equipment anymore, but of their individual components, given developed nations had a great interest in obtaining the components of high material value and no economic interest in keeping the remainder. On the other end of the trade, low-income countries found a way to profit not only for receiving waste from others, but also by selling the high-end components it could obtain from the waste laying in their backyard.

These particularities of the WEEE stream created a shift in the world economy, but also caught the attention of the scientific community. Initially there was an important decontamination and landfilling challenge to overcome, in the attempt of impeding the contamination of soil, air and water due to incorrect disposal. Concomitantly, there was the challenge of understanding and explaining the potential health-related risks of e-waste and to what extent this was a public health issue. Later, it become a resource challenge, when it was noticed that large sums of energy where being used and large quantities of land where being moved to produce goods with concentrated resources and valuable materials (such as printed circuit boards), and then these concentrated goods where buried in the ground for future generations to deal with it. This became so apparent that a new type of mining sprouted recently, the so called “urban mining”, that emerges as an important source of materials (Habuer et al., 2014; Hoornweg and Bhada-Tata, 2012). The magnitude of the material value in WEEE worldwide has been estimated to be 55 billion euros (Balde et al., 2017), or about 63 billion USD. Moreover, the generation of WEEE keeps increasing yearly and it has been the fastest growing waste stream for the past four years (Abdelbasir et al., 2018b; Cucchiella et al., 2015). The current challenge is a combination of all these aforementioned challenges that favor and encourage a holistic approach to tackle the e-waste management problem and the status quo. The ideal model to treat, recycle, recover and dispose is still a matter of research. Individually and in organizations, countries worldwide debate and implement different approaches and, while these challenges are undeniably country-specific, there are important lessons to be learned by comparing different management systems amongst countries (Ongondo et al., 2011).

Brazil and Australia are two important countries within the e-waste management field. They are currently major e-waste generators (Goel, 2017; Robinson, 2009) and share enough particularities to allow the comparison of their e-waste management system. Firstly, they are countries with continental dimensions, which is important due to the initial stage of any waste management system: the collection. While the western European nations and Japan are arguably the current benchmarks in e-waste management worldwide, their territory size implies in a collection system much different from large countries like China, USA, Canada and Russia, ranked amongst the top e-waste generators in the world. The similarities between Brazil and Australia go even further because both countries have low population areas that nonetheless generate e-waste. They also share an expressive amount of outer regional/remote regions with difficult access, which, in turn, make the collection of any waste difficult. Moreover, both countries currently have to import an expressive percentage of their electrical and electronic equipment (EEE) and share a comparable gross domestic product (Brazil with about 2 trillion USD and Australia with about 1.3 trillion, in 2017). Perhaps the most important disparity between these two nations is the population, as Brazil has about 8-fold the population of Australia. Finally, both countries have only recently implemented legislations towards e-waste management. Australia and Brazil introduced their national waste policies in 2009 and 2010, respectively, which enables a comparison to be made concerning the effectiveness of their policies. Furthermore, Australia has defined the roles and responsibilities for most agents involved in the e-waste management and recycling setup, while Brazil has unwillingly left the system to be regulated by the free market regulation due to the lack of legislations. These characteristics, similarities and discrepancies allow important comparisons, which assist in revealing to what extent further regulations are needed to assure best e-waste management and recycling practices.

In light of the aforementioned considerations, the management of waste electrical and electronic equipment becomes a global issue and a major scientific challenge. Not only because of its rising volume, but also because its incorrect management incurs in significant economic losses and environmental prejudice owning to the valuable and hazardous materials it typically contains. However, despite being a known issue, governments and policy makers worldwide still find it challenging to create an efficient and effective e-waste management system. This thesis seeks to discuss the role of economic and political factors by comparing the e-waste recycling system in Brazil and Australia. It intends to show to what extent economic factors play a role towards e-waste management and to what extent legislative framework is necessary. Ultimately, this study seeks to reveal the e-waste management setup in use today in developed and developing counties and to rise several of the challenges that are currently being faced globally, encouraging a crucial discussion and, hopefully, giving way to a better e-waste recycling practice worldwide.

1.2 Objectives

This study is intended to:

- Investigate and characterize the current WEEE recycling scenario in Brazil, and provide useful insights;

- Investigate and characterize the current WEEE recycling scenario in Australia, and provide useful insights;

- Propose a model for the decision-making process used in Australia to determine whether a certain WEEE is recycled domestically or internationally;

- Determine the cost of first stage WEEE recycling in Australia and break the cost down into its individual contributions (first stage recycling is defined later in this thesis and the process breakdown is explained in detail);

- Compare the Brazilian and Australian WEEE recycling system and discuss strengths, weaknesses and possible solutions for the problems found;

- Use Brazil and Australia as examples of developing and developed economies, respectively, to allow a comparison to other countries worldwide;

- Discuss the importance of legislation and regulation in the WEEE management, having the Brazilian and Australian scenarios as examples.

- Finally, provide suggestions for improving existing WEEE recycling practices and developing new policies and practice that can maximize resources efficiency and circular economy.

1.3 Overview of the Thesis Papers

This thesis is organized in six chapters, three of which are scientific papers published in international journals (namely, chapter three, four and five). Chapter two is dedicated to a literature review on the topic of matter. Chapter six includes the discussion of the findings relating all published papers, the conclusion of the thesis and additional sections concerning limitations, contributions and suggestion for future research. Additional sections include the consolidated reference list (combined list of references for the introduction, literature review, all three published papers and discussion) and supplementary materials. The scientific papers allow this thesis to be presented in the "thesis by publication" format. While they are independent publications, the three papers are interrelated and allow further discussion about the topic of matter. The papers are presented in the order in which they were written and published (chronological order). Combined, these papers allow an extensive analysis of the current e-waste management in practice in Brazil and Australia, along with an analysis of the e-waste management setup worldwide. The comparison of these two countries and the evaluation of free market forces provide the framework to discuss the importance of regulations in best e-waste practice and the steps necessary to achieve this best practice. The first paper shows the analysis of the Brazilian scenario, highlighting who are the agents involved in the recycling of e-waste in the country, how the collection is organized, what is the legislation in place and the waste flow chain in the country. The second paper does a similar analysis relating the Australian scenario, but having its national recycling scheme as the main reference. In this sense, it relates the main agents and their roles, the main collection channels, the problems identified in the system and the perspective of the organizers and recyclers working under the scheme. The third paper maintains focus on the Australian scheme, but from the point of view of engineering economics and material analysis. It explains the decision-making process that determines how and why a certain material (or equipment) is kept within the country for domestic recycling or exported for international recycling abroad. Moreover, it highlights the role of regulations in the e-waste recycling sectors, which allows a further discussion about regulations worldwide. In summary, the first two papers describe and characterize two distinct e-waste management systems (Brazil and Australia), while the third analyzes the causes of international trade (or dump) of e-waste. Combined, they allow an important comparison and discussion of the e-waste setup worldwide and give a foundation to argue towards a better e-waste recycling practice in developed and developing countries.

1.3.1 Paper One - Waste electrical and electronic equipment (WEEE) management: A study on the Brazilian recycling routes

Pablo Dias, Arthur Machado, Nazmul Huda, Andréa Moura Bernardes. Waste electric and electronic equipment (WEEE) management: A study on the Brazilian recycling routes. Journal of Cleaner Production, Volume 174, 10 February 2018, Pages 7-16. https://doi.org/10.1016/j.jclepro.2017.10.219

This paper characterizes the Brazilian e-waste recycling system by finding and mapping the e-waste recyclers in the country and identifying the material flow from collection to reuse. It also shows to which extent the government (local, state, and federal) has control over the recycling system and the agents involved in the recycling chain. It defines the different stages of e-waste recycling, highlights the role of each agent, shows what processes are currently being used in the country and what materials are being recycled domestically (versus materials being exported for other countries to recycle).

The findings indicate that the Brazilian e-waste recyclers act mainly in the first stages of recycling, leaving advanced processes (as defined in the paper) to other companies (domestic and foreign). The first stages involve primarily sorting and dismantling, two activities that are predominantly undertaken manually, as evidenced by the main tools used in the recycling facilities. The distribution of recyclers found in the study reveal they are mostly located in the south and southeast region of Brazil, where there is a concentration of population and industrial activity. Moreover, the main channels for e-waste collection in the country are partnerships arranged between private companies and the recyclers. The study also evidenced that the government has little control over who are the recyclers and their activities. The collection and recycling in the country is left to free market, given the lack of regulations towards best e-waste practice and the lack of enforcement of the little regulations that exist. Recyclers, hand pickers (waste scavengers) and other agents compete for the waste that has higher intrinsic value. This competition rises the cost of collection and even governmental organizations were found to profit from the sale of e-waste. Furthermore, the study shows that there are companies specialized in exporting materials/parts from dismantled e-waste. These companies buy high value components from other recyclers and also act as trial/dismantling facilities. The high value components are then exported overseas for countries (namely developed countries) to undertake the advanced recycling processes and recover high value materials. Materials of smaller value than the exported ones are kept within the country and either recycled, landfilled or dumped.

1.3.2 Paper Two - Waste electrical and electronic equipment (WEEE) management: an analysis on the Australian e-waste recycling scheme

Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. Waste electrical and electronic equipment (WEEE) management: An analysis on the Australian e-waste recycling scheme. Journal of Cleaner Production, Volume 197, Part 1, 1 October 2018, Pages 750-764. https://doi.org/10.1016/j.jclepro.2018.06.161

This paper characterizes the Australian e-waste system using the National Television and Recycling Scheme (NTCRS) as the main reference. It shows the main collection channels used in the country, determines the processes used in the recycling facilities and evaluates the extent to which the regulations are being followed. It also allows the scheme organizers (namely co-regulatory arrangements) and the scheme recyclers to share their perspectives, which are assessed in light of the findings of the study. Similar to the previous paper, this study identifies and maps the recyclers in the whole country territory and presents the main destinations of waste after collection and processing. It also summarizes the main shortfalls identified in the system and proposes solutions to those problems having international schemes (or regulations) as examples.

The findings of this study suggest that Australia acts as a precious material concentrator and then exports this material to be processed abroad. The results indicate that Australia mainly undertakes the first stages of e-waste recycling, leaving the advanced processes to international partners. The first stages are primarily sorting and dismantling, mostly done manually, in spite of the identification of a few facilities equipped with automated machinery. It is shown that partnerships between recycler (or co-regulatory arrangement) and local government (local councils) are the main e-waste collection channel. The results suggest that there is no correlation between the number of permanent collection points and the amount of waste collected through the scheme. It also identifies all the recycling facilities working under the scheme, classifies them according to co-regulatory arrangement and maps them along the Australian territory. The findings of this study show that the recyclers forward the materials/components to other companies to continue the recycling process. These companies may be domestic or foreign. The main countries receiving waste are Southeast Asian countries and the main materials exported are those of high intrinsic value. The outcomes of this paper also indicate that, despite the regulations in place, the lack of monitoring leads to low compliance in several sectors of the e-waste recycling chain and that clear definitions within the regulatory framework are necessary to avoid improper (or dishonest) managing, storing and reporting.

1.3.3 Paper Three - Ensuring best E-waste recycling practices in developed countries: An Australian example

Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. Ensuring best E-waste recycling practices in developed countries: An Australian example. Journal of Cleaner Production, Volume 209, Part 1, 1 February 2019, Pages 846-854. https://doi.org/10.1016/j.jclepro.2018.10.306

This paper describes the decision-making process that determines whether a certain e-waste item (or component) will be processed domestically in Australia or internationally. It also seeks to use real world data to calculate the cost of first stage recycling in Australia and to identify what the cost relates to, providing a breakdown of the source of the cost. Furthermore, it relates costs and revenues obtained by first stage recyclers to assess the viability of free market regulation. The values obtained are used to discuss the importance of legislations supporting e-waste management and the result of free market regulation. They also serve as a foundation to explain and discuss the recycling practices in developed countries worldwide.

The results of this study provide important data to dissert about e-waste management worldwide because it reveals real world hard data, quantifying e-waste intrinsic value and e-waste recycling costs. It is shown that the only e-waste items that are not subjected to exportation in Australia are the ones with hazardous characteristics and that have been explicitly prohibited from leaving the country. Moreover, based on the greater profit principle, it brings a decision-making diagram that relates legislation restriction and profit scenarios to determine whether a certain equipment (or component) will be processed domestically or not, considering first stage recycling and downstream recycling. Moreover, the e-waste first stage recycling cost can be broken down into electric energy, machinery (equipment used in processing waste), fuel and labor. Among these individual costs, more than 90% is due to labor expenses and free market will tend to favor export to countries with smaller salaries in e-waste recycling sector than Australia. The evaluation of intrinsic value revealed that only computers (namely laptops and desktops) are capable of financially justifying its domestic recycling. This is only true in certain periods of time, when the commodity prices favor recycling. The recycling of other electrical and electronic equipment depends on a subsidy to be recycled properly, as the material value obtained does not economically justify the recycling cost (or decontamination cost for the case of some hazardous equipment). The results obtained indicate that in countries where labor is expensive (in comparison to other countries, i.e., developed economies), the lack of regulations obliging domestic recycling will imply in e-waste being exported. Furthermore, in the case where e-waste will be recycled domestically, there should be a subsidy from an external party to support the recycling cost, especially for equipment with low material intrinsic value and/or hazardous equipment.

CHAPTER TWO

LITERATURE REVIEW

2.1 Resources

Economic activity is dependent on resources such as land to produce food, raw materials to manufacture goods or energy to power equipment (Merz, 2016). Our current society has become extremely dependent on resources and while these seemed infinite not long ago due to the rate of new discoveries outpacing the rate of consumption, today it is understood that there is a limit (Worrell and Reuter, 2014a). In 2008, it has been reported that humans were consuming 30% more resources than the earth could naturally replenish yearly (WWF, 2008). Currently, ten year later, our overconsumption grew to 70% (GFN, 2018). The use of resources have grown dramatically, especially in the last seventy years (Steffen et al., 2007). More recently, the last few decades have seen the ease in the movement of money, goods and population, resulting in an upsurge of resource consumption and waste generation (Dutta and Goel, 2017). This consumption should increase further given the rise in population that we have been observing: An additional 2 billion human beings were registered since 1993, reaching 7.6 billion people in 2017; and having projections of 8.6 billion in 2030 and 11.2 billion in 2050 (UN, 2017a). In this ever-increasing pattern of consumption, it is clear that a resource crisis is bound to occur, hence the shortage of some specific materials that has already been observed (Dahlquist and Hellstrand, 2017; WWF, 2008). As researchers started thinking about these issues, concepts such as “circular economy” and “cradle to cradle” were created to shape the strategies to avoid a critical shortage of important materials by improving resources efficiency (Berndtsson et al., 2017). Worrell and Reuter (2014a) cite four ways to achieve this:

- Use resources more efficiently in the provision of an activity or product;
- Use less resource-related services;
- Reuse product and services;
- Recycle the resources and materials in products.

These are often used in the industry under the title of 4R (reduce, reuse, recycle and recover) (Goel, 2017; Rao, 2011). The balance principle, nevertheless, dictates that materials that are not used to create durable goods or recycled inputs end up as waste, which makes the improvement of the recovery and recycling of materials paramount (Merz, 2016).

2.2 Recycling

The definition of recycling has slight variations, but the core meaning remains the same: recycling is to close the loop in the life cycle of a material. If recycled, a used product is transformed into raw materials, which are then returned onto the supply chain (Rao, 2011; Worrell and Reuter, 2014a). Recycled materials may also be referred to as secondary materials, as opposed to primary materials (which are extracted from the environment) (Worrell and Reuter, 2014b). Recycling results in benefits such as the reduction of waste, the protection of the environment and the conservation of natural resources. However, large-scale recycling only occurs when the cost of recycling is lower than the cost of manufacturing a product using raw materials. Many materials require more energy in its primary production than recycling, in addition, the waste to be recycled is often more concentrated (purer) than the primary raw material (Hayes, 2003; Worrell and Reuter, 2014a). This justifies the different recycling rates for different materials. In general, metals have recycling rates higher than polymers and ceramics. Grimes et al. (2008) published a work on the environmental benefits of recycling and claimed that the energy requirements and carbon footprint for most recycled metals is 50% to 99% lower compared with primary produced metals. Some examples include ferrous metals (58%), aluminum (92%), copper (65%), nickel (90%), zinc (76%), lead and tin (99%). Hula et al. (2003) have observed that there are several factors which have an influence on the economic and environmental feasibility of recycling a certain waste; they include product structure, materials involved, locations of recycling facilities, applicable regulations, geography, and cultural context. Another study claims there are three main pillars that determine the effectiveness of metals recycling: economic factors, technology availability and societal factors. The first concerns the materials net value, which needs to justify the cost and effort of recycling or mandatory fees/taxes become necessary. The second relates to the process of recycling and the ease in which current technology allows the disassembly and recovery of the desired materials. It also relates to which materials can be recycled and recovered with the technology available. The last relates to the habits of a given group/country towards recycling (Graedel et al., 2011).

Recycling is dependent on economic factors, quality of the recycled goods and convenience to stakeholders. The economic factors are dependent on whether the income generated by the activity is sufficient to sustain the livelihood of those involved in the process or not, and on the quality and quantity of recyclable materials, which need to be sufficient to ensure long-term financial viability of the activity. The quality of the recycled material is related to whether a product made of recycled material can compete with a product made of virgin material or not. Lastly, the convenience concerns the parts responsible for collection, buying and selling waste. A country that can afford door-to-door waste collection or that has more waste drop off locations will be more conducive to recycling than others (Goel, 2017).

Despite all the benefits involved in recycling waste, it is noteworthy that recycling should not be the first course of action towards solid waste management. The priority hierarchy is to favor the waste prevention, followed by reuse, recycling, recovery and – finally – disposal (Nelen et al., 2014; Román, 2012; Tseng et al., 2018).

2.3 Solid Waste - A World Overview

Environmental concerns have risen significantly in the last 50 years, alongside with an intense increase in industrial activities in most countries. Waste generation was mainly observed in the United States of America (Figure 1), European countries and Japan due to their significant industrial activities. However, attention has been diverted towards countries such as China and India because of the development of their industry in the last two decades. This development, alongside with growth in resource consumption and population, make these countries main contributors to the global solid waste generation (Rao, 2011). In spite of its variable definition worldwide (Kawai and Tasaki, 2016), municipal solid waste statistics are able to illustrate the current waste generation situation. Moreover, while municipal solid waste definition does not include hazardous industrial and medical wastes, they are quite difficult to separate when entering the municipal waste stream (Rao et al., 2017). Global municipal solid waste (MSW) reached 1.3 billion tons per year in 2012 and was expected to reach 2.2 billion tons in 2025 (Hoornweg and Bhada-Tata, 2012). Current (2018) estimations suggest the global generation is already between 1.6 and 2.0 billion tons yearly (Waste Atlas, 2018a).

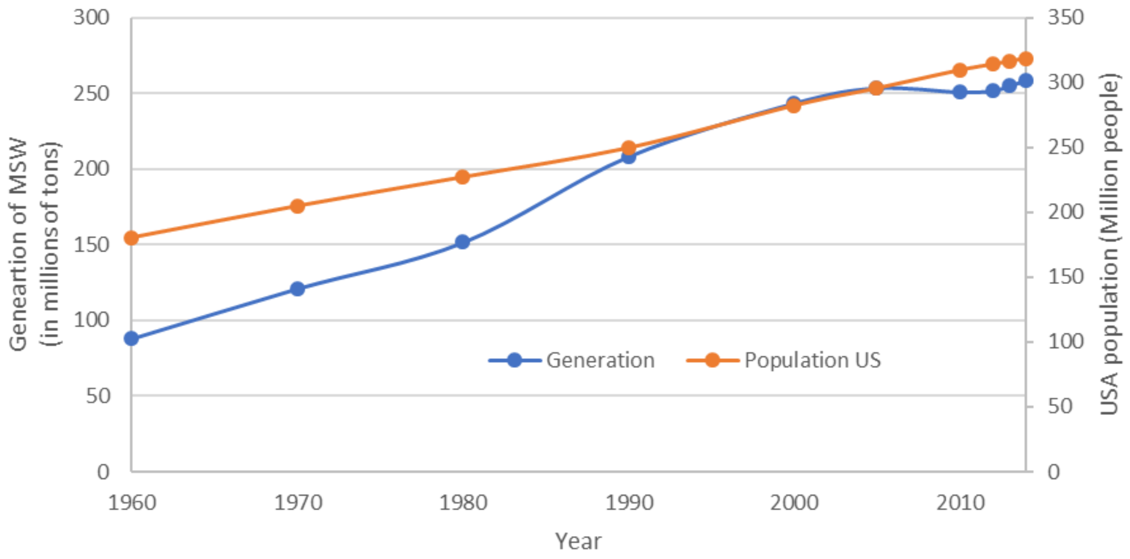


Figure 1: Generation of municipal solid waste (MSW) and population in the USA yearly. Data Source: USEPA (2016); World Bank (2018)

Waste generation has been reported to have a positive correlation with socio-economic indicators (Hoornweg and Bhada-Tata, 2012; Kawai and Tasaki, 2016; A. Kumar et al., 2017). Current estimations show this correlation by displaying Canada, the USA, Australia and Denmark as main per capita world waste generators, alongside with smaller nations such as the United Arab Emirates, Israel, Switzerland, Kuwait and Moldova (Figure 2). The country leading in municipal solid recycling rate is Slovenia (55%) followed by South Korea (49%) and Germany (47%) (Waste Atlas, 2018b). The overall generation, however, has China as the main contributor (about 300 million tons yearly), followed by the USA and India (both around 227 million tons yearly). The next countries on the list are Brazil, Indonesia and Germany, but their share is a fraction of the former, reaching values between 50 and 62 million tons yearly (Waste Atlas, 2018b). The waste generation gap among high-income countries has been reported to range from 1.1 to 3.7 kg/capita-day, while low-income countries the rate is as low as 0.6 kg/capita-day (Hoornweg and Bhada-Tata, 2012; Kandakatla et al., 2017). It is noteworthy, however, that waste generation data from developing countries are generally difficult to obtain (Kawai and Tasaki, 2016). Moreover, developed countries tends to have a reasonably sustainable infrastructure in place to handle the waste they generate (especially hazardous waste), while less developed countries still have a long way to go (Goel, 2017).

If dividing the world by regions, the OECD countries (*Organisation for Economic Co-operation and Development*, namely high-income countries) generate almost half of the world's waste, while Africa and South Asia produce the least (Figure 3).

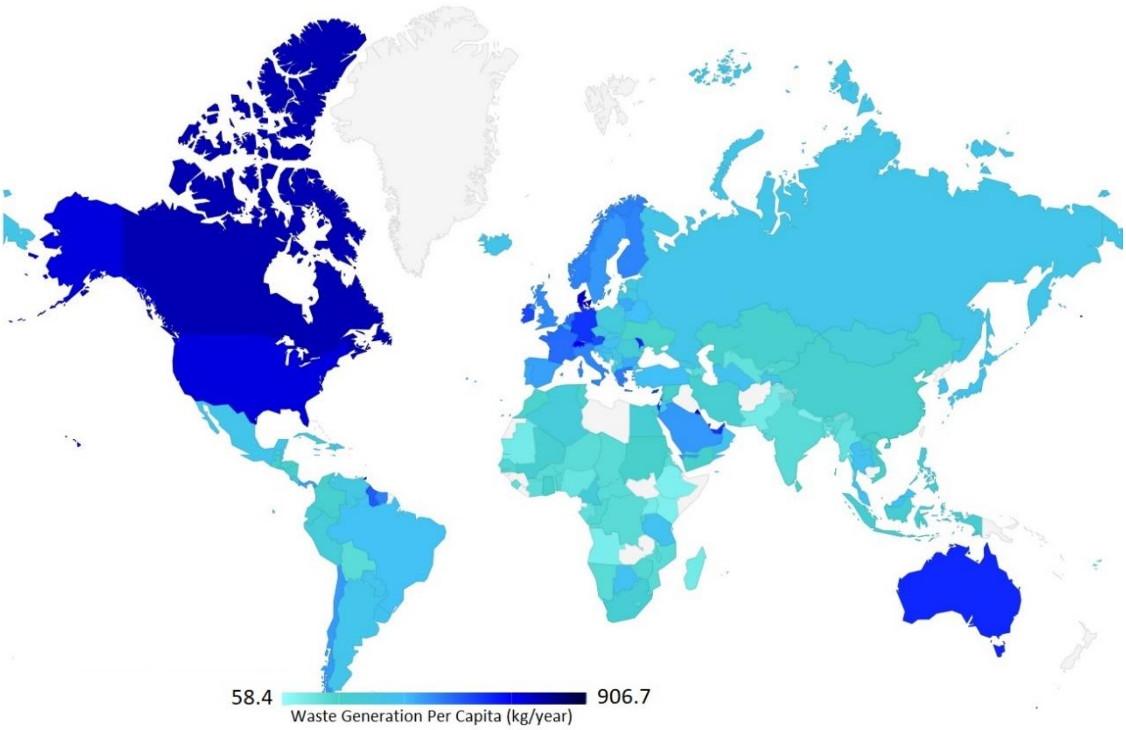


Figure 2: Global municipal solid waste generated per country per capita in kilograms per year. Adapted from Waste Atlas (2018b)

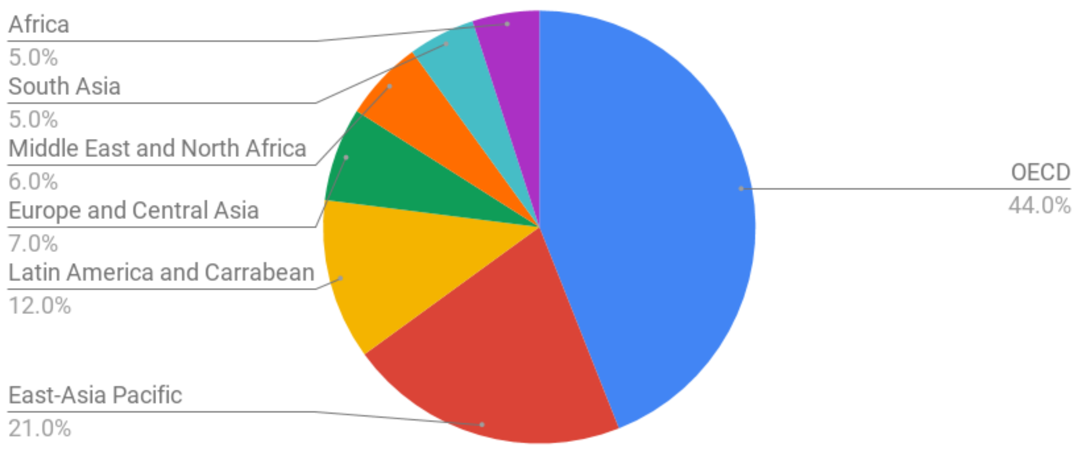


Figure 3: Waste generation by region. Adapted from Hoornweg and Bhada-Tata (2012)

2.3.1 Brazil

Brazil is a continental country situated in South America with a current population of approximately 207.6 million people (World Bank, 2018a). It has a territorial area of 8,515,759 m² (IBGE, 2017), which makes it the fifth largest country in the world, behind Russia, Canada, China and the U.S.A. Brazil is considered a developing country (UN/DESA et al., 2018), where generally the informal recycling sector has a great contribution in the waste management system (Ibáñez-Forés et al., 2018). Brazil currently generates 78.3 million tons of MSW yearly (ABRELPE, 2017), a figure that has been rising recently mainly because of the rapid economic growth the country experienced and changes in the lifestyle of the Brazilian population (Ibáñez-Forés et al., 2018).

The country's collection rate was 91% in 2016 and varies from 79% in the North-east region (which comprehends the state of Bahia, Sergipe, Alagoas Pernambuco, Paraíba, Ceará, Rio Grande do Norte, Maranhão and Piauí) to 98% in the South-east region (which comprehends the state of Sao Paulo, Rio de Janeiro, Minas Gerais and Espírito Santo). From the 78.3 million tons reported to be generated in 2016, 41.7 million tons (58.4%) were sent to landfill (ABRELPE, 2017). In 2017, only 18% of the Brazilian cities have a waste collection service that takes into account different types of waste and separates general from recyclable waste (ABRALATAS, 2017). This figure is a small increment from the previous ones, released in 2013 and 2015, that stated that only 14% and 17% (respectively) of the cities had such service (CEMPRE, 2015, 2013).

According to the Brazilian Constitution, the management of solid waste is a responsibility of the government. While a concession may be granted for private companies to act in the waste activities, these need to be monitored (or supervised) by the public entities (Neta, 2011). In 2015, the sectoral agreement that implemented reverse logistics in packing goods came into force (Ministry of Environment, 2015). This includes packing goods made of paper, cardboard, polymers, aluminum, steel, glass or any combination of these. The implementation was scheduled to last 24 months and secure the recovery of 3.8 thousand tons of packing goods per day (ABRELPE, 2017; Ministry of Environment, 2015).

The main Brazilian legal framework towards waste management in the federate level is the National Policy of Solid Waste (*Política Nacional de Resíduos Sólidos*), also known as National Waste Policy (Brasil, 2010). The policy establishes the general guidelines that the country should follow concerning waste management, responsibility of the waste generators and the government, and applicable economic mechanisms. Among other changes imposed by the national policy is the shared waste stewardship (Brasil, 2010). Waste that was once the sole responsibility of the government also becomes a responsibility of the population and corporations (CEMPRE, 2013). Moreover, the national policy states that solid waste management should prioritize the non-generation of waste, followed by reduction, reuse, recycling and, finally, treatment and disposal of waste in environmentally adequate site. The Brazilian definition for solid waste in its regulations is quite broad, given it states that it is any waste in solid and semi-solid states, resulting from industrial, domestic, hospital, commercial, agricultural, service and sweeping activities. It also includes sludges from water treatment systems and certain liquids, whose peculiarities make it unfeasible to be disposed of in the public sewage system (ABNT, 2004). Another important innovation brought by the National Waste Policy is the recognition of the informal waste workers. Collectors (such as waste pickers or waste scavengers), recyclers (such as hand pickers) and their associations (or labor unions) are mentioned in the policy as essential part of the waste management in the country and as a source of jobs and income (Brasil, 2010). This statement of the policy is of great importance given the informal sector waste workers are often socially marginalized, living and working without basic economic or social security, generally under conditions that are extremely detrimental to health and to family, social, and educational development (Rao et al., 2017).

The framework, however, doesn't define specific goals to be reached through the national waste policy nor holds the waste generators liable using concrete methods (evaluation, monitoring, fines, etc.). Instead, it mentions that these attributions will be addressed in a latter document called the national solid waste plan (*plano nacional de resíduos sólidos*) (Brasil, 2010). The plan was written, elaborated and debated with the community during the years of 2011 and 2012. A preliminary version of it was published in 2011, but it still awaits the approval of the agricultural policy committee to come into force (MMA, 2012). To date (2018), the plan is still in standby and there is not perspective of it being concluded and enforced in the near future (Grandelle, 2018). On top of the specific goals, the national waste plan also was tasked with diagnosing the Brazilian waste scenario to tackle the problem (MMA, 2012). In summary, the policy was not enough to affect the Brazilian waste *status quo* and the plan - that supposably would enforce the policy - never overcame the Brazilian bureaucracy. Even the termination of the open air waste dumps (*lixões*), stated in the national waste policy and reinforced in the preliminary waste plan, has not been accomplished, as Brazil still counts about 3 thousand of those countrywide (Grandelle, 2018).

Open dumping is a common practice in developing countries (S. Kumar et al., 2017) and incineration is rarely a viable option in these countries, partially due to the composition of their waste (high level of organic contents and moisture) and partially because of the high investment and operating costs of the advanced technology required. (Rao et al., 2017). Therefore, low cost waste management strategies are undertaken in developing countries like Brazil and result in negative environmental impacts (S. Kumar et al., 2017).

2.3.2 Australia

Australia is also a continental country and its situated in the Oceania region with a population around 24.6 million in 2017 (World Bank, 2018a). It has a territorial area of 7,692,024 m² (Australia, 2017), which makes it the sixth largest country in the world, following Brazil. Australia is classified as a developed country (UN/DESA et al., 2018) and generated 64 million tons of solid waste (46 million tons excluding fly ash and hazardous waste) in the financial year of 2014-2015 (Pickin and Randell, 2016). This equates to about 2.7 kg of waste per capita and the reported recycling rate was 60% (Pickin and Randell, 2016). Moreover, the MSW generation in 2015 was 13.3 million tons or 561 kg per capita, a figure above the OECD average (523 kg per capita) (OECD, 2018a).

The National Waste policy is the regulatory framework that serves as foundation towards waste management in Australia, it was introduced in 2009 by the Australian Government and states guidelines and general targets that are to be achieved by 2020. It was created to update and integrate the existing waste management policies and regulations (Environment Protection and Heritage Council, 2009; Morris and Metternicht, 2016). One of the biggest changes announced by the policy is the idea of managing waste as a resource - as opposed to disposing of it as if it was worthless - and that this resource should be recovered with local technology having innovation being sought after internationally (Environment Protection and Heritage Council, 2009). Moreover, the National Waste Policy sets other three general goals: avoid the generation of waste and reduce its disposal; ensure that end-of-life management (treatment, disposal, recovery) is undertaken in a safe and scientific and environmentally sound manner; and contribute to the reduction of the emission of greenhouse gases, to the conservation and efficiency of energy, water and land. To achieve its set goals, the policy establishes sixteen priority strategies and focuses on six key areas, which include the shared responsibility throughout the life cycle of a material (including end-of-life) and the generation and provision of waste management data to assist in decision making (Department of the Environment, Water, Heritage and the Arts - Environmental Protection Heritage Council, 2009). Two years after the introduction of the national waste policy, the Product Stewardship Act came into force, which delivers the means to achieve the goals set by the Policy.

The Product Stewardship Act 2011 provides a framework to administer and accredit product stewardship schemes throughout the country. It addresses the environmental, health and safety impacts of products while acknowledging the shared responsibility of the nation towards all products manufactured, imported, sold, consumed and disposed of in the country (Department of Sustainability, Environment, Water, Population and Communities, 2011a; Department of the Environment and Energy, 2011; Herat and Agamuthu, 2012). In 2011, the products targeted for stewardship action were computers, televisions, packaging, tires and mercury containing lights. However, the Act requires a list of products being considered for coverage by the legislation to be published yearly (2017-2018 list is presented in Table 1) and the Act itself has recently been review - as this was a requirement after five years from the commencement date (Department of the Environment and Energy, 2011). The Act is the piece of legislation that sets out the governance arrangements and the power of the Australian Government as regulator. It provides a framework for voluntary, co-regulatory and mandatory product stewardship, establishes the reporting and audit requirements for organizations delivering product stewardship schemes and defines who is liable for a certain class of products (Australia, 2018; Department of Sustainability, Environment, Water, Population and Communities, 2011a).

In spite of the differences among Australian states (waste frameworks and regulation, landfill levies rates, and direct government support), they all share the long-term targets (2020 and beyond) of achieving at least 70–80% recovery rates for all waste streams (municipal, construction and demolition, commercial and industrial) (Randell et al., 2014). The introduction of these targets and recent measures are important for the country, given that in countries with large territorial areas (like Australia, Canada and the USA), landfilling has been the method of choice for disposal of waste (Goel, 2017).

Table 1: 2017-2018 Product list containing the goods that are being considered for coverage under the Product Stewardship Act (Department of the Environment and Energy, 2017).

Class of products	Date of notice	Reasons considering these products
Plastic microbeads and products containing them	June 2017	Plastic microbeads can persist in the environment for substantial periods and have been found to have detrimental impacts on aquatic organisms, ecosystems and the food chain.
Batteries		A significant increase is expected in the number of batteries entering the waste stream in coming years. Many batteries types contain hazardous substances.
Photovoltaic systems		The volume of photovoltaic e-waste is expected to sharply increase in coming years. They may possess valuable and/or hazardous components.
Electrical and electronic products		The National television and computer recycling scheme has favored the disposal of other electronic devices by the community. They may possess valuable and/or hazardous components.
Plastic oil containers		There currently is a successful scheme in place for these products. However, several oil companies have been choosing not to participate in the scheme, which may lead to the withdraw of the scheme altogether.

2.3.3 Waste Management in Developed and Developing Countries

Solid waste management generally involves (i) identifying and categorizing the source and nature of waste, (ii) separation, storage and collection, (iii) waste transport, (iv) processing and (v) ultimate waste disposal. The cost of these activities are mainly associated with the cost of transport facilities, operation (energy/fuel and labor) and real estate (Rao et al., 2017). Furthermore, solid waste management aims to minimize waste, maximize recycling and reuse, and ensure safe and environmentally sound disposal of waste. These objectives should be achieved in a sustainable manner employing and developing the capacity of the community, private enterprises, workers and government (Rao et al., 2017). While the waste management tends to be country-specific, there are general trends that outline developed countries to the detriment of developing countries.

As opposed to developing nations, developed nations usually have centralized waste treatment systems, which result in significant differences in relation to the formers. The segregation of waste, for instance, is a voluntary exercise in most developed countries (especially for biodegradable and non-biodegradable materials), but represents a source of income and allows the formation of a large informal network of people dedicated to waste collection (door-to-door) and meticulous waste segregation in developing nations (Goel, 2017; Hoornweg and Bhada-Tata, 2012). Because of this network, the recycling industry has a stronger presence in less-income countries where financial incentives and door-to-door collection create a convenient scenario towards material recycling. The waste sorting may occur prior to disposal (case of developed nations), prior to collection, during the collection or at the disposal site (Hoornweg and Bhada-Tata, 2012). Schluep (2014a) cites that “collection, manual dismantling, open burning to recover metals, and open dumping of residual fractions are normal practice in most developing and in transition countries”. This also creates two different realities, a contrasting example is that of Switzerland and India: in the former the consumers pay a recycling fee (for collection, treatment, etc.), whereas in the later the collectors in many cases pay the consumers for their obsolete appliances (Sinha-Khetriwal et al., 2005).

Currently, developed economies have a reasonably sustainable infrastructure to deal with waste, while the rest of the world still have a large amount of organizing and implementing ahead of them (Goel, 2017). The disposal of waste on land is still the most common practice worldwide due to its low cost. The main difference between developed and developing economies is that in the former this generally happens in engineered landfills, while in the latter in the form of open dumping (Goel, 2017; Hoornweg and Bhada-Tata, 2012). The choice between landfilling and incineration, however, is not a matter of economic development, but rather a matter of land: in countries where land is plenty, landfilling has been the matter of choice. This is mainly due to the cost– incineration is at least three-fold higher than landfilling (Goel, 2017).

2.4 Waste Electrical and Electronic Equipment

Waste electrical and electronic equipment (WEEE or e-waste) is classified as a solid waste within the hazardous waste category (Goel, 2017). E-waste consists in dead electronic and electrical equipment, it comprehends – but is not limited to - obsolete, broken or used computers, televisions, stereos, photocopiers, printers, faxes, monitors and mobile phones (Mary Westcott, 2012). It also comprehends the less notable equipment such as radios, washing machines, micro-wave ovens, hair dryers and photovoltaic panels (EU Directive, 2012; Robinson, 2009). Moreover, the WEEE definition also includes the components, subset of parts, peripheral accessories and materials used in the manufacturing of these equipment (EU Directive, 2012).

There is no precise figure determining the amount of e-waste worldwide, but it is agreed that it has been rising consistently and should continue to increase as new technologies are released and the lifespan of equipment decreases (Balde et al., 2015; Ongondo et al., 2011). Other reasons for the continuous e-waste increase are the affordable prices of electrical and electronic equipment (EEE), the rapid economic growth, urbanization and growing demand for consumer goods, which increased both the consumption of EEE and the production of WEEE (Babu et al., 2007; A. Kumar et al., 2017). The generation of e-waste appears to be higher in developed countries than in those with developing economies (Goel, 2017), but the WEEE generation has been increasing in both realities (Schluep et al., 2009). Furthermore, a positive correlation between gross domestic product (GDP) and e-waste generated in a given country was confirmed in a recent research. Interestingly, no correlation was found between e-waste generation and population (A. Kumar et al., 2017).

In the search for determining the scale of the e-waste problem, several studies attempted to estimate the production of e-waste globally. In 2009, it was estimated that WEEE generation was between 20 and 25 million tons yearly, originated mainly from the USA, Europe and Australasia (Robinson, 2009). In the same year, it was estimated that the yearly generation of e-waste laid somewhere between 20 and 50 million tons (Schluep et al., 2009) – an upper limit almost twice as high. In 2012, the yearly generated figure totaled about 46 million tons

(Perkins et al., 2014). The latest published studies indicate that the current e-waste generation in the world is between 20 and 50 million tons and should increase between 3 to 4% yearly (Abdelbasir et al., 2018a, 2018b; Balde et al., 2017). Moreover, merely one fifth of all e-waste generated is reported to be collected and recycled (Balde et al., 2017). Currently (2018), e-waste is the fastest growing waste stream in the world (Abdelbasir et al., 2018b; Cucchiella et al., 2015) and the estimates report it should continue to grow (Figure 4).

Figure 4: Worldwide e-waste generation. Total (on top) and per capita (bottom). 2017-2021 are estimates (Balde et al., 2017).

The current e-waste generation pattern poses one of the world's greatest pollution problem. On top of the growing generation pattern, e-waste are a particularly important waste stream because of their potential to be pollutants that pose a risk to the environment and to sustainable economic growth; and the potential to be resources, given the significant concentration of precious metals and high demand materials they contain (Babu et al., 2007; Goosey, 2012; Sugimura and Murakami, 2016a).

The composition of WEEE generally involves a mixture of several distinct materials. They are composed of both inorganic materials and organic chemicals, which contain a number of toxic agents (Fowler, 2017a). The main issues associated with these materials are the lack of appropriate recovery technology (Jujun et al., 2014) and the risk of releasing hazardous substances if the waste is not disposed of correctly (Marwede et al., 2013; Widmer et al., 2005). Hazardous substances found in WEEE include metals such as cadmium, lead, mercury, chromium, arsenic, gallium and silver (Dias et al., 2018b; Goosey, 2012; Widmer et al., 2005); and non-metals such as polychlorinated biphenyls, bromated flame retardants (BFRs) among others (Bakhiyi et al., 2018; Fowler, 2017a). Health problems related to e-waste have developed over the past 50 to 60 years and are accelerating in both developed and developing countries (Fowler, 2017b). The damaging potential includes initiation of cancer along with several other reported public health pathologies (Fowler, 2017a), which are displayed in a non-exhaustive list in Table 2.

Table 2: Major e-waste primary contaminants and their reported consequences. Adapted from Bakhiyi et al., (2018)

Contaminants	Example of WEEE sources	Main types of toxicity
Aluminum	PCBs, microchips, hard drives, LED monitors, plastic housing; plastics, cables and wires containing inorganic flame retardants	Lung irritant, neurotoxic
Antimony	Tin-lead alloys, WPCBs, CRT; LCD TVs; plastics, cables and wires containing inorganic flame retardants	Lung, eye and gastro-intestinal irritant
Arsenic	Dopant for semi-conductors, plasma TVs, LCD monitors and TVs	Carcinogenic, hematotoxic, endocrine disrupter
Barium	CRT, fluorescent lamps, LCD TVs, PTVs, gutters in vacuum tubes	Neurotoxic, cardiotoxic, gastro-intestinal irritant
Cadmium	Batteries, toners, cartridges, plastics, WPCBs, solder, chip resistors, CRT, PTVs, cell phones, infrared detectors	Carcinogenic, cardiotoxic, nephrotoxic, endocrine disrupter
Cobalt	Batteries, hard drives, laptop computers, LCD monitors and TVs, plasma TVs, CRT	Cardiotoxic, allergen (asthma), possibly carcinogenic to human (IARC)
Copper	Cables, electrical wiring, PCBs, microprocessors, terminal strips, plugs, plasma TVs, cell phones	Lung, eye and gastro-intestinal irritant
Hexavalent chromium VI	Corrosion resistant coatings, WPCBs, data tapes, floppy disks, pigments, PTVs	Carcinogenic (lung cancer), sensitizer, skin irritant
Lead	CRT (glass, solder), LCD TVs, PTVs, fluorescent tubes, PCBs, lead-acid batteries	Probably carcinogenic to human (IARC[a]), neurotoxic, cardiotoxic, nephrotoxic, endocrine disrupter
Mercury	Fluorescent tubes, compact fluorescent lamps, batteries, switches, thermostats, sensors, monitors, LCD TVs, laptop computers	Neurotoxic, skin, eye and gastro-intestinal irritant, endocrine disrupter
Silver	Plasma TVs, laptop computers, LCD and LED monitors	Nephrotoxic, reprotoxic
Halogenated flame retardants	PCBs, plastics	Endocrine disrupter, neurotoxic, carcinogenic (chlorinated flame retardants)
Halogen-free flame retardants	IT housing, plastics, epoxy resins in PCBs	Organophosphorus: endocrine disrupter Nitrogen-based: nephrotoxic, neurotoxic
PVC	Wiring and computer housing	Related to toxicity of dioxins and furans generated during PVC burning

[a]According to the International Agency for Research on Cancer (IARC) classification

Most often, the discarded electronic goods end-up in landfills along with other municipal waste or are burnt with no gas emission control, releasing toxic and carcinogenic substances into the atmosphere (Dwivedy et al., 2015). This is especially true in developing countries, where the health related problems seem to be acute (Han et al., 2018; Oguri et al., 2018; Song and Li, 2015). The pollution potential of e-waste goes beyond human health and can contaminate soil, air and water streams (Bakhiyi et al., 2018; Hong et al., 2018; Ikhlayel, 2017). Uncontrolled burning of e-waste (known to be a common activity in some developing countries (Oliveira et al., 2012)), has been reported to release various metals and organic halogen compounds into the environment (soil and ash mixture remainder after burning), which, in turn, are believed to influence the formation of dioxin-related compounds (Fujimori et al., 2016). Furthermore, rainfall can leach heavy metals that are commonly found in WEEE and contaminate soil, ponds and water streams (Figure 5) (Dias, 2015; Dias et al., 2018b; Wu et al., 2015). Several other occupational safety and environmental hazards related to poor e-waste management were presented in a study published in 2002. Hazards range from class cuts from CRT implosion to tin and lead inhalation (BAN, 2002).

There are several worldwide examples of the harmful effects that can result from a poor e-waste management. One of the most notorious is the city of Guiyu (China) where numerous studies have been conducted. The city became an uncontrolled (and unregulated) WEEE discarding and processing hub for the world around 1996 (Li et al., 2019). The recycling processes used in Guiyu were reported to be primitive, crude and carried out without proper pollution control measures (Leung, 2019). The consequences of the e-waste mismanagement in Guiyu include, among others, the (i) highest ever reported brominated flame retardants (BRFs) and organophosphate esters concentrations in the sediments of the town's river (Li et al., 2019), (ii) high levels of carcinogenic substances in duck ponds and paddies, (iii) high levels of air-borne dioxins and polycyclic aromatic hydrocarbons, (iv) heavy metals concentration (especially Pb, Cd and Cu) (Sthiannopkao and Wong, 2013). The consequences of this contamination to the population of Guiyu are still being understood, but there are studies that report higher rates of stillbirth, lower birthweights and lower height for the town's children than the controlled areas, which indicates there is a correlation between exposure to contaminants from WEEE and health burdens (Leung, 2019; Sthiannopkao and Wong, 2013).

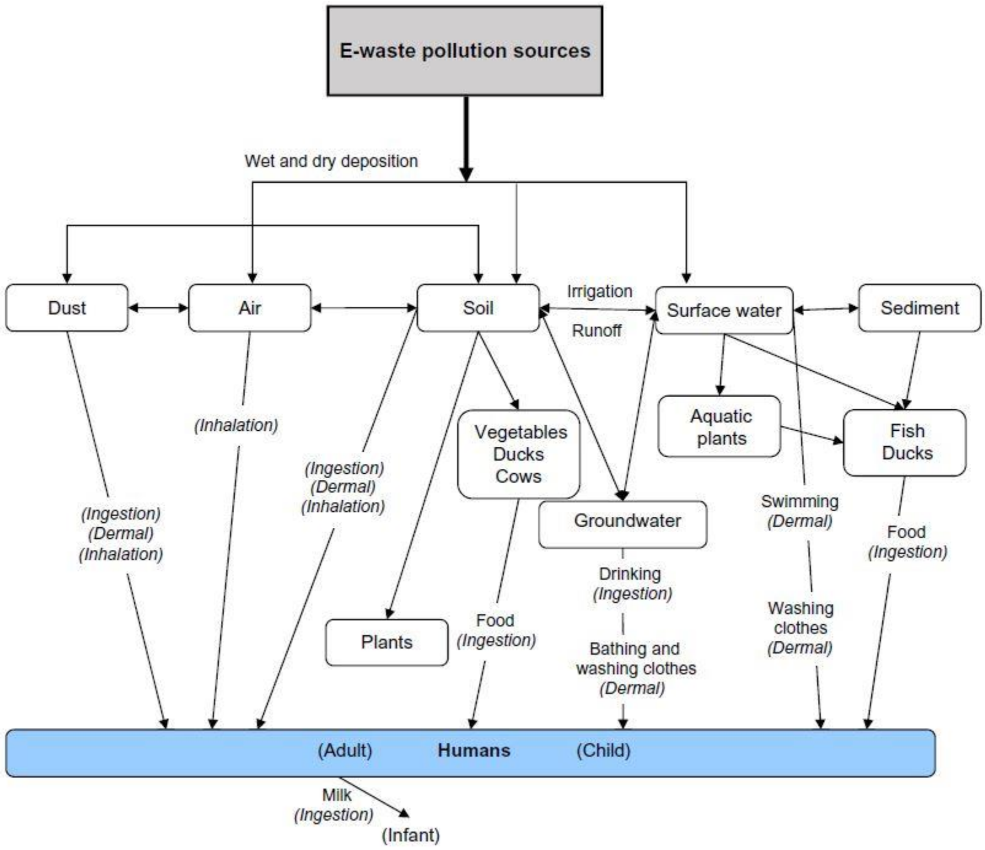


Figure 5: Multiple paths by which humans can be exposed to toxic substances from e-waste (Leung, 2019).

Waste electrical and electronic equipment also consists of numerous precious and scarce metals (Ongondo et al., 2011). The estimate for the total raw material value in 2006-2007 was 45.4 million USD. This included the main metals used in EEE and estimates of how much was available to be recovered multiplied by 2007 prices (Schluep et al., 2009). Following the 2008-2009 crisis, there was a decline in global EEE demand and a decline in copper demand (and price) (Gu et al., 2016). The latest figure estimated that the total value in raw materials present in e-waste equipment reached 55 billion euros in 2016 (Balde et al., 2017), about 60 billion USD considering the mean 2016 conversion rate (Bloomberg, 2018). This includes material value for iron, copper, aluminum, silver, gold, palladium and plastics (polymers) from WEEE worldwide. The main difference between the two is that the former (from 2009) includes all main metals but disregards the plastics, which on the later (2017) represents about 30% of total e-waste raw material value. On the other hand, the later (2017) disregards metals such as tin, platinum and cobalt, which summed up represent about 8% of the total e-waste raw metal value. The significance of the material value is remarkable regardless of which estimate is more precise. The amount of precious materials in e-waste, for instance, is so expressive that their recovery is the major economic driver for recycling of electronic waste (Cui and Zhang, 2008). The valuable material present in WEEE include:

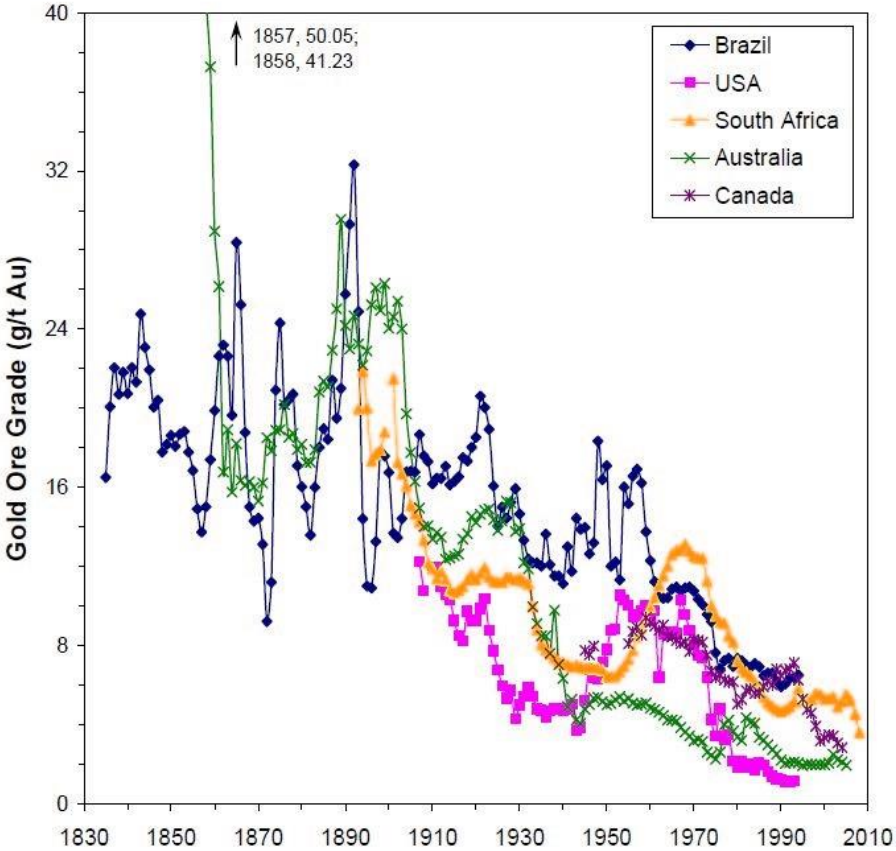
- Commonly found metals such as copper, aluminum, ferrous metals, zinc and nickel (Diaz et al., 2016; Widmer et al., 2005);
- Precious metals like silver, gold, platinum and palladium (Adie et al., 2017; Diaz et al., 2016; Ikhlayel, 2017);
- Other valuable materials including indium, gallium and solar grade silicon (Klugmann-Radziemska and Ostrowski, 2010; Tao and Yu, 2015; Yang et al., 2018);
- Scarce materials and rare earths elements, in particular neodymium, and praseodymium (Goosey, 2012; München and Veit, 2017);
- Other miscellaneous metals such as ruthenium, tin, bismuth, cobalt and selenium (Schluep, 2014b).

These valuable materials are usually found in low concentration within a given WEEE and caught in a mix of complex components, which makes their recovery challenging (Nelen et al., 2014). However, these concentrations are significantly higher than those typically found in the corresponding ores (Cayumil et al., 2016), and have been reported to be four orders of magnitude higher in WEEE than in the primary source for some materials (Table 3) (Ebin and Isik, 2016). Furthermore, the ore grade of primary production has been decreasing for various metals (Figure 6) (Giurco et al., 2010; Simon et al., 2013), which favors the material recovery from WEEE even further. Finally, WEEE recycling may also incur in energy savings, given secondary processing of some materials requires less energy than their primary production. This is yet another reason that advocates towards WEEE recycling (Chagnes and Cote, 2016). Therefore, the appropriate e-waste management and treatment can both prevent serious environmental damage and recover valuable materials (Schluep, 2014b).

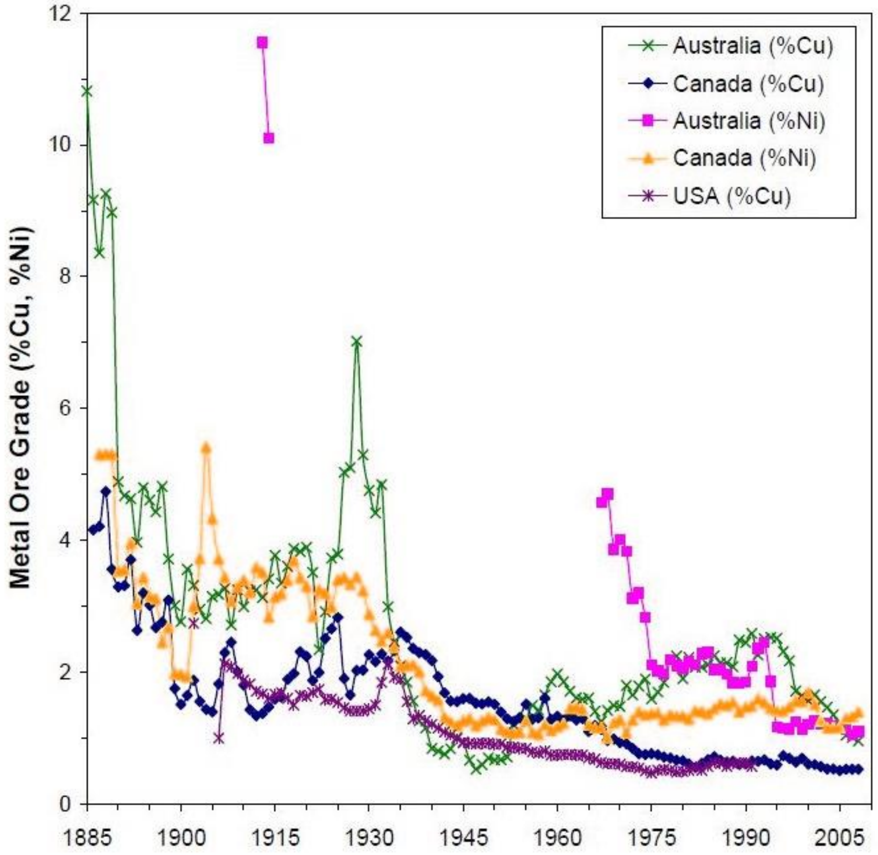
Table 3: Concentration of main elements recovered through pyrometallurgical routes in WEEE in comparison with the average content in their correspondent ores (Ebin and Isik, 2016).

Element	Average minimum content in ore (%)	Average content in WEEE[a] (%)	WEEE/Ore Proportion
Copper (Cu)	0.5	10-20	20-40
Iron (Fe)	30	1-5	0.167-0.033
Aluminum (Al)	30	2-6	0.2
Zinc (Zn)	4	0.5-6	1.5
Nickel (Ni)	1	0.1-2.5	2.5
Tin (Sn)	0.5	1.5-8	16
Lead (Pb)	4	0.3-5	1.25
Antimony (Sb)	3	0.2-1.8	0.6
Gold (Au)	0.0001	0.002-0.03	300
Silver (Ag)	0.01	0.03-0.3	30
Palladium (Pd)	0.0001	0.001-0.02	200
Indium (In)	0.001 (in zinc ores)	0.02-0.04[b]	40

[a]Minimum and maximum values of heterogeneous WEEE stream, PCBs from PCs, mobile phones, and other electronics. [b]Indium content in liquid crystal display (LCD) screens



1857, 50.05;
1858, 41.23
Brazil
USA
South Africa
Australia
Canada
Gold Ore Grade (g/t Au)



Australia (%Cu)
Canada (%Cu)
Australia (%Ni)
Canada (%Ni)
USA (%Cu)
Metal Ore Grade (%Cu, %Ni)

Figure 6: Ore grade variation over the years for gold, copper and nickel (Giurco et al., 2010).

The materials comprised within WEEE vary significantly. Firstly because the range of equipment that fall into the WEEE category is vast and includes products from small consumer devices to large household appliances. Even within individual types of products the material variability is significant (Goosey, 2012). Moreover , the materials in WEEE may also differ according to the year in which they were manufactured (Adie et al., 2017; Robinson, 2009). Generically, WEEE are made up mostly by ferrous metals (about 50% in weight), followed by polymers (approximately 21% in weight), non-ferrous metals (about 13% in weight). The remainder is distributed between glass and other materials (Ongondo et al., 2011). Individual equipment group analysis, however, will reveal a different material distribution (Table 4). LED TVs, for instance, have a higher amount of polymers, while stoves have a larger amount of metals (Veit and Bernardes, 2015). This great variability created the need for a standardized classification, which was proposed by the European Union in 2002 and has been adopted globally by several countries. It originally classified WEEE in ten categories, but changed to six in 2018 (EU Directive, 2012). Amongst other changes from the original ten categories, is the introduction of solar panels (or solar modules), which can be found in categories 4 and 5 (Table 5).

Table 4: General material composition of seven e-waste products (Goosey, 2012; Ikhlayel, 2017).

Material (% by weight)	Laptop	Mobile phone	CRT TV	LCD TV	Refrigerator	Washing machine	Air conditioner
Copper	1.5	-	3.0	0.8	3.4	3.1	17
Aluminum	3.7	2.0	-	3.5	1.3	2.0	7
Iron	29.8	8.0	12.0	39.8	46.6	51.7	55
PCBs	13.7	35.0	7.0	11.0	0.5	1.7	-
LCD glass	-	11.0	-	-	-	-	-
CRT glass	-	-	52.0	-	-	-	-
Plastics	14.5	44.0	23.0	18.5	43.7	35.3	11
Cables	1.0	-	-	1.5	-	-	-
Residues /Other	35.8	0.0	3.0	25.0	4.5	6.2	10
Weight (kg/unit)	3	0.1	25	10	75	40	-

Table 5: Categories of EEE according to the European 2012 Directive (EU Directive, 2012).

Category number and name	Examples
1. Temperature exchange equipment	Refrigerators, freezers, equipment which automatically delivers cold products, air conditioning equipment, dehumidifying equipment, heat pumps.
2. Screens, monitors, and equipment containing screens having a surface greater than 100 cm^2	Screens, televisions, LCD photo frames, monitors, laptops, notebooks.
3. Lamps	Straight fluorescent lamps, compact fluorescent lamps, fluorescent lamps, high intensity discharge lamps - including pressure sodium lamps and metal halide lamps, low pressure sodium lamps, led.
4. Large equipment	Washing machines, clothes dryers, dish washing machines, electric stoves, luminaires, equipment reproducing sound or images, musical equipment (excluding pipe organs installed in churches), large computer-mainframes, large printing machines, copying equipment, large coin slot machines, large medical devices, large monitoring and control instruments, large appliances which automatically deliver products and money, photovoltaic panels.
5. Small equipment	Vacuum cleaners, carpet sweepers, luminaires, microwaves, irons, toasters, clocks and watches, electric shavers, scales, appliances for hair and body care, calculators, radio sets, video cameras, video recorders, musical instruments, equipment reproducing sound or images, electrical and electronic toys, sports equipment, computers for biking, diving, running, rowing, etc., smoke detectors, small electrical and electronic tools, small equipment with integrated photovoltaic panels.
6. Small IT and telecommunication equipment (no external dimension more than 50 cm)	Mobile phones, GPS, pocket calculators, routers, personal computers, printers, telephones.

2.4.1 Legislations and Global Setup

The WEEE rising waste volumes and peculiar characteristics aforementioned created a global export trend, where developed nations sent unwanted WEEE to developing nations. This has been reported in scientific papers to have started from the beginning of the twenty-first century due to large volumes of obsolete EEE in developed countries, and justified as an attempt to bridge the "digital divide" between developed and developing economies (Nnorom and Osibanjo, 2008). Herat and Agamuthu (2012) cited that large volumes were being sent to developing countries for the purpose of reuse, refurbishment, recycling and recovery of precious metals, and that some of the main countries receiving e-waste are India, China, Philippines, Hong Kong, Indonesia, Sri Lanka, Pakistan, Bangladesh, Malaysia, Vietnam and Nigeria. On the exporting end, the following countries were identified sending e-waste to Africa in the beginning of the century: Belgium, South Korea, Finland, Germany, Netherlands, Norway, Israel, Italy, Japan, Singapore, UK and USA (BAN, 2005).

The excuse of the “digital divide” served for the purpose of breaching international treaties that would, otherwise, impede such movement of hazardous equipment. An example of such treaty is the “Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal” (Basel convention hereafter), which was established in 1989. The Basel Convention introduced important changes in the global waste panorama. Its goal was to restrain the illegal waste traffic and to enhance international cooperation towards hazardous waste management (UNEP, 1989). It established that the consent of all the parties involved was necessary prior to the export, import and transport of hazardous waste. Therefore, its introduction has made the transport of waste more difficult worldwide (Li et al., 2013). From 2002, the Basel Convention, following its sixth meeting, identified e-waste as a priority waste stream in the strategic plan of the years to come (Herat and Agamuthu, 2012). Because of the Basel Convention, about one third of the countries that imported electrical and electronic waste banned such practice (Li et al., 2013).

Nevertheless, the Basel Convention did not impact neither the generation, nor the flux of WEEE. This led to the creation of other directives aiming to tackle the e-waste challenge with direct regulations. Two of the most important being the European WEEE Directive (Directive on waste electrical and electronic equipment) and the RoHS Directive (Directive on the restriction of the use of certain hazardous substances), both implemented in 2003, and later updated in 2012 and 2011, respectively (European Commission, 2018). The later banned manufacturing and selling of EEE containing lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and/or polybrominated diphenylethers. This, in turned, obliged other countries that wanted to trade with the European

Union to stop using these substances in the manufacturing of their goods (Veit and Bernardes, 2015). The current maximum levels by weight for the substances restricted by the European RoHS are as follows (European Parliament, 2011):

- Lead (0,1 %)
- Mercury (0,1 %)
- Cadmium (0,01 %)
- Hexavalent chromium (0,1 %)
- Polybrominated biphenyls (PBB) (0,1 %)
- Polybrominated diphenyl ethers (PBDE) (0,1 %)

In 2015, the Directive 2015/863 was published, it announces the addition of four substances (phthalates) to the RoHS list and lower levels of tolerance for the restricted substances. Regulations similar to the European RoHS were also applied in several other countries with the same concept and slight variations, these include Japan in 2000, China, California (USA) and South Korea in 2007, Singapore in 2017 and Turkey in 2018 (RoHS Guide, 2018).

The formerly mentioned European WEEE Directive sets targets for the rate of collection, recovery and recycling, which increase over time. Other requirements include, but are not limited to (EU Directive, 2012):

- All collected WEEE must undergo proper treatment, which means preparing for re-use, and recovery or recycling operations;
- The quality standards for the recycling of WEEE shall reflect the state of the art;
- WEEE can only be exported for treatment outside of the EU if the country exporting can prove that the treatment took place in conditions that are equivalent to the requirements of the WEEE Directive;
- Member states should increase customer awareness by providing information such as the cost of end-of-life processing (at the time of sale of an EEE), not to dispose WEEE as unsorted municipal waste, reverse logistics systems available to them and the potential effects the hazardous substances of WEEE have on human health and the environment;

Moreover, the Directive introduces a greater control over WEEE and its components, requiring equipment to be weighed entering and leaving the treatment facilities (or recycling facilities). It establishes minimum treatments required prior to exportation of any WEEE, that member states must distinguish EEE from WEEE, and also requires several evidences attesting the exported material is fully functional - to avoid deceptive export of WEEE as used EEE. Finally, it encourages the development and pursuit of new technology to recover, recycle and treat WEEE (EU Directive, 2012).

However, as per the aforementioned cases in the beginning of the century, these regulations, treaties and conventions were not enough to stop the e-waste transboundary movement. Slowly, the countries individually began creating their own set of regulations to impede or regulate such movement (Table 6 and Table 7), but in 2013 a similar import/export pattern was still reported (Figure 7).

Table 6: Non-exhaustive list of legislations and regulations implemented to permit or ban import and export of WEEE and used EEE in common source countries (Li et al., 2013)

Country	Year	Legislation and/or regulation	Description
		Source Countries	
European Union	2002	Directive 2002/96/EC on Waste Electrical and Electronic Equipment	The exporter of WEEE should prove that the recovery, reuse and/or recycling operation takes place under conditions that are equivalent to the requirements of the Directive
Japan	2005	Law for the Control of Export, Import and others of specified Hazardous Wastes and other Wastes (Law No. 108, 1992; Latest revision: Law No. 33)	Stipulates export needs the consent from the country of import
Singapore	2008	Import and Export of e-wastes and used Electronic Equipment	The approval for to import and export of hazardous e-waste will only be granted on a case-by-case basis
South Korea	1994	Act on the Control of Transboundary Movement of Hazardous Wastes and their Disposal (1994)	No permission for export is issued without consent from the country of import
USA	2011	HR 2284: Responsible Electronics Recycling Act	Banned the export of certain WEEE: PCs, TVs, printers, copiers, videogame systems, telephones, and similar used electronic products, that contain cathode ray tubes, batteries, switches, and other parts containing lead, cadmium, mercury, organic solvents, hexavalent chromium, beryllium, or other toxic ingredients

Table 7: Non-exhaustive list of legislations and regulations implemented to permit or ban import and export of WEEE and used EEE in common destination countries (Li et al., 2013)

Country	Year	Legislation and/or regulation	Description
		Destination Countries	
China	2008	Catalogue of Restricted Imports of Solid Wastes that can be used as Raw Materials	Junk Electromechanical Products (mainly used for recycling steel) are restricted
Ghana	2011	Ghana e-Waste Country Assessment. SBC e-Waste Africa Project	Permits the import of WEEE, although Ghana has ratified the Basel Convention, it still has not been incorporated into national legislation nor it has not come into force
Hong Kong	2011	Advice on Import and Export of Used Electrical and Electronic Equipment Having Hazardous Components or Constituents. EPD, third ed.	Import/export compliance checking for used EEE
Malaysia	2010	Guidelines for the Classification of Used Electrical and Electronic Equipment in Malaysia	This Guideline assists all parties concerned in identifying and classifying used EEE as WEEE. Malaysia has ratified the Basel Convention, and as a Party must follow the procedures of the Convention for the import and export of e-waste
Nigeria	2011	Guide for Importers of used EEE into Nigeria (2011)	The government bans the importation of WEEE and near-end-of-life EEE. Every importer of used EEE should register with Nigeria's national agency
Thailand	2007	Criterion for Import of used EEE considered as Hazardous Substances	It presents a list of used EEE classified as hazardous substances that will be controlled, but in general allows its importation
Vietnam	2005	Law on Environmental Protection	It encourages waste reduction and recycling, stipulates the responsibilities for waste generators to minimize waste production. Includes articles for hazardous waste management and prohibits the import and transit of all kinds of wastes

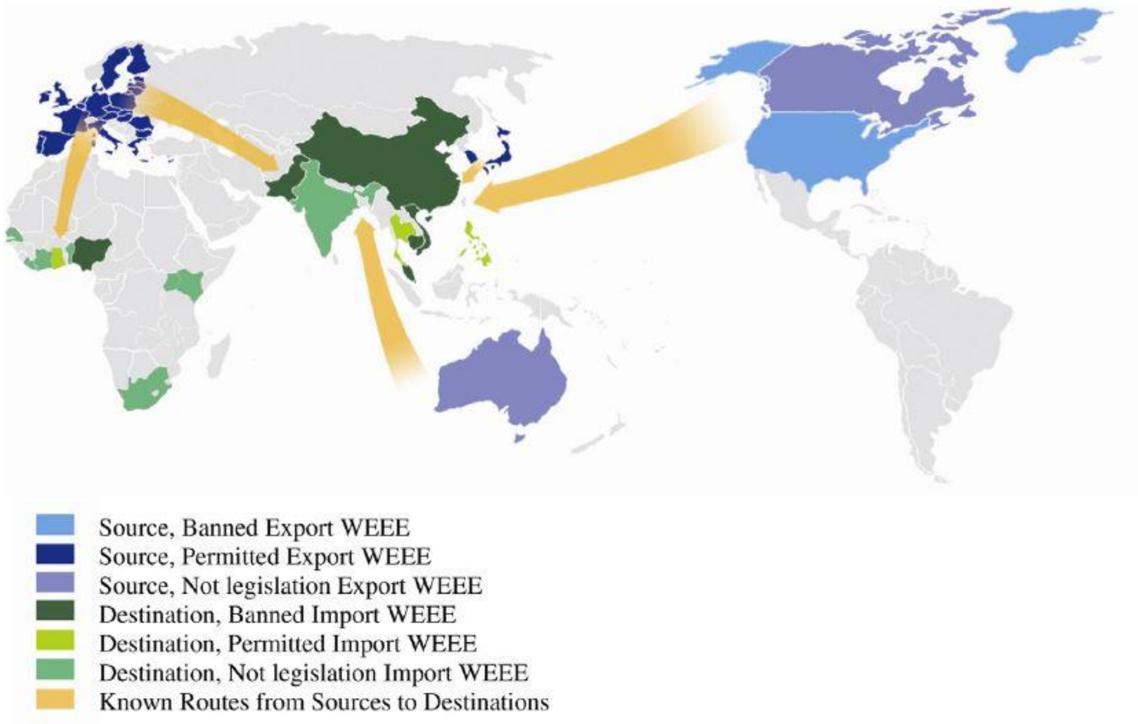


Figure 7: Known routes and permissions/bans for the WEEE imports/exports in 2013 (Li et al., 2013).

Therefore, in spite of national and international effort, e-waste trafficking (illegal movement) from developed to developing countries continued (Premalatha et al., 2014). Recent studies also shown this global transboundary movement (Garlapati, 2016; A. Kumar et al., 2017) and reported additional developing countries as destination places (Figure 8), which implies that this pattern is still in course. In the past three years, the Basel Action Network (BAN) has published several studies on "scam recycling", in which companies from developed nations supposedly recycle WEEE, but in reality export it abroad to junkyards where the waste is dismantled using dangerous and polluting methods (BAN, 2016). Developed countries, large e-waste generators, in the name of international trade - using the "reuse" excuse to save their environment and money flow - dump their e-waste in developing countries like India and China (Goel, 2017).

This scenario calls for a conformity verification system capable of assessing the particularities WEEE management, recycling and treatment. This is to ensure sound end-of-life practices, but also to track double counting of WEEE, which is suspected to happen in some countries as a mean to boost results (Toffolet, 2016). As can be anticipated, this need was filled by several different conformity verification systems, especially in Europe. As a result, trade between member states was made difficult because, for each country, a different set of rules applied. For this reason, the WEEELABEX (short for *WEEE Label of Excellence*) was created. Its objective is to design a set of European standards for collection, sorting, storage, transportation, preparation for reuse, treatment and disposal of all categories of WEEE, whilst harmonizing the rules and procedures for conformity verification in Europe. This would facilitate trade amongst the member states and level the playing field for stakeholders (Leroy, 2012).

Figure 8: Known sources and destinations and suspected destinations of WEEE transboundary movement worldwide (A. Kumar et al., 2017).

In light of the transboundary movement of e-waste worldwide, important changes occurred in 2017 when China, a major waste-destination country, announced stricter monitoring regarding the quality and contamination of the scrap material received. In July 2017, the Ministry of Environmental Protection of China announced at the World Trade Organization (WTO) that “by the end of 2017, China will forbid the import of 4 classes, 24 kinds of solid wastes, including plastics waste from living sources, vanadium slag, unsorted waste paper and waste textile materials” (WTO, 2017). It later confirmed the announcement about the import ban on a range of polymers (highly present in e-waste), which would come into force by the end of 2018 (Resource Recycling, 2018). These changes highly impacted the international scrap trade and diverted the material flow to other Asian countries, specially Malaysia, Vietnam and Thailand (Staub, 2018). The overload in these new destination countries was intense to the point where less than one year later, both the Vietnamese and the Thai government announced they would stop receiving scrap plastics (i.e. also announced import bans) (Resource Recycling, 2018). China has already proposed a total import ban, which would take place in 2020 and includes scrap fiber and every other form of solid waste. These measures were announced with the intent of protecting the environment, improving people's health and favoring domestic material over international (Resource Recycling, 2018; State Council, 2017).

Most developing countries do not have a program for the storage, separation, collection, transport or disposal of waste, nor adequate legislation and/or monitoring over the waste treatment procedures and the risks associated with incorrect disposal/treatment, this is especially true for e-waste (Nnorom and Osibanjo, 2008). Several studies address the consequences of poor end-of-life treatment that happen in developing countries, the main ones involve severe environmental damage and negative impacts on human health (Egeonu and Herat, 2016; Li et al., 2019; Schluep, 2014a; Zhang et al., 2018). These issues should be tackled by increasing the responsibility of the manufacturers (the extended producer responsibility) and through the technology exchange between countries that export and import e-waste (Li et al., 2013).

2.4.2 Recycling WEEE – Processes and Fundamentals

The material recovery present in WEEE may be achieved by the reuse of components, the recycling of the whole equipment (or a fraction of it) or transforming waste into energy (energy recovery) (Nnorom and Osibanjo, 2008). A great deal of material is generally lost in the recycling processes (Chancerel and Rotter, 2009). The advantages of recycling include the formerly mentioned recovery of natural resources (or improvement of resource efficiency), but state-of-the-art recycling can also contribute to reducing greenhouse gas emissions, reducing energy consumption for obtaining a given material and mitigating the climate change impact by avoiding the dispersion of ozone depleting substances (Hagelüken and Corti, 2010; Schluep, 2014b). There are several factors that influence the economic feasibility and environmental consequences of e-waste recycling (Hula et al., 2003; Nnorom and Osibanjo, 2008):

- Product structure

- Materials
- Location of recycling facilities
- Applicable regulations
- Geography
- Cultural context

All these factors combined will determine the feasibility of recycling certain products or goods. Another study uses four key-aspects to evaluate the recycling potential and determine which element should be prioritized in the recycling of WEEE. It relates the quantity of material in specific waste (e.g. gold in PCs), the toxicity of the given material, its market value and technology developed for recycling (Zeng et al., 2017). Thus, there is no single-solution when deciding if and how to recycle WEEE because all these factors will vary on a case to case basis (Sinha-Khetriwal et al., 2005).

Recycling of complex, multi-material consumer products such as WEEE calls for an extended network of different types of processes in order to recover the wide range of materials present. These vary from manual sorting/depollution, shredding, physical sorting and plastic and inorganic treatment processes, to pyrometallurgical technology. The ultimate goal is to achieve new high quality materials to be applied in new products (Van schaik and Reuter, 2012).

The dismantling or shredding of the equipment is the first phase of the recycling process. Dismantling is the process – automated or not – of separating the individual components of an equipment. Shredding is the process of transforming an equipment into fine particles using different types of shredders, grinders or mills. The core difference of these two processes is the output they generate and their cost. Dismantling is regarded as high cost in high-income countries due to the price of labor, while shredding is associated to the initial equipment acquisition cost, the energy it consumes to operate and its maintenance. The former requires a specialized team trained to dismantle different sorts of equipment. The introduction of a new WEEE implies in new training and slower dismantling rates at the beginning. This same process is regarded as low cost in developing countries (Wang et al., 2012), where salaries are generally expressively lower compared to developed nations. In China, for instance, manual dismantling is chosen to liberate the components from WEEE due to low labor costs (Ruan and Xu, 2016). The outputs of dismantling are the sorted WEEE components, usually segregated by material or by common destination (for further downstream processing). Shredding, on the other hand, gives as an output a fine blend of materials that will require subsequent sorting processes (Vongbunyong and Chen, 2015). The output can be slightly controlled by varying process parameters and types of shredders (Hayes, 2003).

After an EEE is dismantled and/or shredded, it needs to be sorted according to its distinct materials. This can be achieved by exploring the difference in properties of the individual materials and the processes include sieving, density separation, magnetic separation, electrostatic separation, separation by color, etc. (Figure 9). The third step (also referred to as end processing) involves specific processes for each class of material (e.g. pyrometallurgy, hydrometallurgy). Finally, the forth step relates to the refining procedures used when a purer material output is necessary. Steps may be repeated until material is recovered/ready to be reused (Goodship and Stevels, 2012; A. Kumar et al., 2017). When dealing with the recycling of metals specifically, the steps tend to include collection, sorting, shredding, physical separation, hydrometallurgical treatment, and smelting (Corder et al., 2015). Materials from all classes (including metals, polymers, and glass) can be recovered using these processes at a rate that depends on various parameters such as the size of the facility and the target electronic products (Babu et al., 2007). In spite of these known processes and their effectiveness, it should be noted that technical know-how for a complete e-waste recycle is still unknown to the scientific and industrial community (Habib Al Razi, 2016).

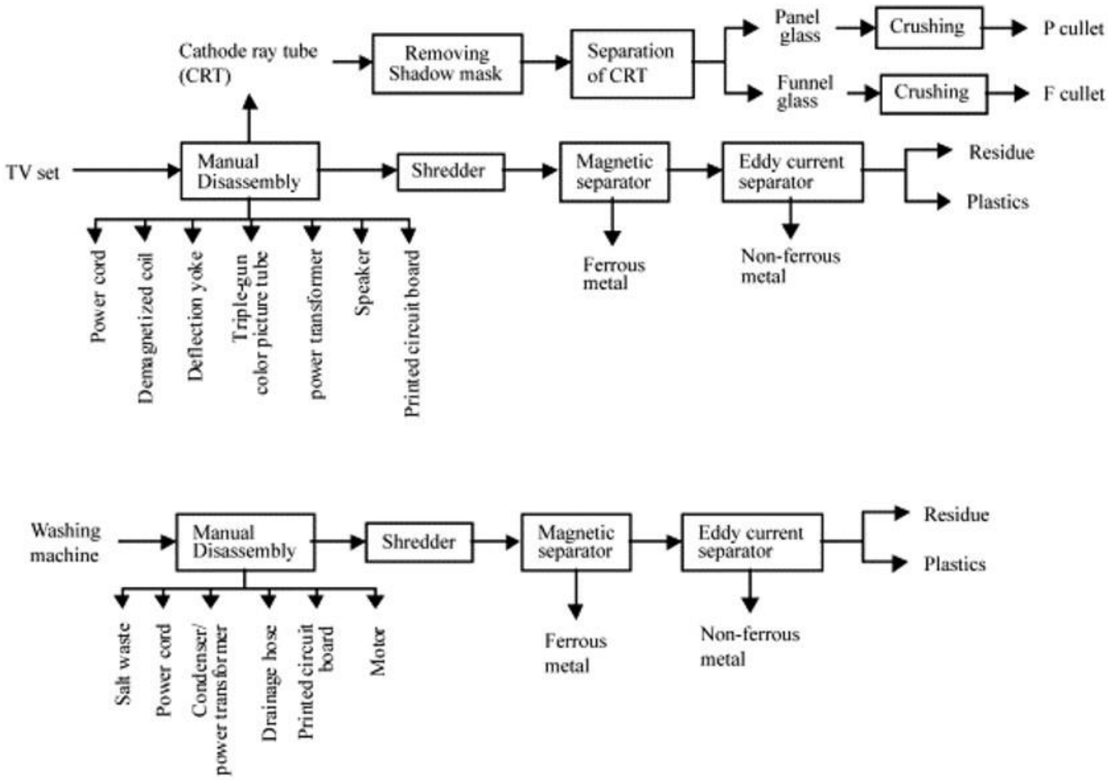


Figure 9: Schematic diagram of the processing steps to recycle two e-waste types and the byproducts they generate (Matsuto et al., 2004).

2.4.3 Reverse Logistics

Prior to recycling processes, however, there is the process of waste collection. This is logical since waste is originally scattered among all the consumers, which, eventually, discard their goods. An important concept applied in the collection of waste (especially WEEE) globally is the reverse logistics, considered an integral part of the holistic waste management process (Islam and Huda, 2018). Kara et al. (2007) mention that “product recovery, which encompasses reuse, remanufacturing and materials recycling, requires a structured reverse logistic network in order to collect products efficiently at the end of their life cycle”.

According to Agrawal et al. (2015), the most widely accepted definition for reverse logistics was stated by Rogers and Tibben-Lembke (1999), and is as follows: “reverse logistics is the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal”. It may also be regarded as the takeback system (especially for WEEE) that collects the discarded goods from the consumers and transports them back to the remanufacturing plant (Kara et al., 2007).

While reverse logistics directly relates to end-of-life goods, it has other applications and motivations. A supplier that offers leased products, for instance, has to create a logistic system capable of transporting its goods back after the leasing period. Thus, dealing with the cost of collecting the leased goods is also part of the business cost (Kleber, 2006). Other examples of situations where reverse logistics can be applied include unsold goods, warranties, product recalls, stock adjustment and repairs (de Brito et al., 2005). The main motivation for reverse logistic systems are reducing production cost by using recovered material or components, reduce overall cost of offered leased products in the marketplace (to increase competitiveness), increase market demand by showing the customers an environmentally friendly image of the company, protecting the products from third parties servicing demand for spare parts and avoid the implementation of environmental legislations (which may restrain the operation of the company) by taking environmentally friendly steps before the laws exist (Kleber, 2006).

The processes comprised in the reverse logistic system include the collection of discarded goods from consumers, the inspection and sorting, and the disposition. These will determine whether a product will be repaired, remanufactured, recycled reused or disposed of (also referred to as the *waste management option*) (Agrawal et al., 2015). The steps and possibilities involved in the process make the reverse logistic a more complex system than forward logistic (Kara et al., 2007) because both forward and backward flows must coordinated to serve two possible demand sources (Kleber, 2006). Nevertheless, the incentive tools used in forward logistics are also employed in reverse logistics, with the addition of deposit fees on the later (de Brito et al., 2005).

2.4.4 WEEE in Brazil

Brazil is amongst the major e-waste generators of the world, along with developed countries such as the USA and several European nations (Goel, 2017). In the Americas, it is the second largest generators, behind the United

States. Its most recent WEEE generation is estimated to be about 1.5 million tons yearly (Balde et al., 2017) and the expected increase between 2013 and 2020 is of 20% (Isıldar et al., 2018). E-waste falls into the coverage of the National Waste Policy (see section 2.3.1, page 34), which required the implementation of a specific sectoral agreement for WEEE. The sectoral agreement is composed of contracts between the government, the manufacturers, the importers, the distributors, or the vendors, with the objective of implementing the shared responsibility concept to the EEE goods. This was first drafted in 2013, but to date the agreement hasn't been approved (Caiado et al., 2017; Ministry of Environment, 2013). Balde et al., (2017) claims one of the main problems in Latin America is exactly the lack of regulations capable of enforcing proper e-waste disposal/treatment.

Research suggests Brazil is still learning how to practice reverse logistics of WEEE, particularly with the environmental licensing of generators, transporters and end-of-life EEE receivers (Araujo et al., 2015). The attitudes of Brazilians towards e-waste also seems to be still behind in comparison to developed countries, given 18% of the population disposes their end-of-life cellphone along with general waste (Moura et al., 2017). Furthermore, while the majority of Brazilians seem to hold a positive intention towards recycling e-waste, only a minority actually carries forward the attitude and adopt adequate recycling practices (Echegaray and Hansstein, 2017). Recent studies also indicate that the lifespan of EEE used in Brazil is decreasing, in particular for cellular phones. (Moura et al., 2017).

Brazil lacks an industry capable of undertaking downstream recycling processes, particularly for printed circuit boards (PCBs) (Oliveira et al., 2012). This was reinforced in a research published in 2017, in which the authors also claim installing such industry requires high investments (de Oliveira Neto et al., 2017). This can be observed in the private sector of recycling companies in Latin America, reported to mainly disassemble computers and cellular phones with the aim of recovering the valuable materials contained therein (Balde et al., 2017). Furthermore, formal reverse logistics seems to be unfeasible in the country due to operational costs and logistical constraints, which opens up space for alternatives such as reverse logistic credits (analogous to the already mature carbon credits) (Caiado et al., 2017).

Informal end-of-life practices towards e-waste are popular in Brazil. In the collection phase, for instance, the country has a significant number of waste pickers who scavenge waste to selectively sort the e-waste materials that can be later sold (Ghisolfi et al., 2017; Guarnieri and Streit, 2015). This results in a recycling system based on handpicked collection (cherry-picking) of exclusively high value components, as opposed to a sustainable collection system (Caiado et al., 2017). A recent research suggest that the informal e-waste recycling market has increased in Brazil (Moura et al., 2017). The processes used in the formal and informal sector in Brazil have been reported in 2009 and are displayed comparatively in Table 8. Supplementary Table C1 (page 224) shows a summary of studies done on Brazil and relates their main findings.

Table 8: Informal and formal processes in the e-waste recycling chain in Brazil (Schluep et al., 2009)

End-of-life management processes	Formal Process	Informal Process
Collection	Yes, consumer to business and business to business	Yes
Manual dismantling	Yes	Yes
Open burning		Yes
Open dumping		Yes
Shredding of white goods	Yes	
Export of PCBs	Yes	
Export of CRTs	No	
Disposal in general landfills	Yes	

2.4.5 WEEE in Australia

Australia currently ranks fourth in the world in e-waste generation per inhabitant, with a total of 23.6 kg/capita, behind Norway, the United Kingdom (and Northern Ireland) and Denmark (28.5, 24.9 and 24.8 kg/capita, respectively) (Balde et al., 2017). In terms of total tonnage, Australia generates 0.57 million tons yearly (Balde et al., 2017) and falls far behind world leaders due to the large population difference, especially in comparison with the USA and China (World Bank, 2018a). An estimate of e-waste generation in Australia from 2010 to 2024 is displayed in Figure 10. In 2006, the Australian Bureau of Statistics (2006) claimed that “obsolete electronic waste or e-waste is one of the fastest growing waste types. Very little of the increasing amount of e-waste generated in Australia is being recycled, with most of it ending up in landfill”. In 2008, a study reported only a small percentage of e-waste was recycled in Australia, particularly low percentages were reported for televisions (1%), computers (1.5%) and mobile phones (4%) (TEC, 2008). This led to an “ever growing e-waste mountain” (Herat, 2008), where significant amounts of e-waste were being sent to landfills (Ongondo et al., 2011). Furthermore, in 2010 there were few facilities assembled in the country for e-waste recycling and the geographical distances to be covered were significant (Davis and Herat, 2010). A commissioned study found there were 14 recycling e-waste facilities of significance operating in Australia in 2010, these had between 10 and 30 employees which undertook various levels of disassembly (according to the output products determined by facility) (Wright Corporate Strategy, 2010). A survey published in 2010 revealed that the population claimed for the introduction of legislative measures capable of managing e-waste with particular support for the introduction of a suitable funding mechanism and a consumer education programme (Davis and Herat, 2010). Accordingly, the biggest challenge for the country has been claimed to be legislation and compliance, given that by 2011 the initiatives to contest the WEEE problem were either too late or too little (Ongondo et al., 2011).

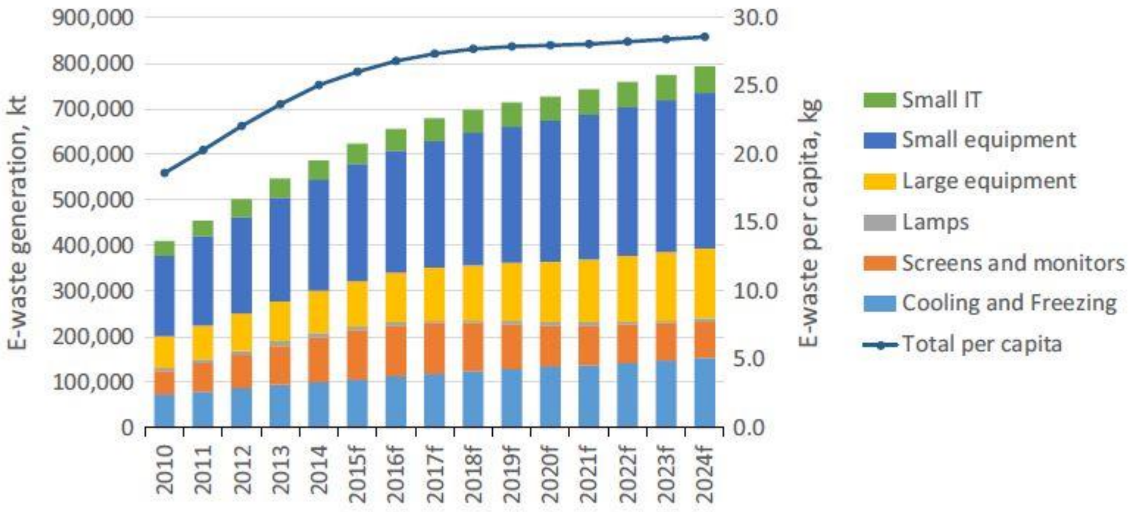


Figure 10: Estimated e-waste generation in Australia (total and per capita) for the six WEEE categories and various years (Golev and Corder, 2017).

The lack of legislation, however, has been tackled in recent years, as Australia currently holds the only law on the management of e-waste in Oceania: The National Television and Computer Recycling Scheme. It has been defined as ”one of the most significant producer responsibility schemes to be implemented in Australia” (Balde et al., 2017). The Product Stewardship (Televisions and Computers) Regulations 2011 and the National Television and Computer Recycling Scheme 2011 (NTCRS) came into effect in November 2011 and, supported by the National Waste Policy and the Product Stewardship Act 2011 (see section 2.3.2, page 36), provide the framework to manage the life cycle of computers, televisions and their peripherals (Morris and Metternicht, 2016). The NTCRS is an arrangement created to link small business and householders to the recycling industry. The scheme aims to collect and recycle e-waste, specifically televisions, computers and its peripherals. In 2015, the scheme had collected and recycled more than 130 thousand tonnes of waste TVs and PCs, which were diverted from landfill, allowing the correct treatment of hazardous materials and enabling the reuse of valuable resources (Department of the Environment and Energy, 2015a). The scheme is similar to the EU Directive, whereby the Member States must establish systems for users and distributors to return household WEEE to collection facilities free of charge and requires manufacturers to finance the collection and recycling of WEEE at these facilities (Lane et al., 2015). One change established by the NTCRS is suggested to be the increase flow of WEEE that are dismantled and/or exported rather than reused as second-hand EEE in Australia, this is due to the diversion the scheme promoted of WEEE previously directed to the not-for-profit sector. A graph containing the estimated destination of e-waste in the country in 2014 is displayed in Figure 11.

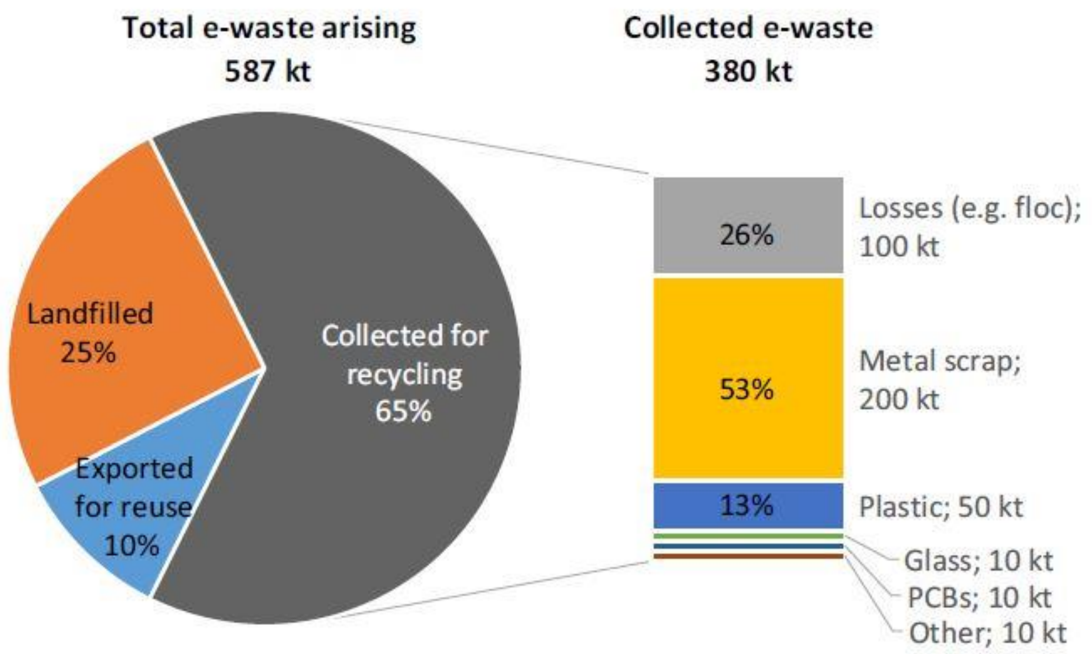


Figure 11: Estimated e-waste destination in Australia (Golev and Corder, 2017).

On top of the NTCRS, there are other regulatory schemes and industry programs for e-waste in Australia. The Mobile Musters program aims to collect mobile phones, its batteries and accessories. It was implemented in 1998 and has collected 1323 tons of mobile phone components since its commencement. The latest report shows a collection of 79.1 tons in the last financial year (Mobile Muster, 2017). Another arrangement is the Australian Battery Recycling Initiative, which aims to collect household batteries and commenced in 2008. It is currently a voluntary scheme, but there are negotiations in course to establish an industry-funded recycling program (ABRI, 2018; Golev and Corder, 2017). The Cartridges 4 Planet Ark is also a voluntary scheme established in 2003. It’s a free scheme for the end user that has collected a total of 39.1 million cartridges since its commencement. In the financial year of 2015-2016, it collected about 1500 tons of cartridges (C4PA, 2018; Golev and Corder, 2017).

There is no statutory bound that obliges the owner of an EEE to dispose of those products in a safe manner. There are minimal penalties for disposing EEE in public, but it is considered a minor criminal offense. Most Australian States and Territories do not have bans on e-waste going into landfill, the exception are South Australia and the Australian Capital Territory (Lane et al., 2015). The state of Victoria, however, has announced a ban on e-waste in landfills that should be implemented in July 2019 (Victoria State Government, 2018).

Research suggests that e-waste collection systems in Australia does not allow a feasible domestic material recovery, which leads to significant material export for processes to be undertaken abroad (Golev et al., 2016; A. Kumar et al., 2017). This has been further explained by Sahajwalla et al. (2016), who claims that “while safe resource recovery from e-waste is technically possible, it is expensive and currently relies largely on access to large scale, high tech furnaces, mostly located in Europe. Many nations, including Australia, have few or no viable resource recovery processes for e-waste. Consequently, some 90% of e-waste from industrialized nations is exported. Instead of being properly processed, much of it is reclassified as second-hand goods and dumped in landfill, where it poses both an environmental and health risks to the surrounding regions”. The lack of scale (enough WEEE volume) is also given as a reason for not having recovery operations in the country in another study (Golev and Corder, 2017). Moreover, the metal downstream recycling industry of the country has been reported to be well-established only for iron (steel scrap). Concerning the non-ferrous metals, there are only separation and smelting facilities for aluminum (Corder et al., 2015). Yet another report, this time from an industry player, agrees with the difficulties of responsibly recycling e-waste in Australia because of the high cost of labor, the low volume of e-waste recycling undertaken, the maturity of the market (low investment in infrastructure) and the availability of appropriate downstream processing (ANZRP, 2015a). The State of Victoria, in the aforementioned process of implementing the ban on e-waste in landfill, has published interesting calculations regarding e-waste recycling costs. It claims that recycling TVs and PCs, for instance, cost between AUD 500 and 1000 per ton, while the cost of landfilling the same items is between AUD 150 and 250 per ton (Victoria State Government, 2015).

The material export for downstream recycling has been matter of Australian research in recent years. A study from 2015 reports that most material recovery (for PCs and TVs) occurs overseas and the role of the domestic e-waste recyclers is restricted to collection and basic separation. It also claims there should be additional mechanisms and standards that ensure sound processing abroad. That is, that ensures the e-waste processing outside Australia is handled under the same minimum standards as the ones practiced in the country (Lane et al., 2015). Corder et al. (2015) showed that approximately half the scrap metal collected in Australia (approximately 2.5 million tonnes per year) is currently being transported overseas. They believe this is partially due to Australia's unique geographic location as a continent, long distances between major cities and industrial centres in regional areas. Research shows that the current economic model used in the country contributes to significant illegal exports of e-waste, given the struggle to maintain a positive economic balance and the constant approach of agents wanting to buy e-waste for unauthorized export (Lane et al., 2015). Thus, the e-waste business in Australia is highly sensitive to regulations, co-regulatory measures and EPA's regulations (environmental protection authority), which highlights the importance of well-structured legislations (Lane et al., 2015). These data are in contrast with the enormous revenue potential from e-waste that Australia has, estimated to be of the order of 2 billion AUD (approximately 1.55 billion USD) per year (including value lost by landfilling metals and lost opportunities in domestic processing of metal scrap). The figure is increased further to more than 6 billion AUD (approximately 4.65 billion USD) if the waste metals are fully recovered (Corder et al., 2015). A summary of the main findings of studies done on Australia is presented in supplementary table C2 (page 224).

2.4.6 WEEE Management worldwide and country examples

WEEE management is a global challenge specially given many countries have no structured system of reverse logistics and most WEEE is still disposed in landfills or in the open places exposed to the inclement weather (Veit and Bernardes, 2015). Several tools were created to tackle the waste management challenge and are being applied to the WEEE challenge, including LCA (Life Cycle Analysis), MFA (Material Flow Analysis) and EPR (Extended Producer

Responsibility). These, however, are generally seen in operation in developed countries (Kiddee et al., 2013). Developed countries tend to have laws and regulation to safely process WEEE. The compliance to these regulations is difficult to assure, given sound processing frequently runs against economic interests (Sthiannopkao and Wong, 2013). These take-back systems and end-of-life processing legislation for the electronics industry were originally proposed because of environmental motives (Stevels, 2007). A schematic of the management of e-waste from consumption to disposal is illustrated in Figure 12.

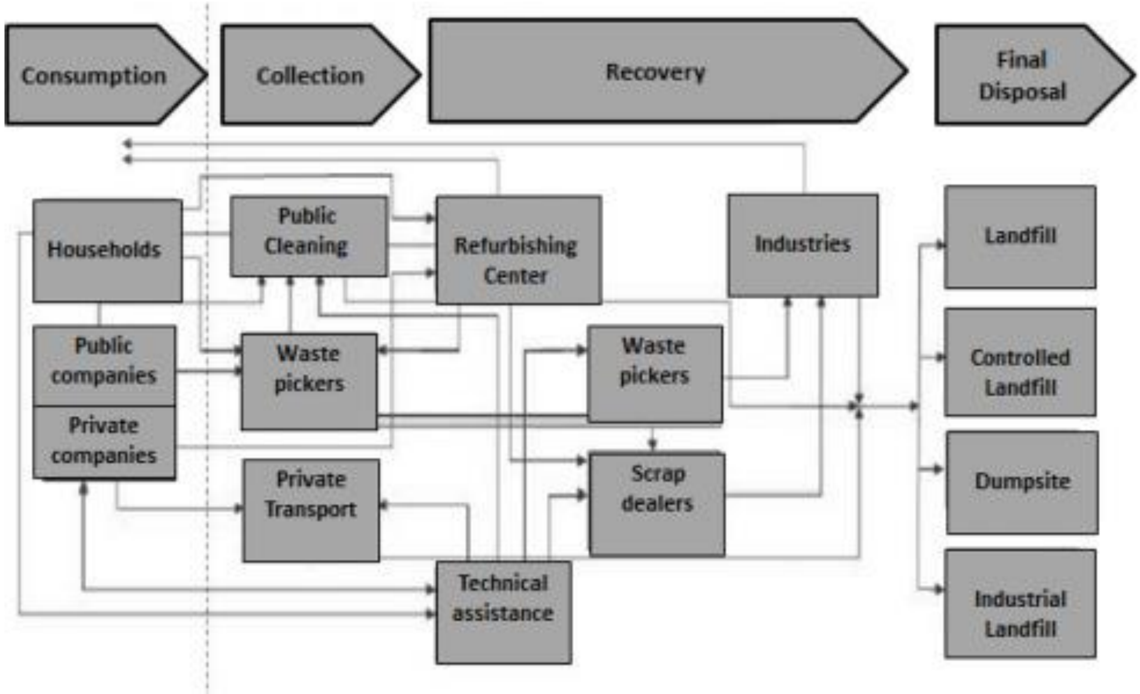


Figure 12: WEEE management flowchart (Caiado et al., 2017).

LCA and MFA assist in WEEE management by providing data concerning critical points in the material life cycle and pointing to appropriate end-of-life procedures (environmentally and economically). The LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). The LCA offers information on eco-design, product development and environmental impacts of a given EEE. It is an appropriate method for comparing WEEE landfilling versus incineration as an end-of-life option, for instance. And the results take into consideration the different scenarios in which the WEEE may be located (Kiddee et al., 2013). The LCA methodology consists of four interrelated steps: Goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation.

In the first step, the boundaries of the system, the necessary data and basic assumptions are defined, as well as the objective of the analysis (assess adequacy of different end-of-life processing method, identify hotspots for eco design, compare different products, etc.). The second step accounts for all the inputs and outputs of the various processes within the system boundaries (energy, material, emissions) based on educated guesses, estimates and/or previous studies. The following step aims to evaluate the environmental impact of the selected inputs and outputs and to classify them into different impact categories (e.g. abiotic resource depletion, global warming, acidification, stratospheric ozone layer depletion, eutrophication). The impacts are then converted into measurable scales using reference compounds. The fourth and last step identifies the significant environmental issues associated with the given case study, the limitations of the assessment and the conclusions and recommendations drawn from it (Gazulla Santos, 2014).

The MFA is a "systematic assessment of the state and changes of flows and stocks of materials within a system defined in space and time" (Brunner and Rechberger, 2016). It uses mass balance principle to identify environmental loadings and their sources, which can assist in decision-making to take countermeasures or to plan for future action such as urban mining. It is, therefore, a tool to manage resources, wastes and the environment. (Brunner and Rechberger, 2016). This tool can assist in developing appropriate e-waste management systems by considering WEEE flow and its assessment in terms of environmental, economic and social values. It can also be used to estimate e-waste generation in a given location (Kiddee et al., 2013).

Extended producer responsibility (EPR) is a policy in which the manufacturer is held responsible for its products when they reach their end-of-life. It is based in the polluter-pay principle and has been widely adopted in e-waste management systems worldwide. Switzerland, Japan, European Union (e.g. UK, Holland, Germany), some regions of the USA and Canada (Table 9), and more recently China have adopted this policy (Kiddee et al., 2013; Wang et al., 2018). The introduction of EPR was important to achieve sustainable e-waste management, it allowed the financing of unprofitable (but necessary) processing steps, the evolution of the e-waste recycling industry, a synergy between policies and legislations and a consumer demand for sound dispose option for e-waste (Schluep, 2014b). The EPR assumes the producer will undertake the financial costs of the end-of-life management of WEEE. In some cases, however, the financial burden is split with different stakeholders, including the consumers who are often required to pay a fee for the processing of its EEE once it reaches the end of its lifespan. These fees must be perceived by the payers as fair, reasonable and based on actual costs of the end-of-life management. They should also be revised periodically as the schemes in place are better understood and audited (MS2 and Perchards, 2009).

Table 9: Extended producer responsibility (EPR) in different countries (Goel, 2017; Premalatha et al., 2014).

Countries	EPR concept
European Union	The directive mainly focuses on reuse, recycle and recovery of e-wastes and dismantling of electronic parts and recycling of materials, proper collection systems to reduce disposal and incorporate best management practices.
Switzerland	This country was the first to develop and implement methods for collection, transportation, recycling/treatment and disposal of e-waste. Three producer responsibility organizations (PROs): The Swiss Association for Information Communication and Organizational Technology (SWICO); the Stiftung Entsorgung Schweiz (SENS); and Swiss Lighting Recycling Foundation (SLRS) oversee these systems based on the concept of EPR.
United States of America	Established funding for the collection and recycling of e-waste. Consumers pay a fee called Advance Recycling Fee (ARF) at the time of purchase that goes to the state and is used to reimburse recyclers and collectors.
Japan	Manufacturers and importers are responsible for taking back end-of-life electronics for recycling and waste management. Consumers pay a fee that is directly used to meet the expenses of recycling and transportation.
South Korea	Local manufacturers, distributors and importers of e-goods are required to achieve official recycling targets. Government keeps an account for depositing funds for recycling, which are refundable depending on the amount of waste recycled.
Australia	Importers, manufacturers and distributors have to subscribe to mandatory, co-regulatory, or voluntary schemes for managing the disposal of computers and televisions.
Singapore	Export, import or transit waste requires a permit from the Pollution Control Department (PCD) of Singapore. If documents are available to support that the products are in good condition and can be reused, only then permission is granted.
China	(a) Pollution prevention and controls on the use, dismantling and disposal of e-waste, under "Technical Policies for Controlling Pollution of WEEE, 2006", (b) Certificate is required for e-waste recycling systems, under "Administrative Measures for the Prevention and Control of Environmental Pollution by WEEE, 2008", and (c) All producers and importers responsible for their products, collection and treatment funds, under "Regulation on the Administration of the Recovery and Disposal of WEEE, 2011".
India	According to its Ministry of Environment, Forest and Climate Change, 2011, producers are responsible for collection of e-waste generated after the end-of-life of the e-products. The

	legislation has been modified in 2015 with new responsibilities for the producers as well as consumers.
African countries	The use of EEE is very less in the African countries. No specific e-waste legislation has been implemented in those countries.

A different management approach for the global WEEE challenge was proposed recently and named Best of two world philosophy (Bo2W). It seeks to achieve the most sustainable solution for developing countries under the current international panorama. In summary, the philosophy claims developing countries should take advantage of the low labor cost to employ manual dismantling to liberate e-waste components. These separated and sorted components would then be exported (sold) to developed economies, where technology and infra-structure is available for sound downstream processing. This theoretically ensures labor and revenue for developing nations whilst ensuring state-of-the-art and environmentally safe end-processing (Goel, 2017; Wang et al., 2012).

Kiddee et al. (2013) list the following as keys to success in e-waste management:

- Develop eco-design devices (EEE thought to be dismantled and recycled at their end-of-life);
- Properly collect e-waste;
- Recover and recycle material by safe methods;
- Dispose of e-waste by suitable techniques;
- Forbid the transfer of used electronic devices to developing countries;
- Raise awareness of the community regarding the impact of e-waste disposed improperly.

Rao et al., (2017) agree on the importance of community awareness campaigns and educational measures that show the negative impacts of incorrect e-waste disposal and their effective disposal value. The authors also claim that these campaigns should inform the roles and responsibilities of the agents involved in the e-waste management, including their rights as citizens to access waste management services. To discourage the international e-waste transfer and enhance proper device collection, country studies on the size and destination of the complementary streams should be performed and used to create specific collection targets per WEEE category to specific countries (Huisman, 2012).

The world is still searching for an ideal WEEE management model. Currently, different countries have different kinds of regulations and take-back systems. Europe might be the best example to illustrate this great variety, as Great Britain alone holds 44 distinct take-back systems (Figure 13). Regulations can allow or prohibit take-back systems to coexist and/or to compete. In some countries, there are compensation calculations to redistribute collection and recycling operational costs to the take-back systems according to the producers they represent. The verdict of whether a system ran by a monopoly or a system ran by companies in competition is more effective, however, is unclear at present. Moreover, the competent authorities hold the essential role of regulating the WEEE management systems to allow them to compete in a fair manner (Toffolet, 2016).

The particularities and characteristics of the WEEE management systems in specific countries are described in the sections hereafter. Data availability, consolidated e-waste management system and importance in the international scenario were the criteria used to choose the countries.

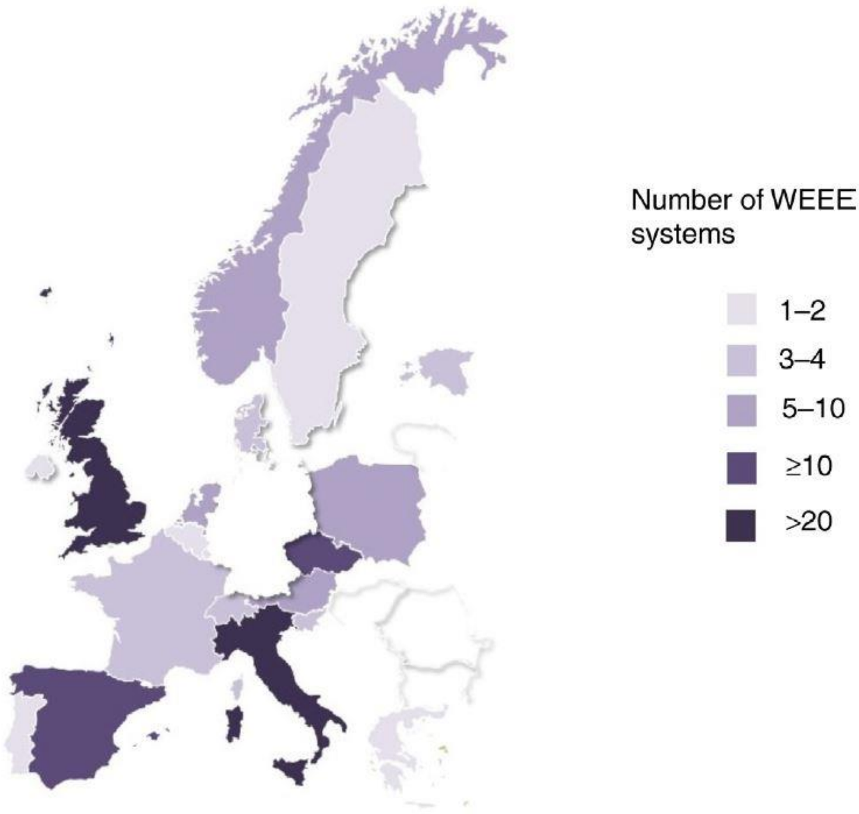


Figure 13: Distinct WEEE take-back systems in Europe (Toffolet, 2016).

2.4.6.1 France

In 2006, France set upon the producers, retailers (under their own brand) and importers the obligation of supporting the end-of-life management of WEEE and achieving the recycling and recovery targets set by the Environmental Code. Producers could either take the responsibility individually or collectively through the so-called eco-organizations. The later were preferred by the majority, which gave rise to the “Eco-systems”, the “Eco-logic” and the “European Recycling Platform” (ERP) (Vadoudi et al., 2015). To finance the operations, consumers pay an eco-fee when buying a new EEE, which is visible at the time of purchase. These vary from a few cents to a little more than tens of euros and were reported to not have changed the purchasing habits of the consumers (Toffolet, 2016). However, revenue for the operation is also obtained by different taxes and by fees paid by the manufacturers, which vary according to the product (based on criteria of durability, toxicity, recycled content and design for disassembly) (Vadoudi et al., 2015). The government participates actively in the whole system by overseeing the arrangements, charging fees, paying agents responsible for collection and recycling, approving these agents, enforcing end-of-life treatment standards and applying penalties to uncompliant manufacturers (Vadoudi et al., 2015).

2.4.6.2 Germany

Germany uses a system dubbed “divided product responsibility”. It requires public sector recycling companies to establish WEEE recycling centers and to accept WEEE free of charge - retailers are also allowed to take back WEEE (UB, 2016). The municipalities, after receiving WEEE from the public, sort the waste into groups prior to the manufacturer pickup (BMU, 2015). The local municipal authorities may then undertake the recycling or forward it free of charge to the existing take-back system. This is quite different to other countries, where local authorities charge the take-back systems for such service (Toffolet, 2016). All EEE manufacturers must adhere to the system, register and assure the its financing. They must also organize the treatment of WEEE and provide proof of such (BMU, 2015). Moreover, they are free to provide their own recycling mechanisms (UB, 2016). Unlike other countries that split “historic” WEEE (waste placed before the system was implemented) according to market share, Germany has a set of criteria to determine which producer should be responsible for it picking up (Ongondo et al., 2011). Under the system, the consumers are required by law to dispose of their WEEE in the take-back facilities (UB, 2016).

The German system works on a competitive basis (BMU, 2015) and it is set to limit the manufacturing clusters. Thus, each producer must collect its share of national obligations under a chief take-back system that ensures the collection costs are shared equally. This chief take-back system is also responsible for determining recovery and recycling targets (Ongondo et al., 2011). The targets rates are specific for the various device classes (UB, 2016). The search for the lowest short-term costs sought by the system, however, resulted in scattered volumes and in the gradual desertion of the market by operators (Toffolet, 2016).

2.4.6.3 Switzerland

Switzerland is considered a WEEE management benchmark as it currently has one of the world’s highest collection rates: more than 79% of the average of all EEE placed onto the market in the country during the three preceding years

(Toffolet, 2016). In Switzerland, the EEE user has the obligation to give back its end-of-life device and all retailers have the obligation to tack back any appliance at no cost. As opposed to many other countries, in Switzerland the legislation does not define how the industry should carry out their responsibility to manage and finance their WEEE recycling. Instead, the actual industry decides how to establish and carry out the recycling. The system is, therefore, voluntary and designed to be more flexible and cost-effective than government-run programs (Román, 2012). The system is currently managed by the producers (manufacturers and importers), which are organized in four PROs (producer responsible organizations). The PROs manage the daily operations, set the recycling fee and license and audit recyclers. The consumers pay a fee when they purchase an EEE (advanced recycling fee), which exempts them from any fees at the time of disposal. Consumers can drop off their WEEE at specific collection points or at retailers – the latter being the main collection network. The role of the authorities is controlling and monitoring the outcomes of the different stakeholders in the WEEE management system. The government oversees the process, frames the basic regulations and licenses the recyclers (Román, 2012). There is about one service provider (retailer or designated take-back site) per 444 inhabitants in the country; recyclers have to operate according to the recycling criteria of ISO 14000 and must have both the PRO license and the government authorization (Morris and Metternicht, 2016).

2.4.6.4 Norway

Norway is a non-EU member in spite of being tightly related to the Union politically and economically. Therefore, Norway has a WEEE management approach quite similar to other EU members, but also has its particularities. The Norwegian producers and importers of WEEE are obliged to be a member of one of the authorized take-back companies, which, in turn, must have an approval from the authorities. Consumer taxes ensures the financial requirements for the end-treatment of WEEE and the collection is organized either on municipal level, by inter-municipal waste companies or by stores. There is a law in force that obliges municipalities to collect WEEE, while the requirement for take-back systems is that they must ensure a free collection from enterprises, distributors and municipalities collecting WEEE (Román, 2012).

2.4.6.5 Japan

Japan's home appliance recycling system was driven primarily because of the shortage of landfill space in the country and the need for resource recovery (Yoshida and Yoshida, 2012). In its system, consumers pay a recycling fee when discarding TVs, air conditioners, refrigerators and washing machines. Retailers have the obligation of taking back items of these four categories, while producers have the obligation of recycling them (Yoshida and Yoshida, 2012). PCs and copiers were later included as voluntary items (Morris and Metternicht, 2016). While being responsible for collecting illegally dumped WEEE and being able to treat some designated WEEE types (Morris and Metternicht, 2016), the Japanese municipalities do not perform the collection and processing recycling operations themselves, instead it is carried out under a producer partnership cluster that is divided between Group A (Panasonic, Toshiba and other) and Group B (Mitsubishi, Hitachi and other) (Yoshida and Yoshida, 2012). There are about 1580 inhabitants per take-back sites in the country and the EEE producers have to meet recycling standards and targets determined by legislation (Morris and Metternicht, 2016). About 78% of WEEE are collected by retail stores, of which 64% are recycled by the producers and the rest is lost because of WEEE entering via channels outside the system and, therefore, without being paid for (Yoshida and Yoshida, 2012). The policy is built around recycling, which restricts product reuse. While the EU countries are mechanizing its operations, Japan still relies heavily on manual disassembly, which is one of the reasons the Japanese overall recycling cost is superior to that of the EU. It is believed that Japan's high recycling cost (and high recycling fee) leads to recycling outside the formal scheme and encourages WEEE export. That's why, in general terms, items taken back free of charge go abroad, whereas items that are paid for enter the domestic used market (Yoshida and Yoshida, 2012). Breaching the law implies in corrective recommendations, corrective orders, or penalties (Morris and Metternicht, 2016).

2.4.6.6 U.S.A

It is impossible to state a single WEEE management in the whole USA country, given it doesn't have a proper federal regulation for it. This is mainly because legally WEEE is generally considered a non-hazardous waste. The system of some of the individual states, however, can be described because the policies are imposed by state government (Li et al., 2013; Ongondo et al., 2011). In general, municipal waste management services are the most common approach to manage WEEE in the country (Ongondo et al., 2011). Moreover, it is illegal for most businesses in the USA to place e-waste in the trash (Namias, 2013). Some states have applied EPR programs that comprise disposal fees, deposit refund systems and mandatory take-back systems for rechargeable nickel-cadmium batteries (Garlapati, 2016); some have prohibited e-waste from being disposed of in the municipal waste stream (Namias, 2013).

In Maine, legislation specifies that each manufacturer is individually responsible for all the collection and recycling cost of its goods in addition to a share of orphan waste, which is waste from producers that have gone out of business or no longer trading. Orphan waste must be covered by any manufacturer with more than 1% market share. Municipalities and collection points are responsible for collecting e-waste and forwarding it onto a consolidator, which counts, weights and identify the brand of each product. Manufacturers can either collect a representative e-waste sample from the collector (based on a return share), pay the consolidator to recycle the e-waste on its behalf, or have their branded products separated and recycle them themselves. Any brand that is not compliant with the legislation is banned from selling its products (McCann and Wittmann, 2015).

The State of North Carolina introduced an e-waste landfill ban and an EPR law comprehending PCs and TVs manufacturers, retailers and local governments. It implemented a free tack-back program for the community, required the liable parties to register (be “certified”) and to pay an annual fee. The EEE producers pays the WEEE recyclers according to its selling share, which becomes their recycling target. Retailers must ensure correct EEE labelling and cross-check manufacturers/brand to make sure they are certified under the State. WEEE is mainly collected by local governments, who must provide annual reports and forward WEEE to recyclers. The role of the State government is screening and certifying the recyclers, registering the EEE producers, regulating the system and financially supporting eligible local governments. The system discourages scavenging and encourages recyclers to improve their recycling processes and efficiency. State law also requires environmentally sound recycling (DEQ, 2018).

The State of California requires retailers to charge a recycling fee from consumers who purchase certain EEE. The focus is mainly on displays (CRTs, LCDs, plasma, etc.). Retailers may retain up to 3% of the fees to cover collection costs, the rest is sent to a board who reimburses recyclers and organizations, which, in turn, provide free e-waste recycling to consumers and businesses (Namias, 2013).

In New York, manufacturers of certain EEE are required to collect and recycle (or reuse) their brands of products at no cost for residents and small businesses. Furthermore, certain WEEE are eligible for free collection through a manufacturer take-back program. The state requires manufactures to establish collection, handling, and recycling/reuse of discarded WEEE, it also establishes annual reuse and recycling targets for all e-waste. Exceeding the imposed targets result in credit, while a shortage incurs in a surcharge. There are several take-back programs, including free postage mail-back system and local collection events (Namias, 2013).

2.4.6.7 Canada

As is the case for the USA, Canada doesn't have a central federal regulation to deal with the e-waste, instead, the provincial government is responsible for regulating its management (Li et al., 2013). This lack of a central government standard does not allow an even competition among recyclers from distinct provinces. By 2014, all provinces but one (New Brunswick) had a proper e-waste management program (Morawski and Millette, 2014). The Canadian WEEE management systems have been designed, and are managed by foundations owned by technology companies (Irani et al., 2016), while the recyclers must meet a standard established by a non-profit entity created by the electronics industry of Canada (Morawski and Millette, 2014).

Recently, the country has implemented an Environmental Handling Fees (EHF) to all consumers when purchasing a new EEE. This is used to cover the cost of the end-of-life management of WEEE; the cost (and therefore the fee) varies according to EEE and location (province). The fee has been implemented in Quebec, British Columbia, Saskatchewan, Manitoba, New Brunswick, Nova Scotia, Newfoundland and Labrador. In the Province of Quebec, recyclers that operate must be verified under the national standard. The drop off point network is made of municipal eco centers, retailers and other organizations and businesses. In the British Columbia, EEE manufacturers and distributors are required to be part of the Stewardship Plan, which is created and regulated by the Electronic Product Recycling Association (EPRA, 2014). The province of Ontario is currently under transition: The Waste Electrical and Electronic Equipment Program ran by Ontario Electronic Stewardship is to be dissolved in the next years and taken over by the Resource Productivity and Recovery Authority (RPPA). The transition is intended to place individual producer responsibility over EEE producers in the province (RPRA, 2018).

2.4.6.8 Taiwan

Taiwan is one of the main references in e-waste management in the Asia Pacific region and has had a steady increase in e-waste recycling in recent years (Fan et al., 2018). Its WEEE handling structure is known as the 4-in-1 recycling program and began to be drafted in 1988 with the Act that mandated an EPR system. By late 1990s, Taiwan already had a money reward program for consumers who took their unwanted computers to designated collection points, which consisted primarily of retailers. These retailers also obtained financial rewards for receiving the used equipment (Lee et al., 2000). From the beginning, policies around the recycling processes stated that the computers had to be processed in a sound manner and included requirements such as avoiding landfilling and incineration, and removing the phosphorescent coating from CRTs (Lee et al., 2000).

The Taiwanese society has had the obligation of recycling its EEE since 2001 and the Taiwan Environmental Protection Administration (TEPA) is the governmental agency responsible for the main activities involved in the e-waste management. It is also responsible for monitoring the flow of waste materials (Shih, 2017). The TEPA is funded by manufacturers who have to pay a fixed advanced recycling fee at the time of EEE sale. This fee is based on the auditing and verification that TEPA runs yearly alongside of industry representatives (Fan et al., 2018; Shih, 2017). The funds are used mainly to subsidize the recycling industry who receives financial rewards depending on the volume (or number) of WEEE it processes. These activities require a system with high levels of monitoring and, therefore, high costs associated with it, which has been described as one of the weaknesses of the setup. Currently, consumers still receive rewards for taking their obsolete equipment to collection points.

The idea behind the 4-in-1 recycling program is that community residents (1), private recyclers/collectors (2), local government (3) and the recycling fund (4) all play a role in the program. Residents must separate and deposit their e-waste in appropriate collection points, private sector operates recycling and collection, local governments organize and sell the appropriate waste to the private companies and the recycling fund (managed by TEPA) subsidizes the operation of the whole system (EPA, 2012). In summary, Taiwan has a competitive e-waste take-back system that is state-operated (Shih, 2017).

2.4.6.9 India

In developing countries like India, the implementation of well-established EPR approaches used in developed countries are ineffective (Borthakur and Govind, 2018; Wath et al., 2010). E-waste is often viewed as a commodity of value, which causes reluctance when deciding whether to dispose of it or not, and the considerable price difference between the new and used EEE in developing countries like India renders in equipment being forwarded for second-hand use multiple times (Borthakur and Govind, 2018; Wath et al., 2010). Moreover, the main collection channel is (informal) door-to-door and involves the purchase of e-waste by the so-called "*kawariwalas*". This system results in a well-established informal network driven by profit and capable of absorbing 90% of the country's e-waste. The recycling processes undertaken in the informal network, however, use rudimentary techniques and, most often, e-waste ends up in landfills mixed with municipal waste (Dwivedy et al., 2015). Therefore, India currently has a voluntary take-back system, where there are no laws to enforce compliance and no penalties for not meeting the EPR goals, which were established in 2010 in the lines of the European EPR directive (Dwivedy et al., 2015). These circumstances create a different scenario from the scenario found in developed countries, since Indian consumers prefer to sell their obsolete equipment in the informal sector (i.e., they expect a profit when discarding their WEEE) instead of adhering to the principles of formal EPR (Borthakur and Govind, 2018; Dwivedy et al., 2015).

2.4.6.10 Nigeria

In 2012, a study reported that there were no serious initiatives in Nigeria concerning WEEE management and that, in spite of some institutional framework, a number of challenges needed addressing due to the lack of: control over the flow of used EEE, legislation to appropriately identify contraband items, public awareness concerning the dangers of handling WEEE, recycling facilities in the country and corporate social responsibility. Moreover, obtaining reliable data on e-waste (generation, export, import, obsolescence rate, discard) is extremely difficult in the country, which increases the problem further (Adediran and Abdulkarim, 2012). These constraints around data reliability are directly affected by the situation of the country that involves illegal imports, informal recycling, and poor formal recycling (Woggborg and Schroder, 2018).

In 2016, however, the country introduced its own EPR program. The program is overseen by the government through the NESREA (National Environmental Standard Regulatory and Enforcement Agency), and utilizes PROs (producer responsibility organizations, like in Switzerland, see 2.4.6.3) to manage the funds collected from e-waste generators (importers, distributors, etc.) and transfer them to licensed recyclers and formal collection centers. The main drawback is that the EPR program does not extend to the informal sector, which plays a dominant role in Nigeria’s e-waste management system (Woggborg and Schroder, 2018). It should be noted, however, that the NESREA has no official presence in 10 out of 36 Nigerian states, which further decreases the reach of the EPR program (Iwenwanne, 2019). The understanding of Nigeria’s current setup also needs to take into account the (i) lack of technology (or industry) capable of undertaking advanced recycling processes (see 2.4.2), which results in formal recyclers sending dismantled components overseas for downstream processing, and (ii) the behavior of the local population, who "are not ready to give out their e-waste for proper collection and recycling because they are expecting financial value for their waste" (Iwenwanne, 2019).

2.4.6.11 South Africa

Measuring and characterizing the e-waste management scenario in South Africa is important because the country is viewed by other African countries as a continent leader for developing sustainable waste management practices (Snyman et al., 2017). South Africa's e-waste management industry, however, is still at its infancy, like is the case for most developing countries (Ledwaba and Sosibo, 2016). There is currently no legislation specifically addressing WEEE, the country is deficient in e-waste recycling infrastructure and industries are not required to submit (or share) data on the e-waste they generate, making available information unreliable and contradictory. The South African government, however, has recently recognized the e-waste as a priority waste stream (Ledwaba and Sosibo, 2016; Snyman et al., 2017).

The WEEE management is virtually voluntary and dependent on individuals, organizations and small companies. In spite of this setup, there are a handful of well-established companies capable of running their business by promoting the value chain of collecting and sorting e-waste to later sell it as a commodity or as concentrated waste components. These businesses collect WEEE by making use of advertisements and word-of-mouth, but also benefit from the informal sector to obtain waste (Snyman et al., 2017). Informal collection is a common activity in the country as "waste pickers" collect e-waste in addition to other waste streams – it was estimated that informal collection accounts for one fourth of the total collection volume in the country (Salhofer et al., 2017). It is also estimated that only 20% of e-waste finds its way to recyclers because of the absence of adequate take-back centers and financing mechanisms for recyclers (Snyman et al., 2017). The recycling processes in South Africa mainly employs dismantling and sorting of simple components, while complex components are shredded and sent overseas (mainly to Asia and Europe) for downstream processing (Lydall et al., 2017; Snyman et al., 2017). A different study, however, claimed there were two companies in South Africa that undertook the extraction of precious metals from complex components such as PCBs (Salhofer et al., 2017). The dismantling of WEEE is not profitable for small businesses, which end up only undertaking it as a secondary activity (Lydall et al., 2017). This information is in contrast to the significant increase in the number of companies the country has seen in recent years (Salhofer et al., 2017). While South Africa may have developed better recycling facilities with respect to the rest of the African continent, it is still lagging behind developed nations in terms of legislation, enforcement and characterization (Ledwaba and Sosibo, 2016).

2.5 Summary

As shown in this literature review, there is still a struggle worldwide to find a solution to the WEEE challenge. Different countries are trying different approaches and there is still little information about the material flow and management systems for several countries, especially for developing nations. Moreover, while the challenges faced in the management of WEEE tend to be country-specific, there are important lessons and insights that can result from the analyzing and comparing WEEE management approaches amongst countries (Morris and Metternicht, 2016; Ongondo et al., 2011; Román, 2012). The comparison of one system to another allows to identify potential areas of improvement and specific qualities that can then be adapted to the existing system in a given location (Sinha-Khetriwal et al., 2005). In light of this, the present thesis aims to shorten the knowledge gap of WEEE management by analyzing the Brazilian and the Australian systems individually and then comparing the two. It comprehends the analysis of material flow, regime-actor and economic panorama within the systems, which combined allow a circular economy study (Yoshida and Yoshida, 2012).

CHAPTER THREE

PAPER 1

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WASTE ELECTRIC AND ELECTRONIC EQUIPMENT (WEEE) MANAGEMENT: A STUDY ON THE BRAZILIAN RECYCLING ROUTES

Pablo Dias[a,b], Arthur Machado[a], Nazmul Huda[b], Andréa Moura Bernardes[a],

[a] Programa de Pós-Graduação em Engenharia de Minas, Metalúrgica e de Materiais (PPGE3M), Universidade Federal do Rio Grande do Sul (UFRGS), Av. Bento Gonçalves, 9500, 91509-900: Porto Alegre, RS, Brazil. Tel: 55 51 33089428 (pablo.dias@ufrgs.br)

[b] Faculty of Science and Engineering, Macquarie University, Sydney, NSW 2109, Australia

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3.1 Abstract

Processing of waste electric and electronic equipment (WEEE) is a growing issue and a worldwide challenge due to an enormously large volume of WEEE being generated around the world. WEEE typically contains valuable and precious materials in addition to some hazardous component, which could potentially lead to significant economic and environmental benefit if recycled properly. In Brazil, the WEEE generation has significantly increased in the past decade and the best process routes to recycle it remain little explored. This study shows a systematic analysis of WEEE processing procedures based on the information found and mapped from 134 recycling companies active in Brazil by contacting them and confirming activity. It was found that in spite of the recent implementation of national waste management policies, federal and local governments do not have control over the number of active WEEE recycling companies in the country. It was possible to explain the role of the different agents in the Brazilian recycling scenario. Moreover, this study shows that 89% of the Brazilian recycling companies only undertake the pretreatment phase in the recycling process – sorting and dismantling - and that at least 92% dismantle WEEE manually. Finally, it is shown that WEEE that is more complex to recycle is still being shipped abroad for foreign downstream companies and that the revenue generated by the WEEE recycling market in Brazil can financially support up to five agents involved in the WEEE flow.

3.2 Keywords

Dismantling; Electronic waste; Material Recycling; Waste Management; WEEE flow;

3.3 Introduction

The trade of electric and electronic equipment rises driven by the technological innovation and by the speed in which these devices become obsolete, consequently a growth in the generation of waste electric and electronic equipment is being observed in recent years (A. Kumar et al., 2017; Oliveira, 2016). Waste electric and electronic equipment (WEEE) or e-waste are all types of discarded electric and electronic equipment (EEE) without the intention of reuse (STEP, 2014). Among the solid waste types, WEEE is particularly interesting because it contains both hazardous and valuable materials, which makes its recycling environmentally and economically meaningful (Ongondo et al., 2011; Zeng, D. et al., 2004; Zhang and Xu, 2016). Hazardous materials commonly found in e-waste include, but are not limited to cadmium, mercury, chromium, lead, silver and flame retardants (P. R. Dias et al., 2016; Widmer et al., 2005). These substances are a risk for human health (Olympio et al., 2017) and for the environment, as they may end up contaminating water and soil (Dias, 2015). Moreover, the recycling of WEEE often contributes to the reduction of primary energy consumption and greenhouse gases emissions (Foelster et al., 2016). Furthermore, e-waste usually contains valuable and critical materials such as gold, palladium, silver, indium and rare earths, which strengthen the benefit of recycling (P. Dias et al., 2016; Diaz et al., 2016; Nelen et al., 2014).

The global generation of WEEE is estimated to be between 20 and 50 million tons every year and rising from 3% to 5% each year (Cucchiella et al., 2015). In 2014, the amount of e-waste generated reached 41.8 million tons (a 5.9 kg generation per inhabitant) with most of the waste being generated in Asia (38.3%) followed by America (28.0%) and Europe (27.7%). The highest waste generation per inhabitant was observed in Europe (15.6 kg per inhabitant), followed by Oceania (15.2 kg per inhabitant) (UNU-IAS, 2014). Moreover, the potential revenues generated by e-waste recycling in the European market reaches up to 2.15 billion euro (Cucchiella et al., 2015).

The generation of e-waste in Brazil is hard to estimate because of the dispersion of agents involved in the life cycle of WEEE and because of the lack of structure for collecting and recycling this type of waste (Araújo et al., 2012). The same difficulties were discussed in a 2006 study that estimated the e-waste generation to be 351 thousand tons per year (UNEP, 2006). In 2008, the national generation of WEEE was estimated to be 710 thousand tons per year (Araújo et al., 2012) and in 2014 it reached 1.42 million tons per year, a 100% increase in 6 years in contrast to a 6.8% increase in population in the same time period (IBGE, 2014, 2008; UNU-IAS, 2014). The feasibility study commissioned by the federal government to assist in the modelling of the reverse logistics in the country also estimated the WEEE generation in Brazil and projected future generation (Supplementary Figure 1) – the estimate for 2014 was 1.1 million tons, a figure 300 thousand tons is smaller than the one from the United Nations University (ABDI, 2013). Recent studies show that subjective obsolescence is one of the main motivations to replace electronic goods in Brazil, suppressing technical failure (Echegaray, 2016).

Solid waste in Brazil is regulated at a federal level by the 2010 Brazilian Policy of Solid Waste (*Política Nacional de Resíduos Sólidos*) (Brasil, 2010), that emphasizes the idea of waste reduction, reuse and reutilization. Changes imposed by the policy include the prohibition of importing hazardous waste that may cause harm to the environment or human health, financial incentives from federal to local councils for drawing waste management plans, the end of so-called "dumps" (improper places where the population discarded their waste) and the implementation of the reverse logistics. Reverse logistics intends on giving continuity to the life cycle of a material by making all those involved in this cycle responsible. Thus, companies that create products are responsible for finding alternatives to the end of their useful life, government is responsible for regulating and collecting the material and the users are responsible for discarding their waste properly (Brasil, 2010; Nelen et al., 2014). Under the Brazilian Policy of Solid Waste, the 26 Brazilian states and Federal District have autonomy to create their own set of laws, which results in a different set of rules for each state.

Ultimately, the state regulations have direct influence in the WEEE recycling processes in Brazil. Finally, the local councils (or municipal councils) are responsible for the solid waste collection. Both local and state governments are required to report back to the federal government all the relevant solid waste information periodically (Brasil, 2010; Oliveira, 2016). In spite of the national policy and other environmental regulations, more than 3,300 counties still dispose their waste in irregular sites in Brazil (Abrelpe, 2016).

The lack of information concerning WEEE generation, flow and perspectives has driven recent studies in Brazil. It was shown that the Brazilian population has a positive intention towards e-waste recycling, but that only a minority actually adopts adequate recycling practices (Echegaray and Hansstein, 2017). The main issue in e-waste recycling was found to be the collection system that fails to gather end of life EEE and separate them properly from other types of waste (Oliveira et al., 2012) and the lack of technology to recycle more complex components such as printed circuit boards (PCB) and cathode ray tubes (CRT) (Ghisolfi et al., 2017; Oliveira, 2016). Other issues reported include the need for environmental education, the urgency for involvement by producer, the installation of e-waste collection stations on retail channels/neighborhoods, the creation of different government incentives, the adaptation of technologies that assist in controlling the e-waste flow and the implementation of procedures that aid the government in enforcing the Brazilian Policy of Solid Waste (Bouzon et al., 2016; de Souza et al., 2016; Guarnieri et al., 2016).

Recent studies demonstrate the need for e-waste research in Brazil. The lack of information concerning e-waste creates an unfavorable scenario towards better recycling practices. This paper is intended to provide a detailed analysis of the Brazilian perspective by mapping and explaining the activity of the recycling companies in Brazil. Moreover, this research proposes the WEEE pathways in Brazil and encourages a more comprehensive recycling in the country by demonstrating the potential revenue generated in each of the recycling flow agents.

3.4 Methodology

The objective of this study was to map the distribution of electronic waste in Brazil, to evaluate what are the procedures adopted by the recyclers in the country and to determine whether electronic waste is being processed rather than dumped or exported. A schematic of the methodology used in this study is shown in Figure 14.

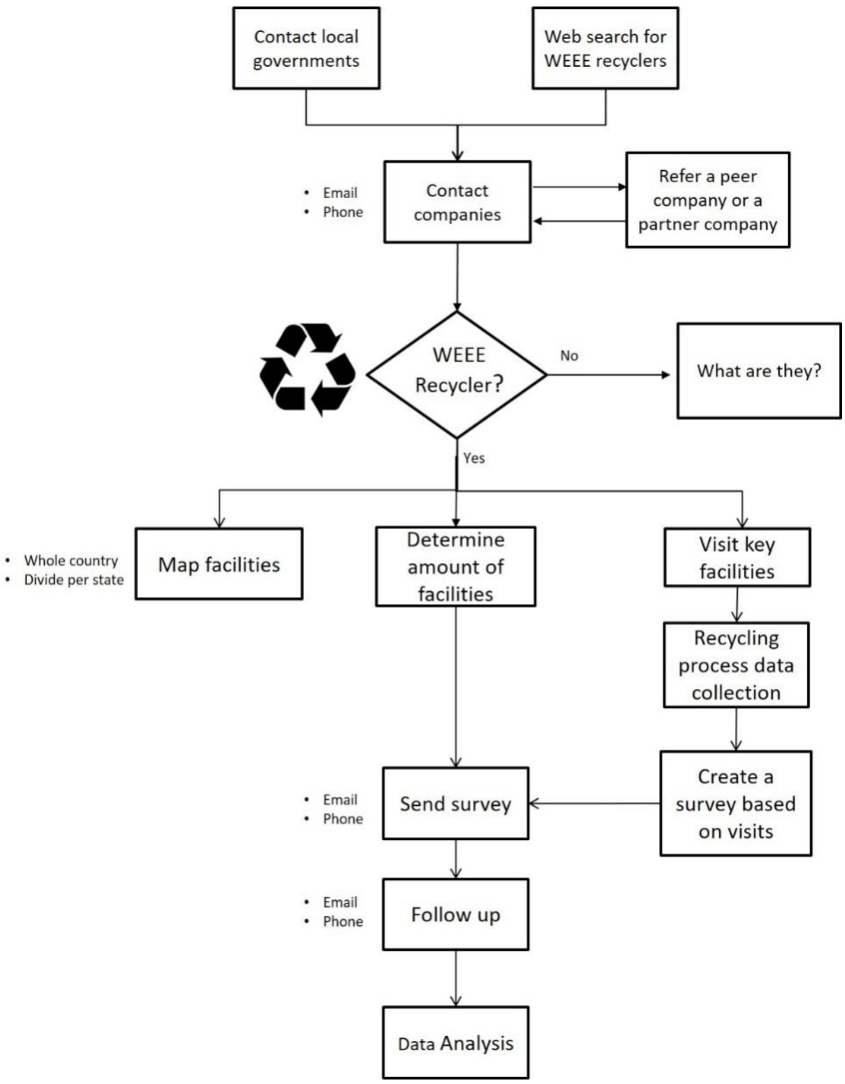

Figure 14: Flowchart of the methodology used in this study.

The first step of this study was determining the number of WEEE recyclers that are currently operating in Brazil and their distribution. Thus, the first step was to contact federal and state governments in order to obtain a list of operating facilities. Initial contacts revealed that the local governments (state governments and federal government) do not have any control regarding the operation of these companies, as they were not properly sorted. Some contacts resulted in a list of "possible companies". Direct contact with companies confirmed whether they were or not recyclers and improved our search for other companies as these usually indicated peer companies or partner companies they worked with. Furthermore, several companies were found from an extensive web search using Google, Bing and Yahoo search engines. The search was conducted in 2016 and 2017.

Once the recyclers were mapped, some key companies in the federal state of Rio Grande do Sul (RS) were visited. Key companies were selected based on location (within a 50 km radius from capital of the state - Porto Alegre) and processing (facility should receive and process an average of at least 5 ton of e-waste per month). Visits intended to observe the procedures used in the recycling facilities. A total of 5 companies were visited in the state of Rio Grande do Sul and their procedures were discussed with both the plant staff and management staff. The understanding of the procedures used in the recycling facilities allowed the creation of a survey intended to reveal how the companies receive the WEEE, how the WEEE was processed/recycled in each company, whether the company served as a material trial facility or if they undertook the whole recycling process and what was the destination of the recycled goods.

The survey was formulated with a total of 8 questions in the form of either tick-box responses, free answer or multiple choice grid (Table 10). Some of the questions allowed respondents to add a different answer. These answers, when appropriate, were added to the original answers group. All different answers were either grouped together to a previous existing answer or counted individually, when appropriate.

Table 10: Questions included in the survey sent to the recycling companies.

Question number	Question	Type of response	Options
1	How do you collect WEEE? How does your company receive WEEE? Please check all that apply	Tick-box	Hand pickers
			Partnership with City Councils/Government
			Direct handover (consumer - company)
			Partnership with other companies (company - company)
			Delivery centers (or collection centers)
			Collection Fairs/Events
			Private collection service
2	How are the components measured after dismantling?	Multiple Choice Grid	Weight
			Unit
			Volume
			Other
3	Which equipment are used in your company? Please check all that apply	Tick-box	Bench drill
			Circular saw
			Electric screwdriver
			Fork-lift
			Shredder
			Others
4	What is the destination of the separate components?	Tick-box	Disposal in household waste
			Internal stocking
			Hazardous waste landfill
			Export
			Sale for partner recycler
6	What processes does your company undertake?	Free answer	-
7	What is your understanding of the WEEE recycling market in Brazil? What is the roll of your company within the existing recycling agents?	Free answer	-
8	Do you export any materials? Which? Where to?	Free answer	-

The survey was sent to 134 companies, which comprises all the companies that were previously engaged and mapped. Since the survey did not require the companies to identify themselves, a follow up email was sent a couple of days after the survey to check if the company had replied. In case there was no confirmation, the companies were contacted by phone as a second follow up step. Some companies preferred to take the survey over the phone. In these cases, the questions and answer options were read over the phone and the respondents would answer each question one by one. The survey received 58 responses out of 134. The responses to the survey were collected from 2016 to 2017 – after gathering all responses, the data was analyzed for further discussion.

3.5 Results

In the first part of the experiment, a list of several possible recyclers was obtained, either provided by the local governments, located online or referred from a peer/partner company. It is noteworthy that the local governments did not have any control whether a company was a WEEE recycler or not. For instance, the government of the state of São Paulo provided a list with 276 companies among which 19 (approximately 7%) were actual WEEE recyclers. The remaining companies on the list were either environmental consultants, polymer recyclers (commodity recyclers), scrap trade companies, logistics centers, construction/demolition waste companies, metal recyclers or were no longer active. All of which were catalogued in the same group as the WEEE recyclers. Although some activities such as metals recycling and polymer recycling are indirectly related to WEEE recycling, these companies do not interact with any electronic waste since the metals and polymers arrive fully segregated. Moreover, this study found a total of 61 companies currently working in the state of São Paulo. Thus, at least 41 (67.2%) were not in the database of the government. A similar misplacement was found in the feasibility study ordered by the government. The study lists 94 recycling facilities, but only 55.3% are active WEEE recyclers (ABDI, 2013). The poor enforcement of extended producer responsibility and other related activities stated in the national policy regulation was discussed in previous studies (Echegaray and Hansstein, 2017; Oliveira et al., 2012), this lack of information observed in both federal and local governments puts yet another barrier in the enforcement of the legislation.

By contacting the recyclers and confirming activity, a total of 134 recyclers were found in Brazil. A distribution map of the recyclers is shown in Figure 15.

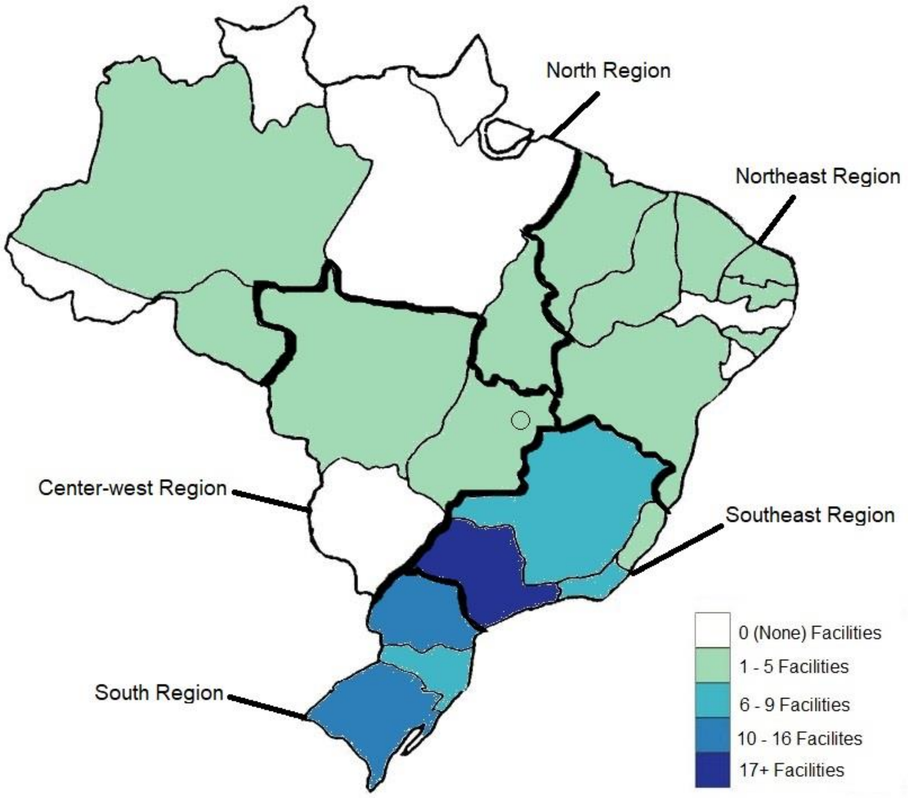

Figure 15: Distribution of the WEEE recyclers in Brazil.

Figure 15 shows that the recycling facilities are concentrated in the south and southeast regions. The densest state is São Paulo (45,5%), which is justified because it has the greatest population (greatest waste production and highest electronic trade) and the highest industry density in the country (IBGE, 2016). The southeast region concentrates 58% of the facilities, followed by the south region (26%). The northeast and the northern regions together possess 14 (10.5%) facilities. A list of the facilities according to the states and the region is displayed in Supplementary Table 1.

Although this study comprehended the whole country, the method of relating the database of the government and the web search may result in failure to identify some companies. The lack of government control as well as the lack of visibility of some companies will certainly lead to gaps between the results obtained in this study and the real amount of recyclers active in the country. Moreover, the active clandestine (or illegal) “recyclers” are also an issue when mapping the amount of WEEE recyclers in Brazil. Clandestine “recyclers” do not wish to be found on the web or in any government database. Clandestine recycling is associated with illegal recycling methods (lack of gas emission control, lack of effluent treatment, lack of appropriate personal protective equipment, etc.), with the lack of appropriate operation license (the Brazilian government needs to issue a license for a company to operate) and with waste obtained from illegal sources (stolen merchandise, illegal imports, illegal exports, etc.). Cable burning, for instance, is known to be a common practice in Latin American cities, as well as informal repair and refurbish markets (Oliveira et al., 2012). According to Agamuthu et al. (2012), the informal recycling sector is very active in developing countries

Once the WEEE recycling activity was confirmed, the company was asked to answer the survey. The survey received 58 responses out of 134, a response rate of 43.3%. Questions 6, 7 and 8 (Table 10) required the company to have the time to discuss or write the answer, thus these questions were not answered by all the companies. Moreover, the level of precision for this survey was calculated as follows (Israel, 1992):

$$no = \frac{Z^2pq}{e^2} \qquad (1)$$

Where n_o is the sample size, Z is the abscissa of the normal curve that cuts off a certain area at the tails, e is the desired margin of error (or level of precision), p is the estimated proportion of an attribute that is present in the population and q is p – 1. By isolation the margin error, equation (1) becomes:

$$e = \sqrt{\frac{Z^2pq}{no}} \qquad (2)$$

However, if a population is finite, the sample size is reduced. The smaller the population, the smaller the sample size because a given sample size gives proportionally more information for a small population in comparison to a large population (Israel, 1992). Thus, sample size n_o can be adjusted according to equation (3):

$$n = \frac{no}{1+\frac{no-1}{N}} \qquad (3)$$

Where n is the new sample size for a finite population, n_o is the sample size for an infinite population and N is the population. Since n is the number of responses obtained (58) and N is the population (134), it is possible to determine n_o and insert it into equation (2) to determine the margin error of the survey. Z is equal to 1.96 for a confidence level of 95% (obtained by statistical tables that contain the area under the normal curve), p is unknown and thus maximum variability is assumed (0.5). Thus, error found for this survey is 9.73% according to equation (2).

When questioned how the companies received WEEE, most recyclers (81.8%) indicated that they have partnerships with other companies, which send their WEEE directly, i.e. company – company (Figure 16A). The other main paths for WEEE to reach the recycler are through a private collection service performed by the recycler (68.2%), direct shipping/handover from consumers, i.e. consumer – recycler (63.6%), collection/delivery centers (43.2%) and partnership with city Councils/Governments (43.2%). Furthermore, 20.5% of the companies use fairs or events to gather WEEE, 13.6% receive WEEE directly from hand pickers and 4.5% responded that they use other methods (not specified in their response). The majority of the companies (79.5%) have more than one method of collecting e-waste. As seen in Figure 16A, the role of hand pickers is not as important in the collection of e-waste as it is for other materials, such as scrap metal. Brazil has a particularly interesting success case in recycling scrap metal, this success is associated with waste pickers that selectively segregate metals from general waste and that are responsible for delivering the scrap metal to the recyclers. It was reported that there are over half a million waste pickers in the country (Ghisolfi et al., 2017; Oliveira et al., 2012).

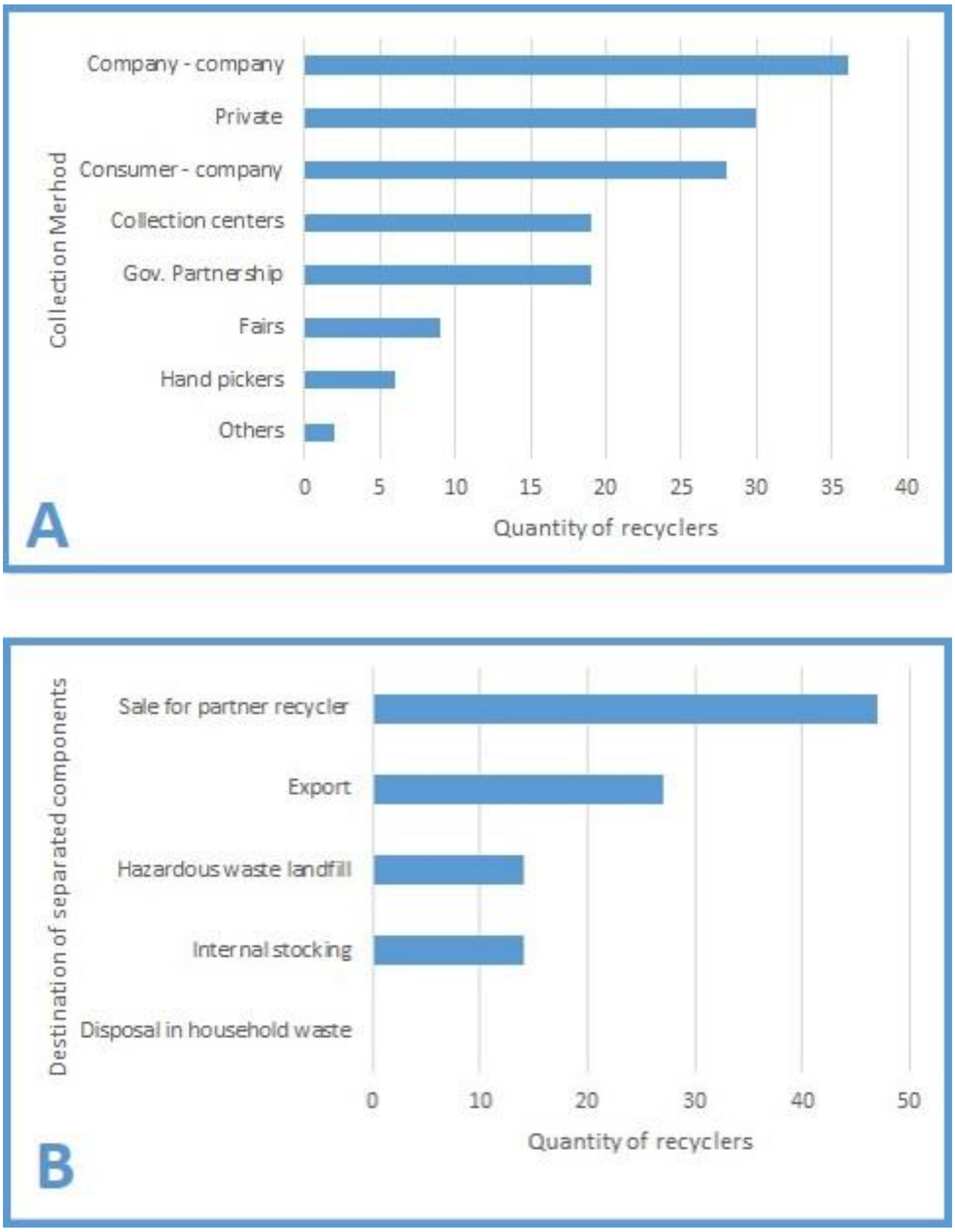

Figure 16: (A) Response to question 1 – WEEE collection method (B) Response to question 4 – destination of the separated components

When questioned what the destination of the separated components was, most companies (81.0%) responded that they sell the components to downstream recyclers, which indicates that the companies only undertake the first stages of recycling. Moreover, 27 (46.5%) of the questioned companies responded that they export separated components, this data is in accordance to Oliveira (2016) that states that most Brazilian recyclers simply separate the WEEE and export the complex components, leaving polymers and glass in Brazil. Fourteen companies (24%) responded that some components go to internal stocking and 14 (24%) responded that a fraction of the components go to hazardous landfill. No companies responded that their waste goes to household disposal (Figure 16B).

Based on previous works (A. Kumar et al., 2017; Zhang and Xu, 2016; NIIR Board of Consultants & Engineers, 2015), on the visits and on the responses obtained with this study, a process flowchart illustrating the WEEE recycling steps for all classes of materials was generated (Figure 17). The flowchart separates the recycling in four main phases: i) initial trail and dismantling process; ii) mechanical and physical separation processes; iii) specific recycling process; iv) refining processes. WEEE recycling includes a pretreatment phase in which the waste is grinded and/or dismantled, a material separation phase, in which the materials are grouped by a series of mechanical processes such as sieving (size separation), density separation, eddy current separation (electrical properties), magnetic separation, X-ray separation (structure properties), hand picking or automatic sorting (color, structure, weight, etc.). The next phase includes the specific recycling processes for each group of materials and, finally, the refining processes that may be used for a purer outcome.

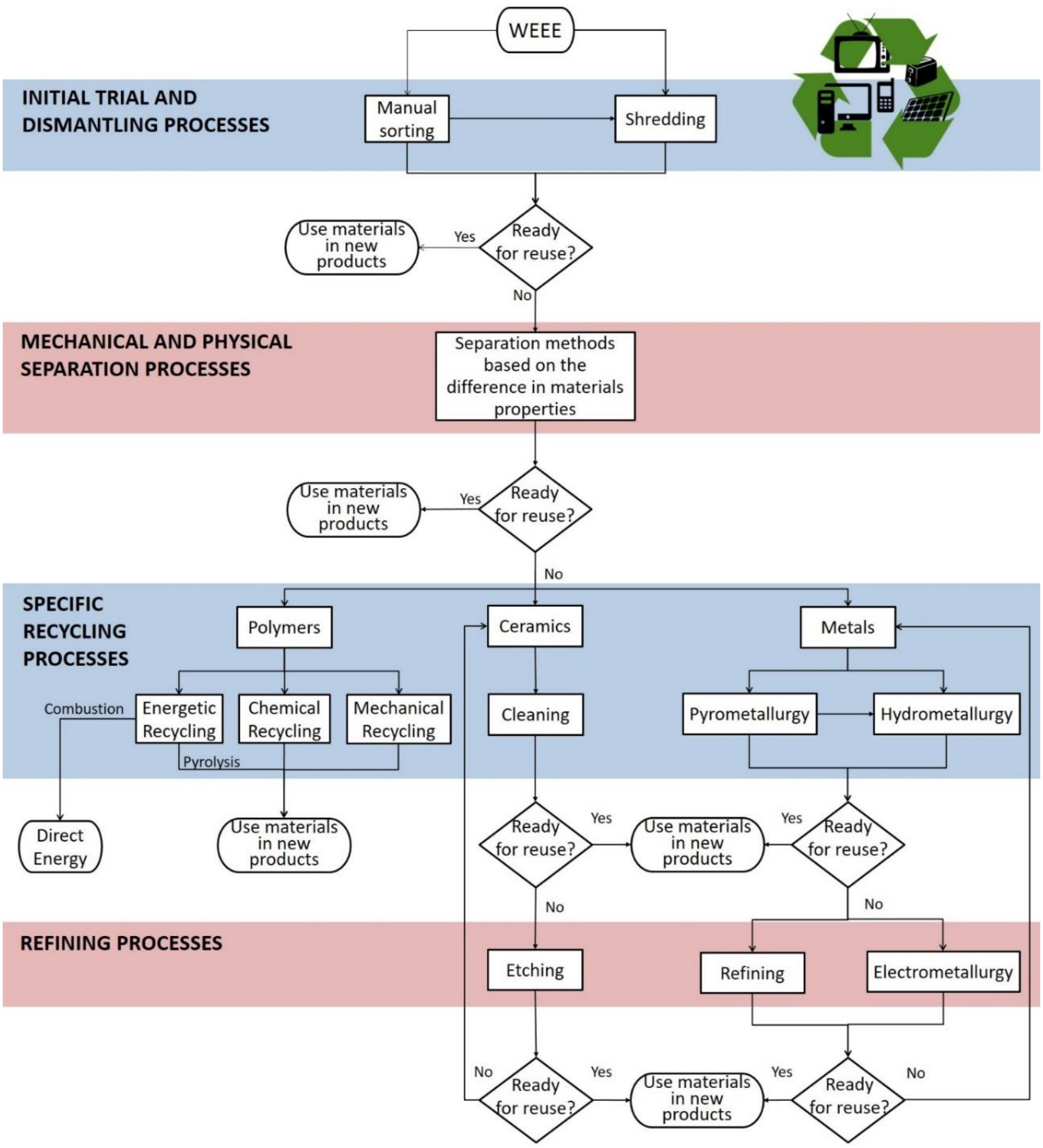

Figure 17: Schematic flowchart demonstrating the processes used in the recycling of WEEE.

The visits and surveys showed that the Brazilian companies are mainly focused on the first recycling phase. 89% of the companies only undertake the dismantling process. As shown in Figure 18, the tool that is used the most in the recycling facilities is the electric screwdriver (92%), which is manually operated. Other equipment used in the recycling facilities include fork-lift (67%), bench drill (53%), circular saw (31%), manual tools (17%), - such as hammers, set of screwdrivers, pliers – shredder (10%) and other equipment (10%) that include air compressor, pneumatic tools and eddy current separator. The separated components are usually measured by weight.

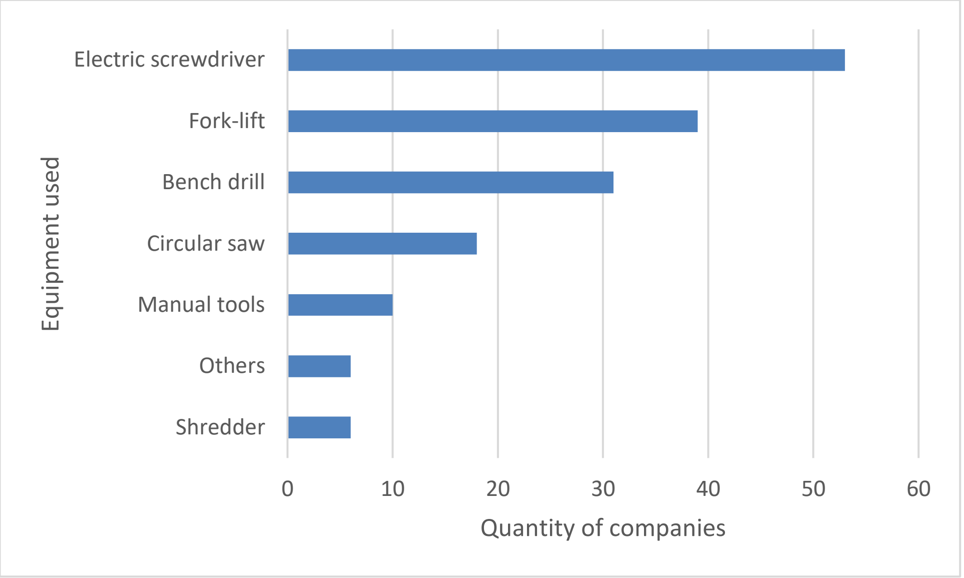

Figure 18: Response to question 3 – equipment used in the facilities.

Labor is divided per equipment per person (e.g., one person dismantles one computer and then moves on to the next one). Materials that are easily separated by manual dismantling such as copper, aluminum, iron and a range of polymers are sold by these companies to local recyclers (most of which are scrap dealers), who then undertake the specific recycling processes and the refining processes. Moreover, the complex materials or complex components such as printed circuit boards (PCBs), external hard drives, computer memories, computer processors and coolers are exported to be recycled abroad. Thus, the Brazilian role in recycling these components is dismantling (mostly manually), sorting (mostly manually) and grinding. Foreign companies undertake all the other recycling processes. These findings are in agreement with Cecere and Martinelli (2017), who state that the knowledge in the field of e-waste recycling is concentrated on a few countries and that though developing countries are often involved in some phases of e-waste development, they do not contribute to the creation of knowledge in this field. Exporting countries found in this study include: United States of America, Belgium, Japan, Netherlands, Singapore and Germany. Torres and Ferraresi (2015) claim Brazil also exports e-waste to Canada and Japan. This research has identified a total of 8 companies (one of which has 6 facilities) dedicated to buying these complex-recycling components from local companies, grinding the components and exporting them to companies abroad. The 13 facilities operate in São Paulo (45%), Paraná (23%), Amazonas, Rio Grande do Sul, Pernambuco and Rio de Janeiro (each accounting for 8%). Figure 19 reveals a schematic flowchart for WEEE processing routes in Brazil.

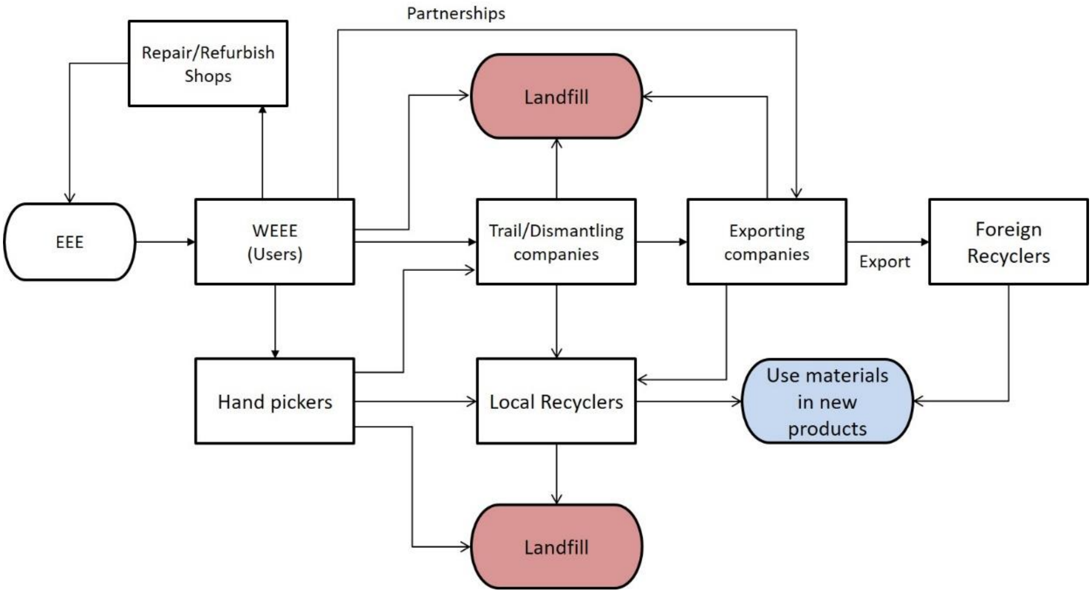

Figure 19: Schematic flowchart demonstrating routes of WEEE in Brazil.

The role of each of the agents involved in the WEEE flow is as follows: Users are responsible for turning EEE into WEEE; they are households, companies, offices, universities, shops, etc. From the users, WEEE can take different paths, as displayed in Figure 19. If disposed along with common waste, WEEE can go to landfill or it can be collected by hand pickers, who selectively sort out materials that have aggregated value and can be sold. If disposed correctly, WEEE should go to the local recyclers or to the trail companies. The role of the trail companies is dismantling the equipment and sorting the different materials, as shown in the first phase of Figure 17. They then send each sorted material to a proper recycler (e.g. polymers scrap to polymer recyclers, aluminum to aluminum recycler, glass-to-glass recycler). Local recyclers receive the sorted materials and undertake the specific recycling processes (Figure 17). Some local recyclers also act as trail companies undertaking the first and third phase of the recycling process. The second phase is skipped because no complex component is recycled. Both local recyclers and trail companies do not separate materials from complex components - these are forwarded to the exporting companies. The role of the exporting companies is gathering, grinding (or shredding) and shipping all the complex components to foreign recyclers. Some components such as hard drives are not grinded. Moreover, several of the exporting companies are also a trail company. Thus, they receive WEEE from the users and from other trail companies. Foreign recyclers undertake all phases indicated in Figure 17. They receive the material, grind it (if not yet grinded), separate the materials using different methods, undertake the specific processes for each material and refine materials that need refining. It was reported that the price paid for exported materials may vary from 5 to 30,000 US$ per ton, according to the component. Payment is generally made at the time of shipping. However, it should be highlighted that some exporting companies are branches for international companies and, therefore, the material exported is sold for a symbolic value to the mother company so it can further recycle the waste abroad.

The market relationship demonstrated in Figure 19 is as follows:

- The foreign recyclers benefit from selling their end products, but pay the exporters.
- The exporters benefit from the purchase of the foreign companies, but pay for the trail companies, hand pickers and sometimes users.
- The trail companies benefit from the exporters purchase and from the recyclers purchase, but pay the hand pickers and often pay the users for their WEEE.
- Recyclers benefit from selling their end products, but also pay the trail companies and the hand pickers.

Figure 20 exemplifies one of the routes that WEEE can take in the Brazilian recycling market. As WEEE goes downstream in the chain, the volume decreases because each agent selectively separates components. While volume decreases, the value of the materials increase because the concentration of precious and rare material increases. This increase ultimately leads to an increase in the purchase of WEEE as it goes down the chain, which is in accordance with the findings of Golev and Corder (2017). As discussed in Figure 19, WEEE can take a route as short as *Users-Exporting companies-Foreign recyclers*, but can also take a long route such as the one showed in Figure 20. This route involves 5 agents and all of these agents obtain financial profit out of their work. Thus, the revenue generated by the WEEE recycling market is enough to financially support up to 5 agents involved in it: hand pickers, trail companies, local recyclers, export companies and foreign recyclers - as highlighted in the hatched circle of Figure 20.

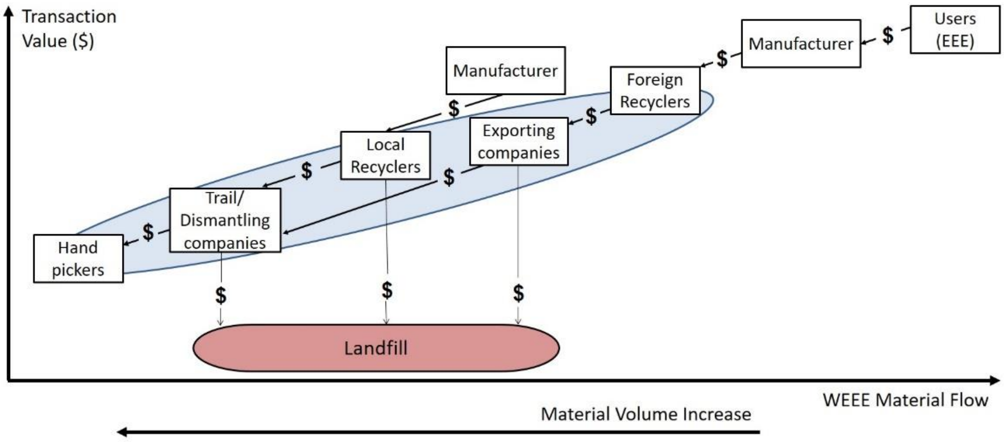

Figure 20: Schematic flowchart demonstrating one of the possible routes and the revenue involved in the WEEE market in Brazil.

Some users (responsible for turning EEE into WEEE) even benefit from selling WEEE, but this is usually limited to big offices and universities that have large waste volumes. The WEEE market also comprehends the companies that maintain the landfills, the repair or refurbish shops and the EEE manufactures. The government participates in this market by charging for the licensing of the recyclers, collecting taxes and dealing with the cost of collection and disposal of municipal waste. According to the exporting companies, there is no tax for exporting the WEEE components. The flow observed in this study demonstrates that little has changed in the past 5 years in Brazil, since the country still lacks companies capable of undertaking the complete recycling process, as stated in 2012 by Oliveira et al. (2012).

3.6 Discussion

This study has shown that federal and local governments do not have control over the number of active WEEE recycling companies in the country. The database of the government does not distinguish e-waste trail companies, environmental consultants, polymer recyclers (commodity recyclers), scrap trade companies, logistics centers, construction/demolition waste dealers or metal recyclers. Furthermore, in spite of needing the proper licensing to operate in Brazil, this research found only a minority of e-waste recyclers through the government database. Recent studies point out that one of the main issues in the Brazilian situation is the lack of enforcement of the national regulation and policies by the government (Echegaray and Hansstein, 2017; Guarnieri et al., 2016; Oliveira et al., 2012) and the uncertainty related to economic issues in reverse logistics (Bouzon et al., 2016). The scarcity of information and control concerning the e-waste recycling market found in this study impose yet another challenge in the enforcement of the legislation.

The search for e-waste recycling companies found a total of 134 recycling facilities and 13 exporting facilities. Despite the extensive search for recyclers and the use of different searching methods (web search, peer reference and government database), there is certainly a gap between the number of recyclers found in the study and the real amount of recyclers – this is strengthened by the known operation of illegal/informal recycling, as stated by de Souza et al. (2016) and Oliveira et al. (2012). The mapping revealed that most of the recycling companies are in the southeast region, followed by the south region, northeast region, center-west region and north region. The distribution of recycling companies is coherent with both the population density and the industrial activity of the regions.

The visits and the survey showed that most of the Brazilian recycling facilities are trail companies responsible for undertaking only the first stages in WEEE recycling: sorting and dismantling. Components that are easy to separate and easy to recycle are recycled within the country – these include components made mostly of copper, aluminum, iron or polymers. Complex components are sorted, dismantled, grinded and shipped abroad for foreign downstream companies to overtake the recycling process – these include printed circuit boards (PCBs), hard drives (HDs), computer memories, computer processors and coolers. While copper, aluminum and iron are valuable metals that need to be recycled, the exported components are rich in gold, platinum, silver and rare earths, which are precious metals with high market value. Therefore, the feasibility of recycling these complex components is dependent on high logistics cost associated with the shipping of these components, as stated by (Ghisolfi et al., 2017). Many studies suggest that Brazil exports complex components due to the lack of a reliable collection system and the lack of technology (de Souza et al., 2016; Oliveira et al., 2012, p. 2; Oliveira, 2016; Torres and Ferraresi, 2015). However, the number of companies whose activity is manly the export of complex components - which requires a minimum collection structure - has been increasing. Additionally, the statement of technology deficiency is tackled by the strong primary metallurgical industry that Brazil has, which produces most of the metal content found in the complex WEEE components, such as gold, indium, refined lead, tin, silver, refined nickel, etc. (British Geological Survey, 2017; CETEM, 2017). Furthermore, it is important to highlight that the concentration of high-value materials in these complex e-waste components is usually about four orders of magnitude higher than in the virgin ore bodies and that the process steps for recovering materials is reduced in comparison to primary metallurgy (Ebin and Isik, 2016; Gumley, 2016).

3.7 Conclusions

The growth in WEEE generation and its disposal is a global issue. The situation in Brazil is critical given the recent increase in WEEE generation and the inefficient recycling system. This study contributes by characterizing the e-waste market in Brazil, highlighting the WEEE flow possibilities and the revenue generated by it. Moreover, this study was capable of mapping the recycling facilities in Brazil, which assists in enforcement of the current regulations and in the creation of further related regulations. The results presented here show that the Brazilian recycling market operates towards the concentration of the most valuables materials present in WEEE and then ships them abroad. Nevertheless, it is shown that in the current Brazilian recycling market, revenue generated by the WEEE recycling market is enough to financially support up to five agents involved in the WEEE flow. These arguments encourage future studies to evaluate to which extent the country is unable to recycle complex components such as printed circuit boards.

3.8 Acknowledgments

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CHAPTER FOUR

PAPER 2

Pablo Dias, Andréa Moura Bernardes, Nazmul Huda. Waste electrical and electronic equipment (WEEE) management: An analysis on the Australian e-waste recycling scheme. Journal of Cleaner Production, Volume 197, Part 1, 1 October 2018, Pages 750-764. https://doi.org/10.1016/j.jclepro.2018.06.161

WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT (WEEE) MANAGEMENT: AN ANALYSIS ON THE AUSTRALIAN E-WASTE RECYCLING SCHEME

Pablo Dias[a,b], Andréa Moura Bernardes[b], Nazmul Huda[a]

[a] Faculty of Science and Engineering, Macquarie University, Sydney, NSW 2109, Australia(nazmul.huda@mq.edu.au)

[b] Programa de Pós-Graduação em Engenharia de Minas, Metalúrgica e de Materiais (PPGE3M), Universidade Federal do Rio Grande do Sul (UFRGS), Av. Bento Gonçalves, 9500, 91509-900: Porto Alegre, RS, Brazil. Tel: 55 51 33089428

4.1 Abstract

Solutions for the global arising waste electrical and electronic equipment (WEEE) challenge are constantly being proposed and implemented worldwide. To be in pace with the world, Australia debuted the national computer and television recycling scheme (NTCRS) in 2012 and has already diverted thousands of tons of WEEE away from landfill. In this study, the structure, collection methods and recycling processes of the scheme are analyzed considering the perspective of different agents involved in the scheme. The recycling facilities working directly under the scheme as first stage recyclers are identified and their operational procedures are investigated. The results show that there are currently 31 facilities, that they mainly process waste using manual sorting and manual dismantling; and that material recovery requires further downstream processing, which is undertaken domestically and internationally. The exports have been growing since the commencement of the scheme and should continue to grow unless incentives for domestic downstream processing are implemented. Moreover, this study analyzes the roles and responsibilities of the different agents working under the NTCRS. It is shown that local councils are important e-waste collection channels, but they hold little responsibility within the

Abbreviations

DVD – Digital video disc	CRT – Cathode ray tube	CRA – Co-regulatory arrangement
CD – Compact disc	PC – Personal computer	EOL – End of life
FY – Financial Year	TV - Television	LCD – Liquid crystal display

EEE – Electric and electronic equipment
MOUSE - Manually-operated user-select equipment
NTCRS – National television and computer recycling scheme

legal framework of the scheme. Furthermore, co-regulatory arrangements are responsible for assuring that the outcomes of the scheme are achieved, yet their responsibility of auditing the recycling and recovering processes stops at first stage recycling. Finally, this study reveals challenges and proposes solutions for the scheme, which, when perfected, can be replicated as a WEEE management model for the world.

4.2 Keywords

Australia; Computers; Electronic waste; Recycling; Televisions; WEEE management;

4.3 Introduction

Waste electrical and electronic equipment (WEEE) - or e-waste - consists in dead electronic and electrical equipment and its current generation pattern poses one of the world's greatest pollution problems. The main issues are the lack of appropriate recovery technology (Jujun et al., 2014) and the risk of releasing hazardous and toxic substances, which may cause serious damage to the environment and to human health, if the waste is not discarded correctly (Rajarao et al., 2014; Widmer et al., 2005). Moreover, e-waste contain some valuable metals in concentrations significantly higher than those typically found in corresponding ores (Cayumil et al., 2016). Thus, the recycling of these equipment leads to positive economic and environmental consequences (Zhang and Xu, 2016).

In 2009, the majority of e-waste was being produced in Europe, the United States and Australasia (Robinson, 2009). The later, Australasia, was ranked second highest in the waste generation per inhabitant in 2014, reaching 15.2 Kg per capita (UNU-IAS, 2014) and having Australia as its main contributor (20.1 Kg per capita) (STEP, 2014). Australia is a large country (7,692,024 Km^2) (Australia, 2017) with a relative small population (23.8 million in 2015) (UN, 2017b). This low population density and lack of national regulatory framework to deal with e-waste resulted in large amounts of WEEE being sent to landfills (Ongondo et al., 2011).

The lack of national regulation also meant the local councils were responsible for developing individual strategies and acting on e-waste management (Davis and Herat, 2008; Ongondo et al., 2011). In the last decade, however, the Australian Government has tackled the issue by creating specific legislations. According to Morris and Metternicht (2016), there are four key pieces of legislation addressed to manage WEEE:

- National Waste Policy 2009 (Environment Protection and Heritage Council, 2009);
- Product Stewardship Act 2011 (Australia, 2016);
- Product Stewardship (Televisions and Computers) Regulations 2011 (Australia, 2011);
- National Television and Computer Recycling Scheme 2011 (NTCRS) (Australia, 2011).

The later two came into effect in November 2011 and, supported by the National Waste Policy and the Product Stewardship Act 2011, provide the framework to manage the life cycle of computers, televisions and their peripherals (Morris and Metternicht, 2016). The scheme requires importers, manufacturers, and distributors to subscribe to mandatory, co-regulatory, or voluntary schemes to regulate the disposal of end-of-life units (Premalatha et al., 2014). These arrangements are responsible for organizing the collection and recycling of e-waste on behalf of their liable party members (Department of the Environment, 2015a). Despite the name of the scheme making reference to computers and televisions, it targets copying machines, DVD/CD drives, keyboards, mouse, printers, scanners, hard drives, motherboards, webcams, monitors (LCD, CRT, plasma, projection), televisions (LCD, CRT, plasma, projection), laptops and PCs (Australia, 2011; Department of Sustainability, Environment, Water, Population and Communities, 2011b).

The main agents involved in the scheme and their roles are as follows:

- Liable parties (Figure 21A): required to join the scheme and responsible for funding the scheme. The liable parties are manufactures, users, distributers and importers of electric electronic equipment above thresholds of 15000 units of computer peripherals or 5000 units of TVs, computers or printers.

- Co-regulatory arrangements (CRA) (Figure 21B): enterprises responsible for achieving the scheme's outcomes, organizing collection and recycling and communicating this information to the public.
- Electronic waste recyclers (Figure 21C): contracted by the CRAs to undertake "first stage recycling" in Australia (as per the regulations).
- Australian Government (Figure 21D): calculates the arising waste based on import data, ensures the compliance of the liable parties and that the scheme outcomes are met by the CRAs.

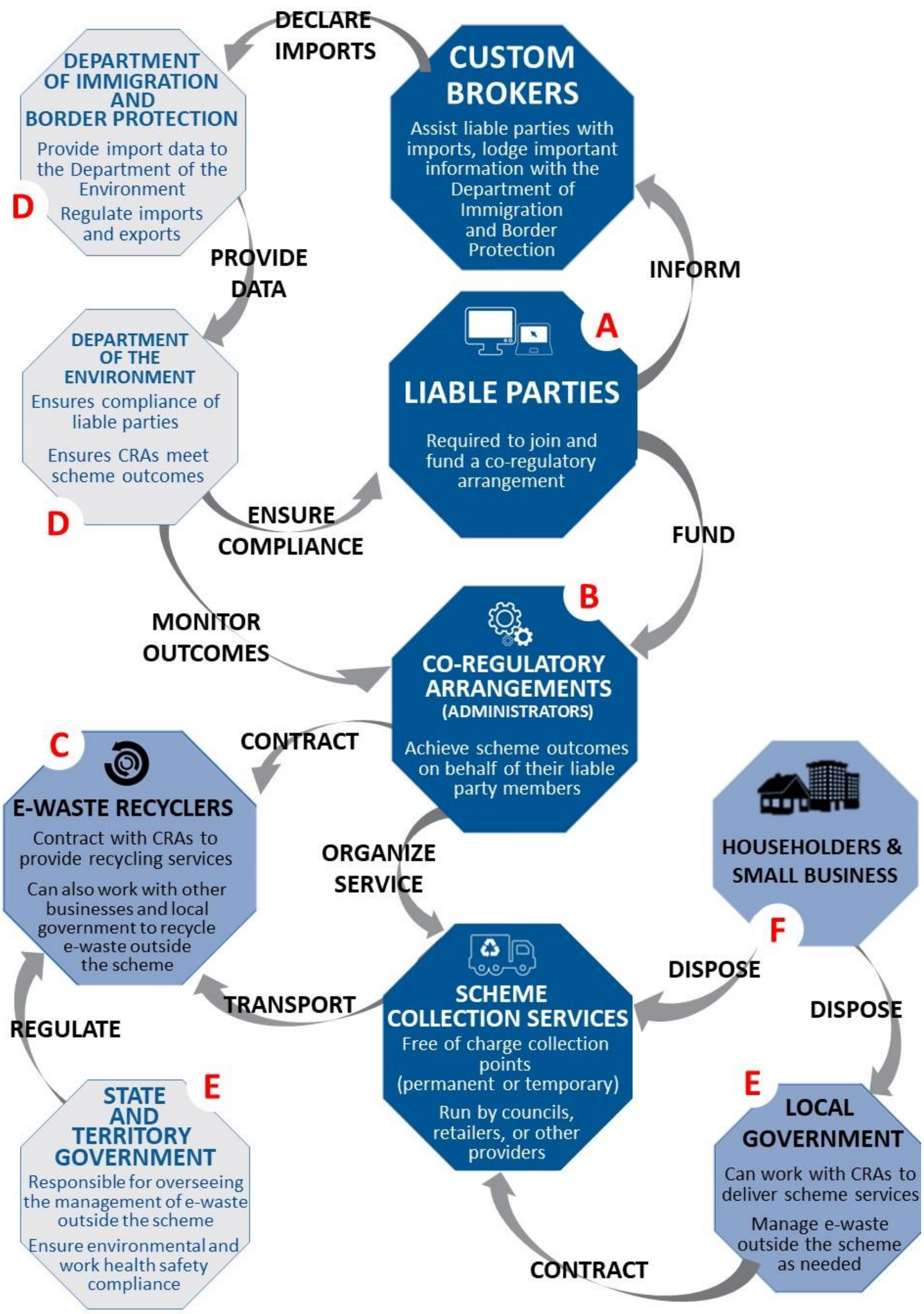

Figure 21:Roles and Responsibilities – NTCRS (Adapted from Department of the Environment, 2015b)

The state and territory governments are responsible for waste collected outside the scheme (Figure 21E). They may work with CRAs and e-waste recyclers if the wish, but there is no obligation. The same happens with the households and small businesses (Figure 21F), they can access the recycling services free of charge, but have no obligation to participate on the scheme (Bruce Edwards and Declan O'Connor-cox, 2014; Department of Sustainability, Environment, Water, Population and Communities, 2011b; Department of the Environment, 2015b).

The NTCRS commenced in 2012, it initially had three approved CRAs and a recycling target of 30% (w/w) for the financial year (FY hereafter) of 2012-2013 (Department of the Environment and Energy, 2015a; Herat and Agamuthu, 2012). Currently (in 2017), there are four CRAs, the recycling target is 50% (w/w) and the material recovery rate has to be at least 90% (w/w), the recycling target increases incrementally and should reach 80% by FY 2026-27 (Figure 22) (Department of the Environment and Energy, 2015b; Herat and Agamuthu, 2012). The recycling facilities must operate under the standard for collection, storage, transport and treatment of e-waste (AS5377) (Australia/New Zealand Standard, 2013) and must report back to the CRAs, which are required to report to the Government (Department of the Environment and Energy, 2015b). Thus, the whole scheme is industry funded and operated, but it is regulated by the Australian Government (Amanda Rishworth, 2013).

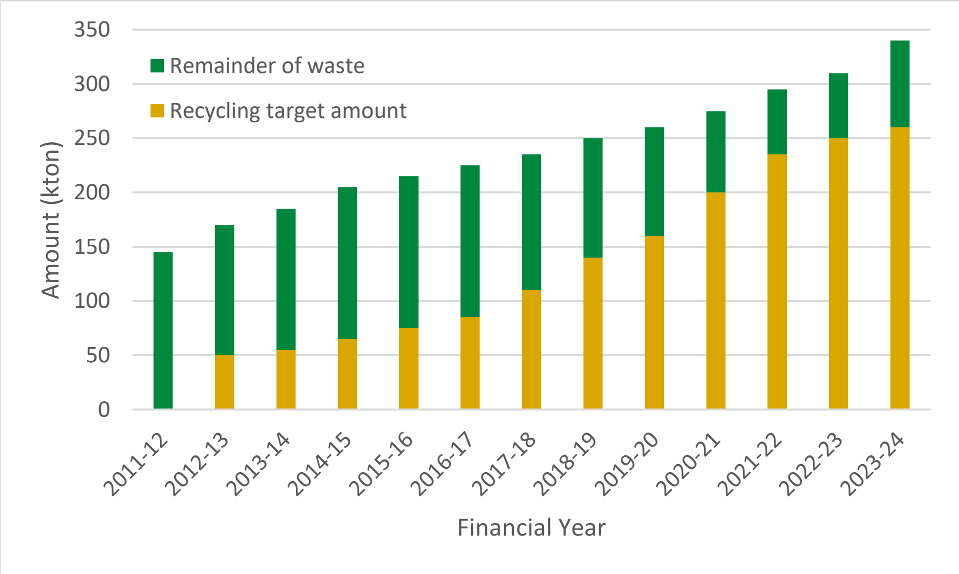

Figure 22: Projection of waste arising and the proportional target amount (Adapted from Bruce Edwards and Declan O'Connor-cox, 2014).

Previous studies on the NTCRS show that the current pieces of regulation are not effective in managing WEEE in Australia (Morris and Metternicht, 2016) and that the processes used in recycling within the country are low technology and labor intensive (Lane, 2014; Wright Corporate Strategy, 2010). Low tech processes usually present human health risk because of contaminants remaining in recycled materials, inappropriate disposal or contaminants entering the environment due to volatilization (Herat and Agamuthu, 2012). Moreover, the country exports about half its waste scrap metal overseas for processing (Corder et al., 2015). It was also reported that the scheme lacks transparency of its financial mechanism and there is little incentive for domestic materials recovery versus international recovery (Golev and Corder, 2017; Gumley, 2016; Lane et al., 2015). Australia lacks knowledge about who are the actors and organizations around material accumulation and recycling, which are the existing collection systems and how they work, and what are the formal and informal frameworks involving material recycling (Lane, 2014).

Considering these studies about the Australian recycling scheme, one can observe aspects in which the scheme differs from what is being implemented in other countries worldwide and, while it claims to have diverted great amounts of e-waste from landfills, its outputs, procedures, byproducts are still unknowns. Moreover, the scheme seems to have problems in its structure given the lack of incentive, transparency and knowledge discussed in these studies. In this context, the objective of this study is to analyze and assess the Australian e-waste recycling system, having the NTCRS as the main reference. This paper is intended to improve the discussion for the Australian perspective by mapping and explaining the activity of NTCRS recycling companies, discussing the current e-waste scenario in Australia, identifying strengths and weaknesses and proposing solutions to the problems identified. Finally, this study intends to highlight the perspective of the e-waste recyclers and co-regulatory arrangements, which has been little explored. The analysis of WEEE management systems is a matter of research since it (i) shows to the scientific community to what extent a system is working, (ii) allows future studies to compare different systems and (iii) enlighten policy makers in crucial points of improvement and flaws of a given system.

4.4 Methodology

The four major methods for qualitative research were used in this study: observation, analyzing texts and documents, interviews and making use of visual materials (Silverman, 2015). The mixed-method used in the study is shown in Figure 23 and described in the sections hereafter.

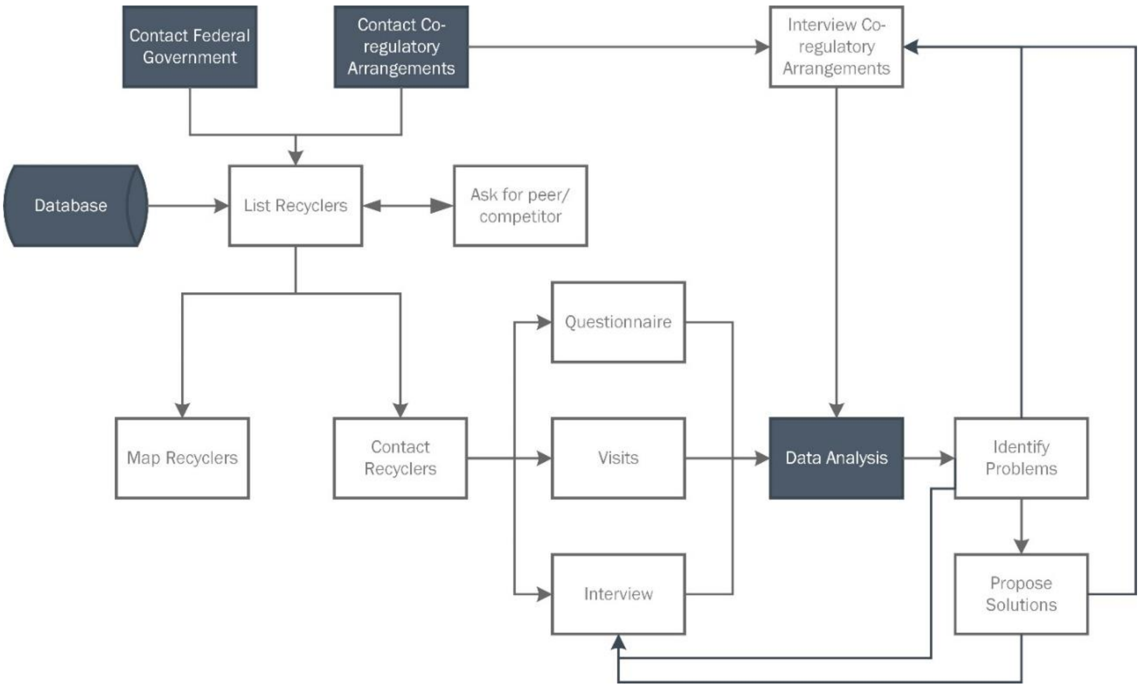

Figure 23: Flowchart of the methodology used in this study.

4.4.1 Scheme Analysis

The NTCRS is a complex system comprised of several agents. Its structure has been analyzed using the literature available in the database of the government, the database of the different companies involved in the scheme, previous studies on the scheme and on the available scientific literature. Moreover, information that was not available on literature was obtained using online questionnaires, face-to-face interviews and site visits (see 4.4.3). This study was carried out applying qualitative analysis methods presented by (Punch and Oancea, 2014); and (Thorne, 2016), i.e., the study maintained a continuous search for patterns through reflexive iteration, grounded interpretation and by keeping the data in a suspension state which, according to the authors, allow to analyze the structure of the scheme through different perspectives and the progressive comparison of the results to the literature. Triangulation concept was applied to validate the information having inputs from recyclers, CRAs and literature. Moreover, data obtained among recyclers and CRAs was cross-referenced to increase the level of confidence.

4.4.2 Defining boundaries for data collection

Preliminary consultation with the Australian Department of the Environment (Stewardship & Waste) and with the CRAs were conducted via email in 2016 in order to understand the distribution of NTCRS service providers. This allowed the recycling companies to be characterized according to number of facilities, location, CRA and size. Wright Corporate Strategy (2010) mention there were 14 facilities responsible for the majority of the waste recycled in 2010, but a precise number was not found in any database. This study identified 31 recycling facilities working under the NTCRS; their activity was confirmed by contacting them and/or the CRA they work with.

4.4.3 Data collection (perspective input)

In order to obtain more information about the organization of the NTCRS and the e-waste flow in Australia, visits (field observation) and face-to-face semi-structured interviews (Silverman, 2015) were conducted. The interview was aimed at the recyclers working under the scheme, similar to the research conducted by Lane et al. (2015) to allow comparisons. An online questionnaire was also conducted to attend the needs of facilities that are located in outer regional areas or that wanted to remain anonymous. The online questionnaire contained the interview questions in the form of either tick-box responses or free answer (Supplementary table 1). Tick-box alternatives were obtained during interviews and based on a previous study (Dias et al., 2018c). All tick-box questions allowed respondents to add different answers. These answers, when appropriate, were added to the original answers group for the following respondents. All different answers were either grouped together to a previous existing answer or counted individually, when appropriate. The questions (of both interview and questionnaire) aimed to identify what was being exported and where to, what were the routes e-waste took within the NTCRS, how the recyclers operated (processes and equipment), how much more e-waste they could process (if any), how was the collection system, among others. Moreover, face-to-face semi-structured interviews were also set up with the CRAs to obtain their perspective and feedback on the issues raised and identified.

The questionnaire received 27 (87.1%) answers from the 31 recycling facilities working under the NTCRS (14 during interviews and 13 online). The error associated with the responses gathered for a finite population can be calculated (Israel, 1992). Assuming maximum variability (0.5) and for a confidence level of 95%, the error associated with this questionnaire is 6.89%. The responses were collected in 2017 and analyzed for further discussion. Visits and interviews (during the visits) comprehended 14 recycling facilities (45%) and 3 CRAs (75%). Ten permanent collection points were also visited in order to observe the collection and storage systems.

4.4.4 Scheme assessment – Solutions and second feedback

After every visit/interview, potential and ongoing problems of the scheme were identified and solutions for those problems were proposed. These problems and solutions were included in the following interviews and were discussed with local recyclers and CRAs. The discussion led to clarifications of some issues raised and confirmation of others. The solutions proposed were debated to understand if they would fit the scheme or if they have been tried before by any of the agents. An example of this was questioning whether the collection system could be shared among CRAs, if this has been tried before, if it is working and what problems were encountered. This methodology using the input of emerging insights into constructive interviews and reflexive iteration (visiting and revisiting the data) has been reported to progressively lead to refined focus and understandings (Srivastava and Hopwood, 2009).

4.5 Results

The results obtained from the mixed-method approach are described in the sections hereafter.

4.5.1 What changed with the implementation of the NTCRS?

Recyclers have reported that the amount of incoming e-waste increased greatly with the introduction of the scheme. Shortly after, the number of competitors rose, which decreased the e-waste amount per facility. The public drop off has also been reported to increase because of the drop off fee removal and because people became aware of a safe disposal option. The scheme has introduced greater waste data control because of the reports that need to be handed to the CRAs, which ultimately rose the operation cost for recyclers. Overall, the scheme represented an increase in the activity of the recyclers both in terms of number of employees and waste processed.

4.5.2 The NTCRS structure

Australia has little domestic manufacturing of EEE, the majority is imported (Dollisson, 2017; Golev et al., 2016). The liable parties (mainly importers and distributors) sell EEE to consumers, who later dispose of EEE as WEEE. Under the scheme, WEEE is collected and redirected to different domestic recyclers, where it gets dismantled and sorted into different parts – this is the first stage recycling mentioned in the regulations (Australia, 2011). WEEE is then sent for downstream processing domestically or internationally. Some materials such as steel, aluminum, copper, glass and lead acid batteries are recycled within the country, while polymers, printed circuit boards, cables, hard drives and other batteries (non-lead acid) are typically exported for further processing abroad (Figure 24). A list of materials recycled under the scheme is presented in supplementary table 2.

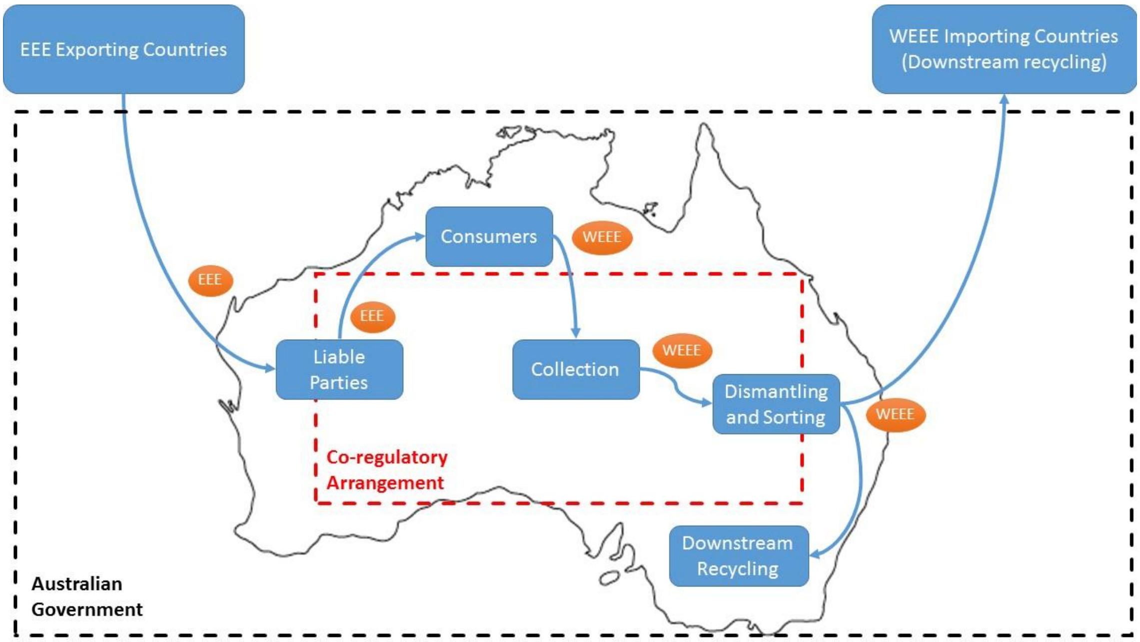

Figure 24: Current structure, WEEE flow and responsibility boundaries of the NTCRS.

The federal government is responsible for calculating the arising waste for a certain financial year. This is done by taking into account the total weight of imports over the last 3 years and a scaling factor (Department of the Environment, 2015c). The government has control over what is imported into the country and has estimated the amount that was already in the country before the scheme started. These estimations combined with the products that are sent for reuse internationally and the lag between the import and the disposal may lead to differences between the calculated amount of arising waste and the real amount. This mismatch has been reported by Lane et al. (2015), who presented four areas for improvement when calculating the arising waste for the scheme. Moreover, being an OECD country, Australia can only export waste to recovery facilities "which will recover the wastes in an environmentally sound manner according to national laws, regulations and practices to which the facility is subject." (OECD, 2008). The Australian federal government has no authority over the recycling processes used in other countries. Thus, despite restricting the export of the dismantled parts to countries that possess adequate technology to recycle, the specific outcome and processes used cannot be determined and are difficult to track. Furthermore, the CRAs do not have the responsibility of auditing downstream recyclers – domestic or international.

4.5.2.1 Co-regulatory arrangements (CRA)

The co-regulatory arrangements share the duty of making sure the targets of the scheme are met. However, the scheme has been set up so that they are in constant competition with each other. This competition has resulted in changes in the number of CRAs over the years and in changes within the CRAs. Supplementary figure 1 shows the number of approved CRAs active since the scheme commenced. Supplementary table 3 displays the approved CRAs and relates them to other names and companies to ease the understanding of the system. Figure 25 shows the evolution of the market share over the years since the scheme commenced. In the current market distribution (2017), ANZRP deals with most of the waste (24,260 tons - 51%), followed by MRI, EPSA and ECycle. Reverse E-waste had a participation of about 10% during the financial year of 13-14. In recent years, MRI PSO (former DHL) has been losing market to the other CRAs – from the FY of 2012-2013 to 2015-2016, MRI PSO has experienced a decrease of more than 50% of e-waste collected (in tons). The biggest increase was achieved by EPSA, which had a 157% increment in e-waste collected from when it first entered the market. Moreover, there is no evidence that the number of CRAs is related to the e-waste collected within the NTCRS – while there was an increase in both number of CRAs and e-waste collected from the first to the second FY of the scheme, the following FY shows a decrease in e-waste collected with no variation on the number of CRAs. From FY 14-15 to 15-16, e-waste collected and recycled increased whereas the number of CRAs actually decreased.

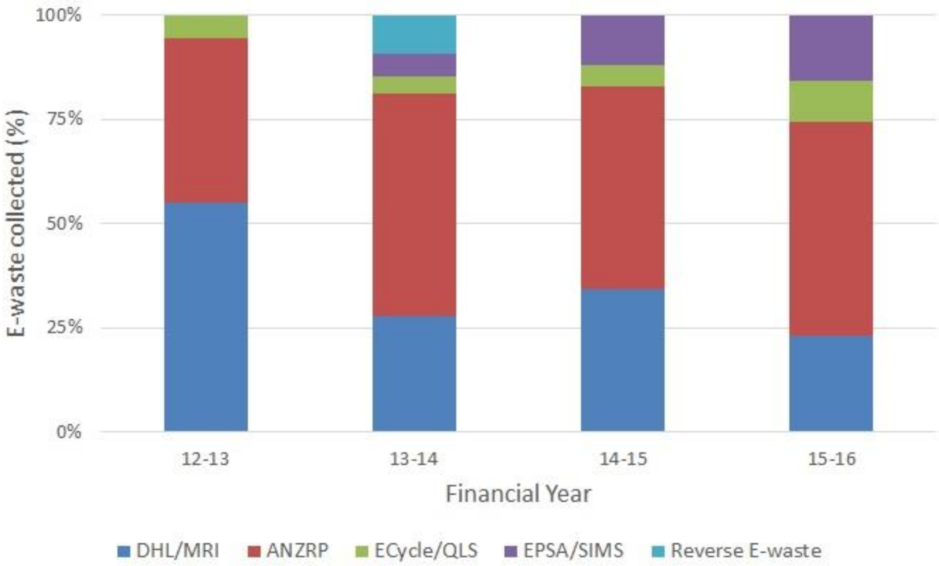

Figure 25: Market share (waste collected) among CRAs in different FY Data sources: (Department of the Environment and Energy, 2016, 2015c, 2014).

4.5.2.2 Recyclers

The 31 recycling facilities found in this study are responsible for undertaking the initial processing of e-waste (disassembly or shredding), as specified in the regulations (Australia, 2011). Other than having their processes in accordance with the standard for collection, storage, transport and treatment of e-waste (AS5377) and reporting back to the CRAs, the e-waste recyclers in Australia operate autonomously.

A distribution map of the recycling facilities, the influence of CRAs and the population density in Australia is shown in Figure 26. These facilities are key in determining to which extent e-waste is processed within the country. In general, there is one facility for every 500,000 inhabitants per state – Western Australia and New South Wales have a shortage in this sense. A detailed map per state is shown in supplementary figure 2.

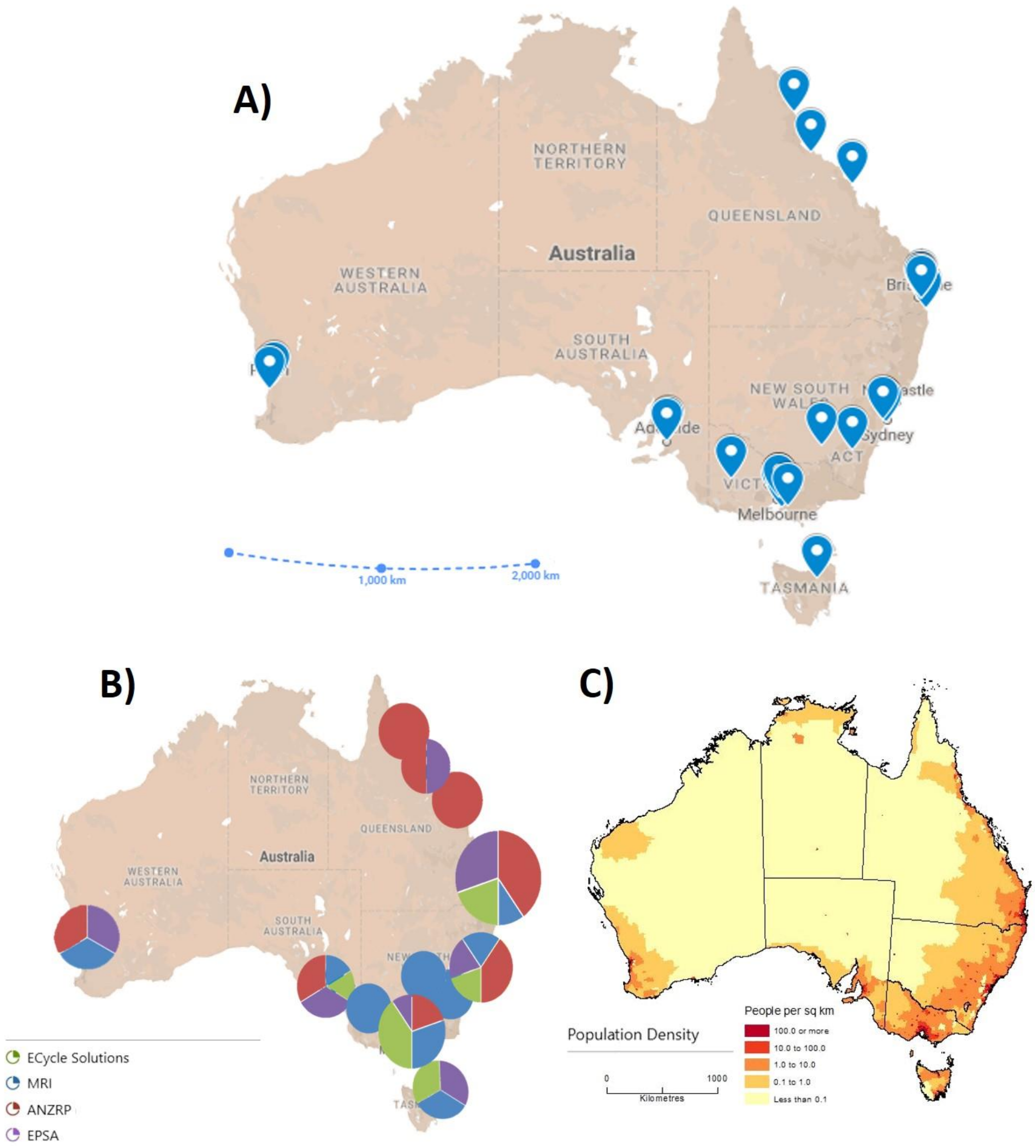

Figure 26: A) Distribution of WEEE recyclers under the NTCRS in Australia. B) Influence of CRAs per facility per location. C) Population density in Australia in 2016 (ABR, 2017).

There are currently 18 recycling companies working under the NTCRS (some with more than one facility, which totalizes 31 recycling facilities). These recyclers have contracts with the CRAs. The e-waste may be provided by the CRA or gathered by the recycler, it depends on the contract and if the recycler has the structure to operate the logistics. Currently, the distribution of recycling facilities per CRA is as follows: ANZRP (31.8%), MRI (27.3%), EPSA (20.5%), Ecycle (20.5%) (Figure 26). The relationship between recycler and CRA is displayed in Figure 27. Apart from these 31 facilities, other recycling facilities work indirectly with the NTCRS:

- Independent recyclers (not directly affiliated with any CRA) that recycle NTCRS goods and report the recycled material on behalf of liable parties. That is, the recycler reports to the liable party, which reports to its the CRA, which reports to the government;
- Liable parties that have their own recycling plant and do not need to contract third party recyclers for e-waste processing;
- International and domestic downstream recyclers that receive e-waste previously processed by the 31 facilities formerly mentioned.

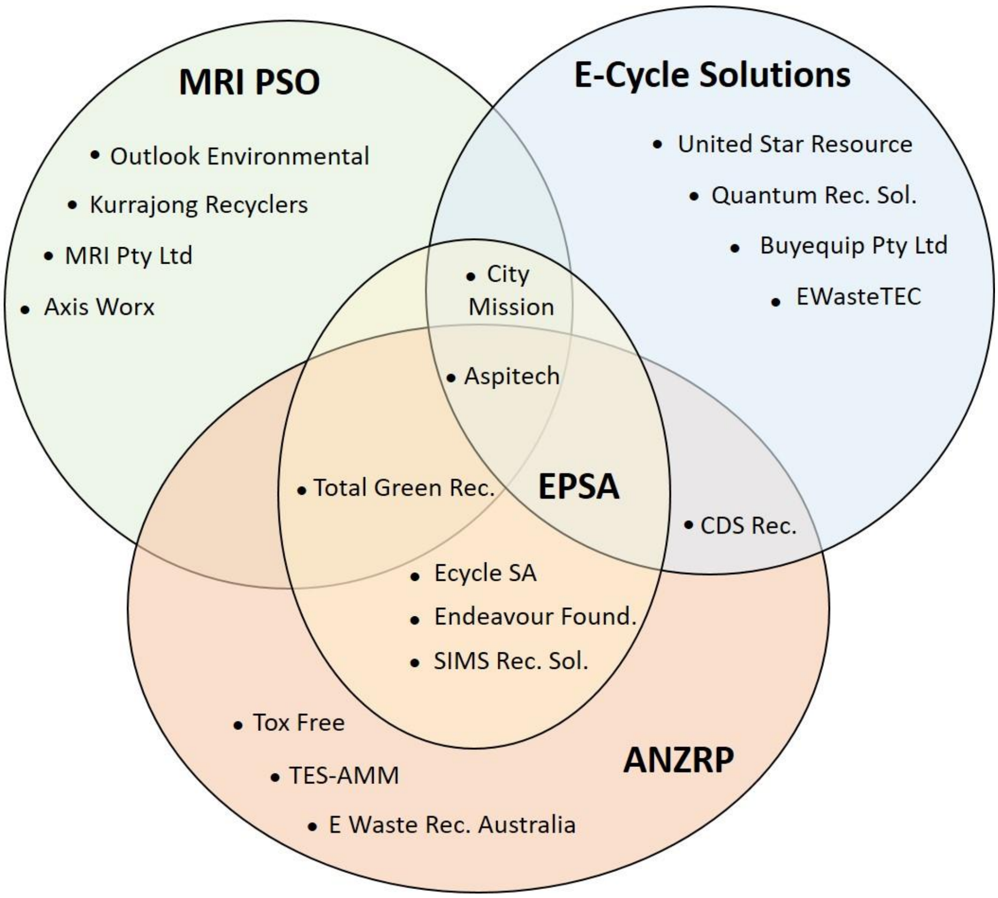

Figure 27: Distribution of recyclers according to CRAs. Note: Aspitech underwent a rebranding and is now Electronic Recycling Australia.

Figure 27 shows that several recyclers are engaged with more than one CRA. A recycler may be shared among CRAs for several reasons: geographical position of the facility, social purpose, structural capacity. City Mission, for instance, is the only e-waste recycling facility on the island of Tasmania (Figure 26). Aspitech (Electronic Recycling Australia) is the only recycler shared among all the CRAs – mainly due to its location (South Australia) and its structural capacity. The shared facilities operate in the same way the exclusive recyclers do: they receive waste from a certain CRA, measure it, process it, record the activity and report back to the CRA. The difference is that a shared facility must have waste log entries associated with the respective CRA responsible for that waste. When questioned, the CRAs mentioned there is no downside in sharing recycling facilities among themselves. This study has not identified any problem related to sharing facilities. In fact, sharing should be encouraged as it may increase the total e-waste recycled whilst decreasing the energy/fuel consumption for recycling by avoiding long distance shipping and transportation.

4.5.2.3 Collection

Similar to what is observed with the number of CRAs, the number of permanent collection points does not seem to have relation with the quantity of e-waste collected or recycled within the scheme (Figure 28).

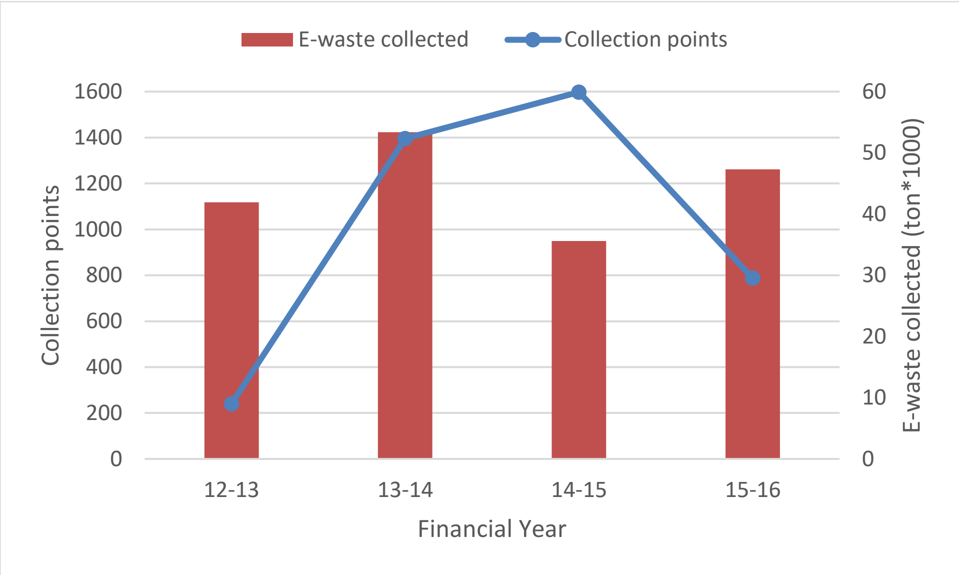

Figure 28: Relation between e-waste collected and permanent collection points (sum of all CRAs) per financial year. Data source: (ANZRP, 2016, 2015b, 2014, 2013; DHL, 2015, 2014, 2013; ECycle Solutions, 2016, 2015, 2014, 2013; EPSA, 2016, 2016, 2015, 2014; MRI PSO, 2016; Reverse E-waste, 2014)

The scheme requires that all CRAs must provide reasonable access drop off points (collection points) to all Australians according to population density: Metropolitan, Inner Regional, Outer Regional or Remote areas (Department of Sustainability, Environment, Water, Population and Communities, 2011b). The reasonable access requirement is important, but it needs to be optimized. In the current setup, all CRAs end up competing for e-waste throughout the country. In metropolitan areas, the competition seems to work well, but in the other regions, it is not cost effective nor environmentally friendly. The little waste obtained from these regions reported by the CRAs, does not pay the logistics cost of picking it up.

Some CRAs have agreements in which they share certain permanent collection points. The sharing occurs for two main reasons: reasonable access and profit. A CRA with a developed logistics operation makes a profit by sharing some collection points with other CRAs, while the CRA hiring the collection point has more means to meet the reasonable access requirements. The WEEE collected in these drop off locations is shared among CRAs and reported accordingly. This sharing of collection point is not beneficial to the population because the more shared points, the less overall collection points. However, it supports the operation of the scheme, since some CRAs have a greater capacity of recycling, while others have a greater capacity of collection/logistics planning. Furthermore, as shown in Figure 28, the increase in collection points does not reflect in an increase of WEEE collected.

When questioned how they collect or receive WEEE, most recycling facilities (89% of respondents) indicated they have partnership with city councils/government (Figure 29). Other collection methods are through (i) partnership with other companies, i.e. direct handover company – recycler (78%), (ii) direct handover from users, i.e. consumer – recycler (67%), (iii) delivery centers or collection center, e.g. retailers (56%), (iv) private collection service performed by the recycler (48%), (v) WEEE collection fairs and events (30%) and (vi) hand pickers (19%). Moreover, most recycling facilities (80%) have more than one method of collecting e-waste. These results reveal that councils are the main linking agent between public and recycling, yet these agents have little or no responsibility within the regulations of the scheme. Moreover, hand pickers having a role in the Australian e-waste market is remarkable, especially considering that the minimum wage of the country is among the highest in the world (OECD, 2016). This highlights the value of NTCRS goods, estimated to be about US$ 120 million in recovery value in 2014 (Golev and Corder, 2017).

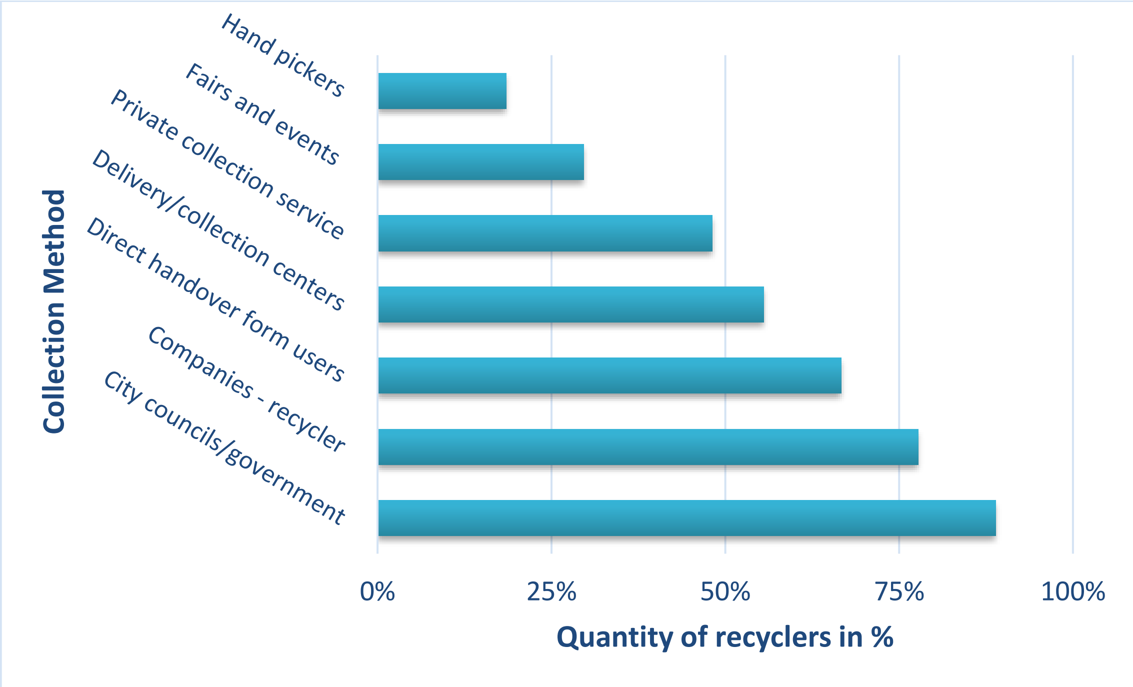

Figure 29: Response of recyclers about how WEEE is collected

4.5.3 E-waste recycling in Australia - First stage recycling

Concerning the recycling processes used, all the facilities (100% of respondents) indicated they use manual dismantling and manual sorting. The other main processes used are shredding/grinding (45%), magnetic separation (35%) and eddy current separation (25%). Automatic dismantling, automatic sorting, sieving and density separation are used by a minority of the questioned companies (Figure 30A). Downstream processes such as smelting, leaching and electrowining are not used in any of the recycling facilities working directly under the NTCRS. The equipment used by the recyclers are in accordance with the processes, the main being forklifts and electric/pneumatic screwdrivers. As far as mechanical and physical separation processes (as defined in previous works, Dias et al., 2018), besides the magnetic conveyor and the eddy current conveyor, high technology separation such as the x-ray separation and the Blubox (shredding and material separation altogether) were reported to be used in only one recycling facility.

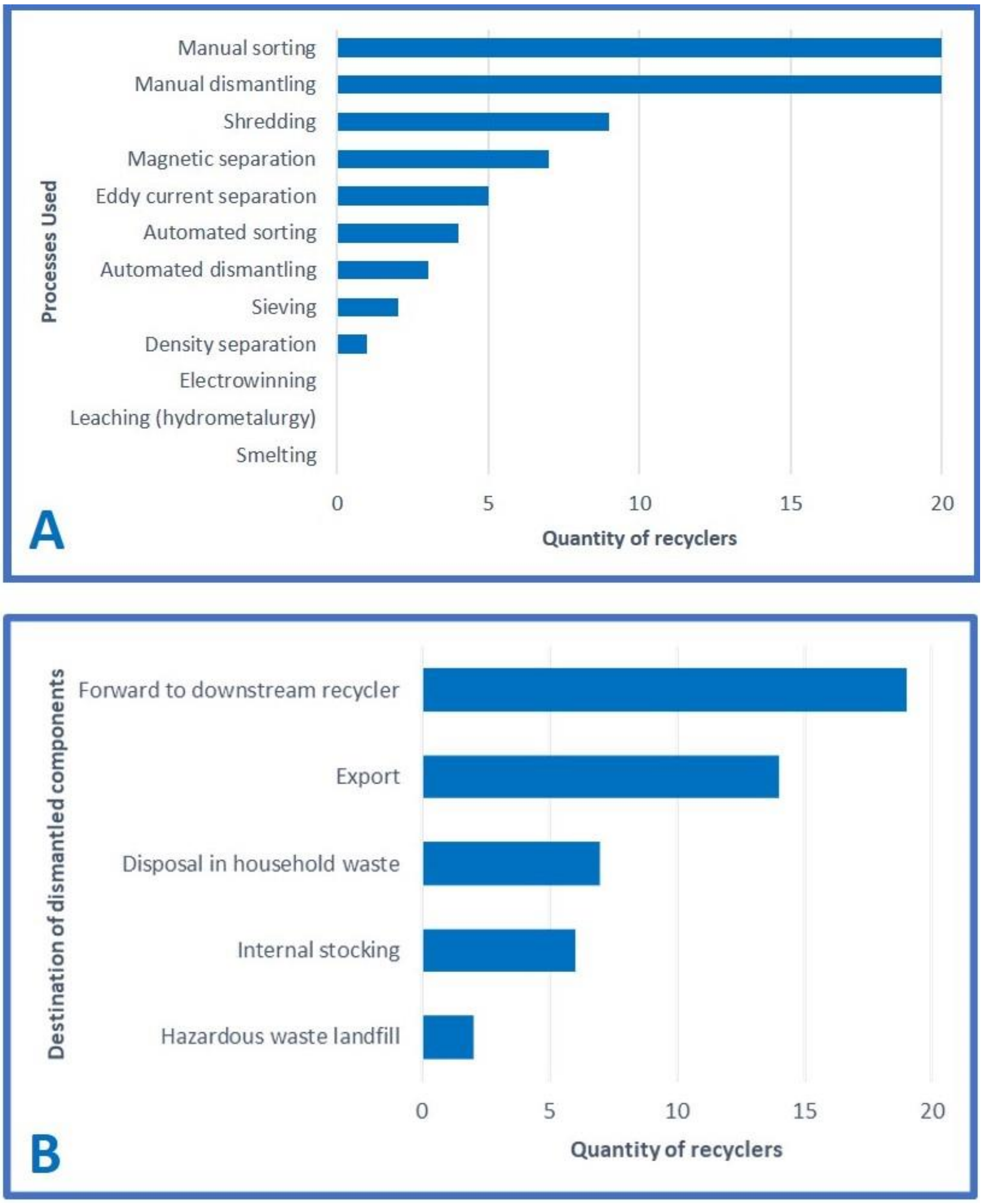

Figure 30: (A) Response to which processes are used (B) Response to destination of the dismantled components

When questioned about the destination of the components after the first stage recycling, the majority of the recycling facilities (76% of respondents) indicated they forward the components for downstream processing. Other possibilities for the dismantled components are export (56%), disposal in household waste (28%), internal stocking (24%) and sending some components to hazardous waste landfills (8%). Forwarding components for downstream processing can result in a profit or a loss for the recycler according to the component: hazardous components such as mercury lamps, CRT glass, batteries and tonners are usually a liability, while components mainly made of steel, aluminum, copper are typically profitable. The components that are generally disposed as household waste are the ones made out of polyvinyl chloride (PVC), expended polystyrene (PS), timber products and small bits that may be lost during the process. Internal stocking is used to build up volume for certain components before forwarding them for further processing – the nickel connector present in CRT tubes is an example of a component usually stocked.

Since the commencement of the scheme, the export of components has been growing, from FY 14-15 to 15-16 there was a 48% increase, while e-waste collected increased by 33%. From FY 15-16 to 16-17 there was a 24% export increase, while e-waste collected increased by 9.6%. Currently (2017), 52% in weight of all the e-waste collected under the scheme is exported. High value components such as printed circuit boards, hard drives, processors are typically exported. Given the lack of specific recycling processes in the country, the current setup of the scheme should lead to bigger exports of valuable waste (Figure 31). Other components such as cables and polymers are also currently being exported. The main countries receiving waste are China, Japan and Indonesia (Figure 31). The main reasons for exporting reported are the lack of specific recycling processes (also referred as "lack of technology"), lack of a consumer market capable of undertaking recycled products, lack of manufacturing industry capable of using recovered commodities and high cost for downstream recycling in comparison to other countries. The distribution of Figure 31 is approximate since data of one CRA could not be obtained –total exports, however, are exact.

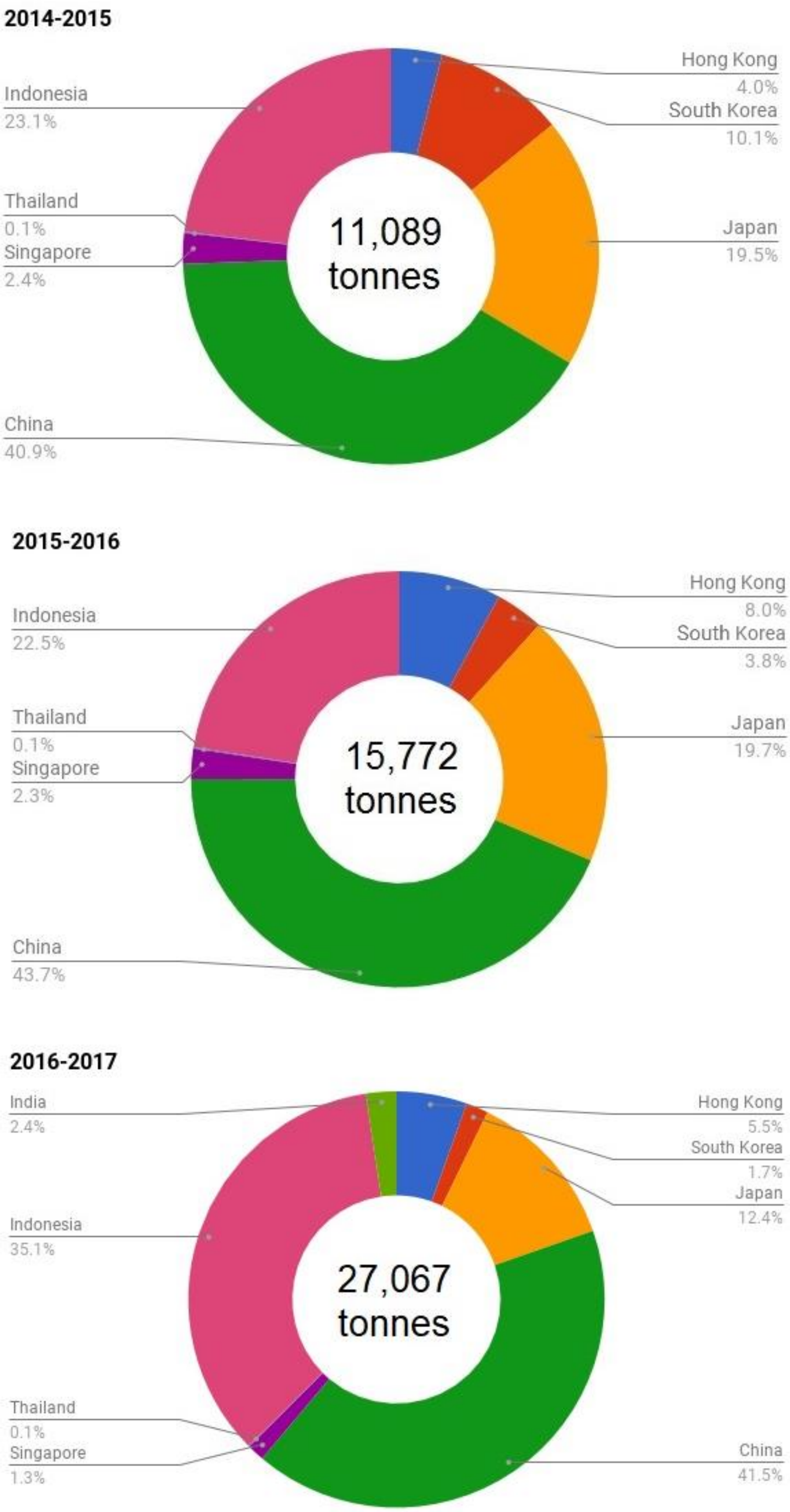

Figure 31: NTCRS material export for FY of 2014-2015, 2015-2016 and 2016-2017. Data source: (ANZRP, 2016; Department of the Environment and Energy, 2016; ECycle Solutions, 2016; EPSA, 2016; MRI PSO, 2016).

4.5.4 Capacity of recycling facilities

In respect to the capacity of the recycling facilities, the majority (87% of respondents) claimed they are not working at full capacity, while the remaining claimed they are. When interviewed, the facilities mentioned it is easy to increase productivity by contracting more people. This is in accordance with the findings of Wright Corporate Strategy (2010), that indicate that additional processing capacity can be obtained by doubling or tripling operations shifts, without needing to invest heavily in new infrastructure.

Moreover, when questioned whether the scheme should be broadened or not, all the recyclers and CRAs interviewed responded positively. They all believe the scheme should be broadened to include other appliances such as audio equipment (*stereo*), DVD players, microwave, shavers, hair dryers, electric toothbrushes, earphones, vacuum cleaners, modems and other telecommunication equipment. Broadening the scheme would mean higher volumes of material being recycled, which is beneficial for consumers, CRAs and recyclers. On the other hand, broadening the scheme culminates in increasing the product range of current liable parties and including new liable parties in the scheme. For this scenario, two different perspectives were given by the CRAs: (i) The broadening of the scheme would mean the cost of recycling would be more spread among liable parties and would make the scheme overall more efficient, therefore, it could result in savings for the liable parties. (ii) The broadening of the scheme would increase the range of products of certain manufacturers/importers and this would increase the cost of the scheme for these liable parties.

4.5.5 The lack of monitoring

Although the Australian Standard (AS5377) has been implemented, the visits to the recyclers and collecting points revealed e-waste being stored on the outside with no shelter from rain, which breaches the section 2.4.1b (Australia/New Zealand Standard, 2013). In the current scheme setup, there is little monitoring among agents. This facilitates the manipulation of data, such as over reporting and double counting (intentional or not). These situations have been reported by some agents during interviews and though there is no proof that this is happening, an increase in monitoring and reporting creates a scenario in which it is more difficult to claim false data.

4.6 General Discussion

The NTCRS is unprecedented because it is the first national scheme designed for a continental country like Australia. The scheme adapted references from leading WEEE management programs, such as the material recovery target from the Japanese system (Hotta et al., 2014), the allocation of roles and responsibilities to key stakeholders from the Swiss system (Morris and Metternicht, 2016) and the recycling/collection target from the European system (EU Directive, 2012). However, its greatest merit is perhaps organizing a collection system in a country that has a hundredth of the population density of these benchmarking nations. A collection system that is free to the public, reaches remote areas, has increased the amount of e-waste recycled and is completely funded by the industry that produces the waste in the first place. The NTCRS is an example for large territorial countries such as the USA, Canada, Brazil and Russia, which are still struggling with a national legislation capable of handling the e-waste issue. In spite of its strengths, this study identified crucial points of improvement that should be addressed to enhance the WEEE management. The CRAs are the main agents of the scheme, they are responsible for the majority of the operation, maintenance and monitoring, and their role is clearly stated in the legal framework around the NTCRS (Department of the Environment, 2015b). However, the scheme has two main deficiencies that should be tackled by CRAs and, therefore, included in their responsibilities: monitoring of downstream processing and consumer awareness.

The recycling system in place today creates a scenario in which the material is hard to trace, since the recyclers working directly under the scheme (first stage recyclers) are not able to recycle the material into its recoverable form, and this is usually done by further downstream recyclers. Downstream recyclers are, according to the findings, monitored by first stage recyclers. However, the responsibility of assuring the scheme outcomes are met is of the CRAs. Thus, the inclusion of downstream auditing and/or monitoring seems reasonable to ensure that the material recovery target is being achieved (Figure 32). Moreover, this would encourage domestic recycling over international, given the former is easier to audit. Gumley (2016) and Lane et al. (2015) claim there is a need for regulation and control of exported e-waste sent for processing overseas. This study showed that on top of better monitoring of the international e-waste processing, the monitoring of processes and collection in Australia also needs improvement to guarantee compliance with the current regulations and to enhance the efficiency and transparency of the scheme.

Consumer awareness is extremely important in programs such as the NTCRS, given consumers are the source of WEEE. The lack of awareness regarding the existence of the scheme in Australia, the fact that the drop off is free and that WEEE are generally hazardous, creates an unfavorable scenario for recycling. Moreover, it has been reported that “consumer willingness to discard EOL products is the most important demand-side variable for product collection” (Wright Corporate Strategy, 2010). Thus, the increase in consumer awareness should be a responsibility of the CRAs (Figure 32) that can be met through its liable parties with initiatives as simple as attaching a sticker to their products advertising the NTCRS. Nonetheless, local and federal government should also incorporate the responsibility of creating public (consumer) awareness.

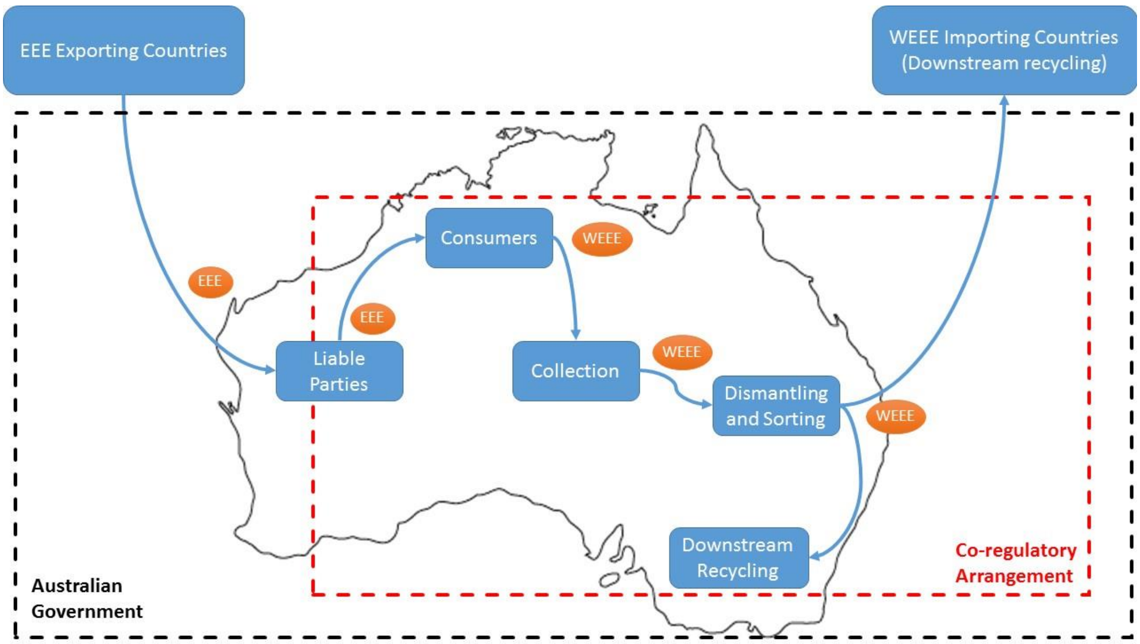

Figure 32: Proposition of responsibility boundaries for the CRAs (increased in relationship to Figure 4).

The improper storage of e-waste (see 4.5.5) can be avoided by requiring local councils and retailers to report the amount of e-waste collected to the federal government (as shown in Figure 33), the later can cross-reference the data with information provided by CRAs. Furthermore, this would allow the federal government to analyze whether specific drop off locations are actually collecting waste or simply being used to count towards reasonable access (this would highlight one-day collection point with no publicity and no collection that have been reported by some interviewees – referred to as "tick-the-box collection point"). The reporting could be based on the model of Japan, where the number of units collected per prefecture is published for public access (Hotta et al., 2014). Moreover, if the different agents were to monitor each other, the compliance with the regulations should increase. Collection services, for instance, could have the responsibility of monitoring the storage of collection points to assure the compliance with the Australian Standard (AS5377).

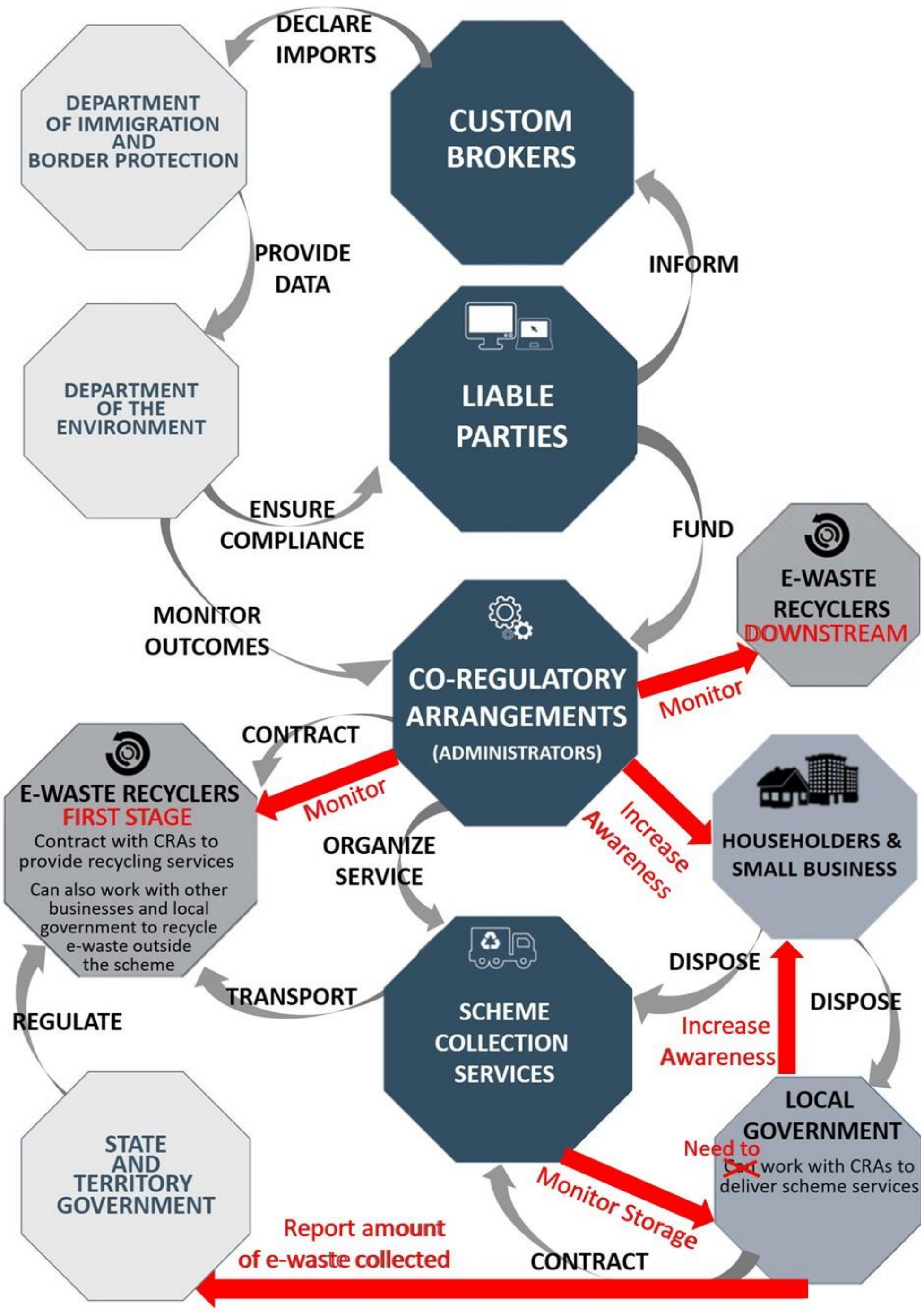

Figure 33: Proposition of added roles and responsibilities (based on Figure 1).

A review in the way reasonable access is met may lead to savings for the scheme as a whole. By splitting the non-metropolitan areas among CRAs every FY or having them operating in different periods along a FY, the cost of collection can be reduced and the population may have access to a service that is more consistent. Morris and Metternicht (2016) argued that the current setup leads the population losing confidence and willingness to participate in the scheme due to

CRAs stopping the collection services without notice and/or Australians having to travel over 100km for the nearest drop off point. An improvement in the reasonable access provisions of the Regulations can lead to a better service with a lower economic and environmental cost. Furthermore, broadening the scheme (see 4.5.4) to include other WEEE would be beneficial for the community, councils, recyclers, CRAs and environment. By broadening the scheme, the volume of material collected through the NTCRS increases, which offers a better offset especially for the collection in non-metropolitan areas. The broadening would also result in a better service for the community that currently has some of its e-waste rejected in certain collection points due to them not being part of the NTCRS.

The term "recycle" has a vague definition in the Regulations, given it indicates that some e-waste should be recycled under the scheme, but defines this recycling as the "initial processing of the product for the purpose of recovering usable materials, and includes disassembly and shredding of the product" (Australia, 2011). This allows a recycler to disassemble a product only to a certain extent, leaving the rest of the recycling to downstream partners outside Australia. Moreover, there is no definition whether the waste needs to be recycled within the country or elsewhere. In 2010, it has been reported that downstream recycling in Australia is limited to glass, steel, plastics, and some electrical cables (Wright Corporate Strategy, 2010). The results of this study indicate that little investment was made in downstream recycling technology as the scenario remains pretty much the same due to lack of infrastructure as previously reported, but also due to drop in commodity prices and international shipping prices, which favors waste export. As a matter of fact, some components reported in 2010 as being recycled domestically, such as plastics and electric cables, are currently being exported; this trend should increase (see 3.3) unless the setup of the scheme changes to encourage domestic recycling over international. Golev and Corder (2017) have reported that this export for overseas processing is an economic loss for Australia. Furthermore, the low-tech and labor intensive processes undertaken domestically, reported by Lane et al.(2015) and Wright Corporate Strategy (2010), are still in practice, which is contrary to the initial proposition of the National Waste Policy that states that “resource should be recovered with local technology having innovation being sought after internationally" (Environment Protection and Heritage Council, 2009). In order to improve the WEEE management in the country, Australia should install downstream recycling facilities (pyrometallurgy, hydrometallurgy, electrowinning) capable of undertaking the vast majority of e-waste it produces. This may demand government infrastructure investment concomitantly with e-waste export ban to assure the volumes needed for the downstream processing are available.

A summary of the points raised in this study and the solutions presented to enhance the scheme is displayed in Table 11..

Table 11: Summary of the identified strengths and weaknesses, and proposed solutions.

Strengths	**High recovery material rate (90%)**
	Progressive collection target
	Collection service for outer regional and remote areas
	No public drop off fees
	Liable parties as the source of funding
	Increased employment in the e-waste recycling sector
	Overall increase in e-waste collected and recycled
	Development of a collection system for continental counties;
Shortcomings	International recycling favored over domestic
	Most FSR are not able to recycle the material into its recoverable form (this is usually done by further downstream recyclers)
	Agents required to assure material recovery (CRAs) have no obligation to audit the formerly mentioned downstream recyclers
	The term "recycle" has a vague definition in the Regulations
	The material is hard to trace after FSR
	Reasonable access setup is not cost efficient or environmentally friendly
	The lack of monitoring allows breaches (such as double counting and improper e-waste storage)
	Shortfall of defined responsibility for the local councils and local recyclers
	Absence of agents responsible for increasing general community awareness
Proposed Solutions	Include auditing and/or monitoring of downstream processing and increase of consumer awareness as responsibilities of the CRAs
	Have local councils and retailers report the amount of e-waste collected to the federal government
	Have collection services monitor e-waste storage at collection points
	Share the reasonable access requirement among CRAs
	Broaden the scheme to include other related and common household WEEE
	Specify, in the regulations, to what extent the collected WEEE have to be recycled/disassembled
	Invest/favor the development of a domestic downstream recycling industry

4.7 Conclusions

The National Television and Recycling Scheme (NTCRS) is a significant step towards better WEEE management; it is a product stewardship and extended producer responsibility success case that can be replicated in other countries. The implementation of the NTCRS has led to many positive outcomes such as an increase in the employment in the e-waste recycling sector, an overall increase in e-waste collected and recycled since its inception and, consequently, a significant increase in e-waste diverted from landfills. Like any other recently implemented pilot scheme, it has shortcomings that are presented and discussed in this paper. The most important achievement of the research conducted and showed on this paper is demonstrating that the enhancement of the NTCRS encompasses redefining the roles and responsibilities of the agents involved in the scheme, sharing the logistics, recyclers and resources to optimize the recycling rates and to enforce the regulations and, therefore, assure maximum compliance and minimum environmental damage. While the management of WEEE is dependent heavily on country-specific factors, several of the shortfalls and suggestions for improvement presented in this work can be generalized to other WEEE management systems, especially in countries of continental dimensions. Schemes like the NTCRS are being (and should be) implemented worldwide, and therefore, an improvement in the NTCRS may lead, ultimately, to an improvement in WEEE management in the world.

4.8 Acknowledgments

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CHAPTER FIVE

PAPER 3

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Assuring Best E-waste Recycling Practices in Developed Countries: An Australian Example

Pablo Dias[a,b], Andréa Moura Bernardes[b], Nazmul Huda[a]

[a] Faculty of Science and Engineering, Macquarie University, Sydney, NSW 2109, Australia (nazmul.huda@mq.edu.au)

[b] Programa de Pós-Graduação em Engenharia de Minas, Metalúrgica e de Materiais (PPGE3M), Universidade Federal do Rio Grande do Sul (UFRGS), Av. Bento Gonçalves, 9500, 91509-900: Porto Alegre, RS, Brazil. Tel: 55 51 33089428

5.1 Abstract

The waste electrical and electronic equipment (e-waste) management is one of the great challenges faced in the twenty-first century due to the steep e-waste increase worldwide and their potential to be both a source of valuable materials and a hazardous source of contamination. In this study, the management of e-waste is discussed having the Australian recycling scheme as an example. The investigation on the actual recycling process and the associated cost analysis revealed important outcomes for the decision-making process of determining which equipment (or materials) will be exported and which will be recycled domestically. It is shown that scrap computers are the only equipment with enough intrinsic value to justify the domestic recycling without requiring any external subsidy. Furthermore, the importance of such subsidy, of regulations and monitoring are discussed, principally for e-waste with an intrinsic value smaller than computers. The results indicate that labor accounts for more than 90% of the cost of first stage recycling in Australia, which can be extrapolated to countries where labor is expensive. Finally, in the interest of achieving a better waste management worldwide, this study provides arguments to encourage a better monitoring of the recycling processes undertaken internationally and/or the promotion of downstream recycling processes in developed countries.

5.2 Keywords

Electronic waste; Recycling; Recycling Cost; Waste management; WEEE management;

5.3 Introduction

In the current ever growing population (and ever growing consumption per capita), improving resource efficiency is crucial (Worrell and Reuter, 2014a). In addition to consumption reduction, other actions towards waste minimization such as reuse of products and recycling have an important role in contributing towards a sustainable resource management (Nelen et al., 2014; Worrell and Reuter, 2014a). While municipal solid waste had the world's primary focus during the beginning of the 21st century, the attention has now shifted to waste electrical and electronic equipment (WEEE) – also known as e-waste (Premalatha et al., 2014). WEEE are old, end-of-life or discarded appliances that use electricity or, in a broader definition, obsolete devices dependent on electric current or electromagnetic field to work properly (European Commission, 2011; Schluep, 2014b). They are a particularly important waste stream because of their potential to be pollutants or resources (Sugimura and Murakami, 2016b). They include a mixture of organic and inorganic materials, which contain toxic agents, such as cadmium, lead, mercury and bromated flame retardants (Bakhiyi et al., 2018; Fowler, 2017a), as well as valuable and scarce material, such as copper, gold, platinum and rare earths (European Commission, 2017; Ikhlayel, 2017).

Leaving e-waste recycling to the free market - dependant on the intrinsic value of the materials contained therein - is not enough, mainly due to the high cost of decontamination (Toffolet, 2016). Thus, in the interest of maximizing resources efficiency and minimizing the amount of e-waste sent to landfills, several nations introduced take-back systems and regulatory frameworks to sort and manage this specific waste stream by applying concepts of extended producer responsibility (EPR), product stewardship (PS), collection and recycling targets. Some examples include the French Eco-systèmes (Toffolet, 2016), the Japanese Recycling Act (Hotta et al., 2014), the German ElektroG (Wang et al., 2017), the Australian NTCRS (National Television and Computer Recycling

Scheme) (Morris and Metternicht, 2016). These, however, are almost exclusively found in OECD countries (Schluep, 2014b).

In the current global setup, e-waste in a given country is either landfilled domestically, recovered domestically or exported (A. Kumar et al., 2017). In 2013, Li et al. (2013) showed the global trend of WEEE export: developed nations such as the EU countries, USA, Canada, Japan and Australia shipped their e-waste to developing countries in south-east Asia and Africa. When import restrictions were enforced in a given destination country (e.g. China), new destination countries with inadequate WEEE recycling facilities appeared (A. Kumar et al., 2017; Shinkuma and Huong, 2009). Later, in 2014, Premalatha et al. (2014) suggested that in spite of national and international efforts to revert the situation, the trafficking of e-waste from the economically better-off countries to the less economically well-off countries continued. In 2016, e-waste was still being sent to Africa or Asia under false pretences of used goods ("second-hand"), as opposed to waste (Garlapati, 2016). These used goods have been reported to lead to illegal re-exportation (Shinkuma and Huong, 2009) and are sometimes recycled in destination countries, instead of reused (Sugimura and Murakami, 2016b). Illegal exportation of waste happens mainly to countries less demanding in environmental terms, which can provide cheaper outlets (Tansel, 2017; Toffolet, 2016). In 2017, the same trend remains, and additional developing nations destinations were reported (e.g., Brazil in South America and Mexico in North America) (A. Kumar et al., 2017; Tansel, 2017).

Among the reasons for these legal or illegal exportations, Sthiannopkao and Wong (2013) explain that while developed countries have laws to recycle WEEE safely, the compliance with such laws frequently runs against economic interests. Sugimura and Murakami (2016), for instance, claim that there is no economic incentive for scrap dealers to sell domestically in Japan. Another reason is lack of viable resource recovery processes in industrialized nations (Sahajwalla et al., 2016). Moreover, the market value of a given material may vary whether its recycled abroad or domestically (Sugimura and Murakami, 2016b).

The consequences of this trans-boundary e-waste movement have been widely reported in scientific literature. The lack of regulation and/or enforcing leads to the “get the best, dump the rest” policy, where waste with little value is dumped or incinerated causing severe environmental damage and posing human health risks (Egeonu and Herat, 2016; A. Kumar et al., 2017; Sahajwalla et al., 2016; Schluep, 2014b, p. 25; Yoshida et al., 2016). Because of the low labor cost, developing countries apply labor intensive processing as the main treatment to separate materials and components, open burning to recover metals and open dumping to dispose of residual fractions (Schluep, 2014a). In these countries, the informal recycling sector is largely active (Herat and Agamuthu, 2012; Rochman et al., 2017) and the potential health related problems seem to be acute, especially due to lack of proper handling of the waste (Han et al., 2018; Oguri et al., 2018; Oliveira et al., 2012; Song and Li, 2015).

The main solutions proposed to tackle the current setup include the ban of end-of-life electronic devices export (including devices labelled as “for reuse”) (Bakhiyi et al., 2018; Egeonu and Herat, 2016; Kiddee et al., 2013; Sugimura and Murakami, 2016b) and the introduction of a certification system and/or an international processing standard (e.g. WEEELABEX) (Leroy, 2012; Li et al., 2013; Toffolet, 2016).

In Australia, the recent creation of the regulatory framework and the national recycling scheme (NTCRS) have been able to divert significant amounts of e-waste from landfill. However, due to the lack of a downstream recycling industry and the shortfall of a mechanism to promote downstream recycling, the majority of the e-waste collected through the scheme is exported for processing overseas (Golev et al., 2016; Lane et al., 2015). Exports have grown in recent years (Dias et al., 2018a), but knowledge about how WEEE is processed in the destination countries, as well as the environmental and health damages of the workers being caused, is still insipid. Therefore, the questions concerning the choice between export and domestic recycling, in continental developed nations, is still a matter of research, especially studies that take into consideration real-world scenarios and deal with the cost of recycling (Islam and Huda, 2018). How is the decision-making process to determine whether a certain e-waste will be exported or not? To what extent is the difference in wages paid to the e-waste labor force important in determining where the waste will be processed? What is the importance of legislation in ensuring best e-waste recycling practices? Can developed countries fully recycle e-waste without subsidy? What is the cost of first stage recycling in high labor cost countries? This study aims to address these key questions and give a foundation for them to be answered.

5.4 Methodology

5.4.1 The recycling routes – possible scenarios

E-waste recycling, for this study, was broken down into two stages: i) first stage recycling as per the Australian regulations (Australia, 2011), which include initial trial, dismantling and shredding of a product and ii) downstream recycling, which includes advanced physical separation, specific recycling and refining processes (Dias et al., 2018b). There are currently three possible outcomes for e-waste collected in Australia through the national scheme (NTCRS): (I) Both first stage and downstream recycling occur in Australia –i.e. Domestic first stage and downstream recycling, (II) Domestic first stage recycling and international downstream recycling, (III) International first stage and downstream recycling. The outcome is dependent mainly in market forces and they can be explained by looking at the revenues and cost associated with the recycling process (Equation (1).

$$\boldsymbol{P} = \boldsymbol{R} - \boldsymbol{C} \tag{1}$$

Where P is profit, R is revenue and C is cost. The revenues and costs for a NTCRS first stage recycler (FSR hereafter) in Australia are summarized in Table 12.

Table 12: Revenues and costs associated with first stage recycling in Australia.

Designation	Description	Revenue or Cost	Unit
A	Money received from co-regulatory arrangement	Revenue	$\frac{\$}{mass}$
B	Material sale to domestic downstream recycler	Revenue	$\frac{\$}{mass}$
C	Material sale to international downstream recycler	Revenue	$\frac{\$}{mass}$
D	Collection	Cost	$\frac{\$}{mass}$
E	Processing	Cost	$\frac{\$}{mass}$
F	Shipping (freight)	Cost	$\frac{\$}{mass}$
G	Council rebate	Cost	$\frac{\$}{mass}$
H	Landfill	Cost	$\frac{\$}{mass}$
I	Real estate/Facility (rent)	Cost	$
J	Certifications	Cost	$

The FSR receives money from the co-regulatory arrangements per mass of processed material (A); this money originates from the liable parties, who are required to fund a co-regulatory arrangement (Dias et al., 2018a). After gathering the material, the FSR may dismantle and sort the waste into its various components or it may undertake minimal waste processing (such as removing the batteries) and then export the majority of the product for it to be dismantled overseas. After dismantling, the FSR can sell the separated components to domestic (B) or international (C) downstream recyclers (DSR hereafter). The costs associated with the collection (D) of e-waste through the scheme may or may not be a responsibility of the FSR. Nevertheless, it accounts for a cost because if the co-regulatory arrangement does the collection, this will certainly incur in a decrease in revenue A (Table 12). The cost of processing (E) encompasses all the energy, manpower and machinery used to run the recycling operation. The cost of freight (F) may include ground and/or maritime transportation of processed e-waste from the FSR to the DSR. Some councils charge a rebate (G) from the FSR for the e-waste the former has collected (this generally only occurs in metropolitan councils that deal with large volumes of e-waste). The cost of landfill (H) is associated with the federated state in which the waste will be landfilled, the hazardousness of the waste and the amount of waste being discarded. Finally, there is the cost of leasing (rent) a facility for operation (I) and the cost to obtain compliance (J) with the Australian-New Zealand standard for collection, storage, transport and treatment of end-of-life electrical and electronic equipment - AS5377 (Australia/New Zealand Standard, 2013), which became mandatory from June 2016. The cost to obtain the certification includes the actual certification fee, the cost of installing undercover areas, safety and security measures and the administration cost associated with auditing, reporting and tracking of materials.

The profit equation for each of the three possible scenarios is described hereafter. **Scenario I** – Domestic FSR and DSR: The profit for scenario I (P1) is given by equation (1) relating the costs and revenues presented in Table 12. In this scenario, C equals zero given the processed e-waste is not being sold

$$\frac{\boldsymbol{P1}}{\boldsymbol{m}} = \boldsymbol{A} + \boldsymbol{B} - [\boldsymbol{D} + \boldsymbol{E} + \boldsymbol{F} + \boldsymbol{G} + \boldsymbol{H}\,(\boldsymbol{1} - \boldsymbol{e}) + \frac{\boldsymbol{I}}{\boldsymbol{m}} + \frac{\boldsymbol{J}}{\boldsymbol{m}}] \qquad (2)$$

overseas.

Where A, B, D, E, F, G, H are defined in Table 12, m is mass of waste and e is efficiency, given in percentage. Thus, if the dismantling process is 100% efficient, the term (1-e) becomes zero and there is no landfill cost. If, however, the process if 60% efficient, the term becomes 0.4 because 40% of the material in weight needs to be landfilled. Since most of the terms are mass dependent, the equation can be simplified by dividing the whole equation by the mass, which results in equation (2). The same will be done for the other scenarios.

Scenario II – Domestic FSR and international DSR: The profit for scenario II (P2) is given by equation (3) taking into account that B equals zero, since the processed waste is being sold internationally and not domestically. Also the cost of freight F becomes F' to highlight that one is domestic freight and the other is international, respectively.

$$\frac{\boldsymbol{P2}}{\boldsymbol{m}} = \boldsymbol{A} + \boldsymbol{C} - \left[\boldsymbol{D} + \boldsymbol{E} + \boldsymbol{F'} + \boldsymbol{G} + \boldsymbol{H}(\boldsymbol{1} - \boldsymbol{e}) + \frac{\boldsymbol{I}}{\boldsymbol{m}} + \frac{\boldsymbol{J}}{\boldsymbol{m}}\right] \qquad (3)$$

Scenario III – International FSR and DSR: The profit for scenario III (P3) is given by equation (4) taking into account that B equals zero, for the same reason of scenario II. The processing cost of FSR is also zero, given the process is not undertaken by the FSR ($E = 0$). The landfill cost is also zero in this scenario, given the waste is being exported. Therefore, the international recycler would deal with any waste arising from the first stage recycling ($H = 0$). Finally, the revenue generated by the sale of components C becomes C' to highlight that one is the price received for the dismantled components and the other is for the whole equipment (as is), respectively.

$$\frac{\boldsymbol{P3}}{\boldsymbol{m}} = \boldsymbol{A} + \boldsymbol{C'} - \left(\boldsymbol{D} + \boldsymbol{F'} + \boldsymbol{G} + \frac{\boldsymbol{I}}{\boldsymbol{m}} + \frac{\boldsymbol{J}}{\boldsymbol{m}}\right) \qquad (4)$$

5.4.2 The market forces – determining the scenario

The FSRs are responsible for the decision of whether to undertake the first stage recycling or not, and whether to sell the material to domestic or international recyclers – this happens because the regulations in place have a vague definition for the term "recycle" (Dias et al., 2018a). Legislation and technology availability play an important role and have priority over the market forces in determining which route e-waste will take. Legislation refers to rules and regulations that restrain free exchange, e.g. Australia has restrictions on which countries can receive e-waste material, according to OECD regulations (OECD, 2008). Thus, even if a country offered a better price for a certain e-waste material, the FSR might not be able to go forward with the transaction because of these regulations. Similar restrictions apply to the transboundary movement of hazardous waste. The availability of technology is also fundamental. If the country does not have the capability of recycling a certain material/component, it eliminates the possibility of domestic downstream recycling. For the majority of the NTCRS e-waste components in Australia, however, legislation allows both domestic and international downstream recycling and the technology is available domestically.

The outcome of the possible scenarios is generally determined according to the profit it generates, the greater profit being favored. The decision varies according to equipment (computer, printer, CRT, etc.), component (circuit board, hard drive, glass, etc.) and period (because B, C and F vary with the price of commodities, volume of international trade, etc.). Therefore, the decision is constantly updated by the FSR and can change from time to time. A flowchart representing the decision-making process is displayed in Figure 34.

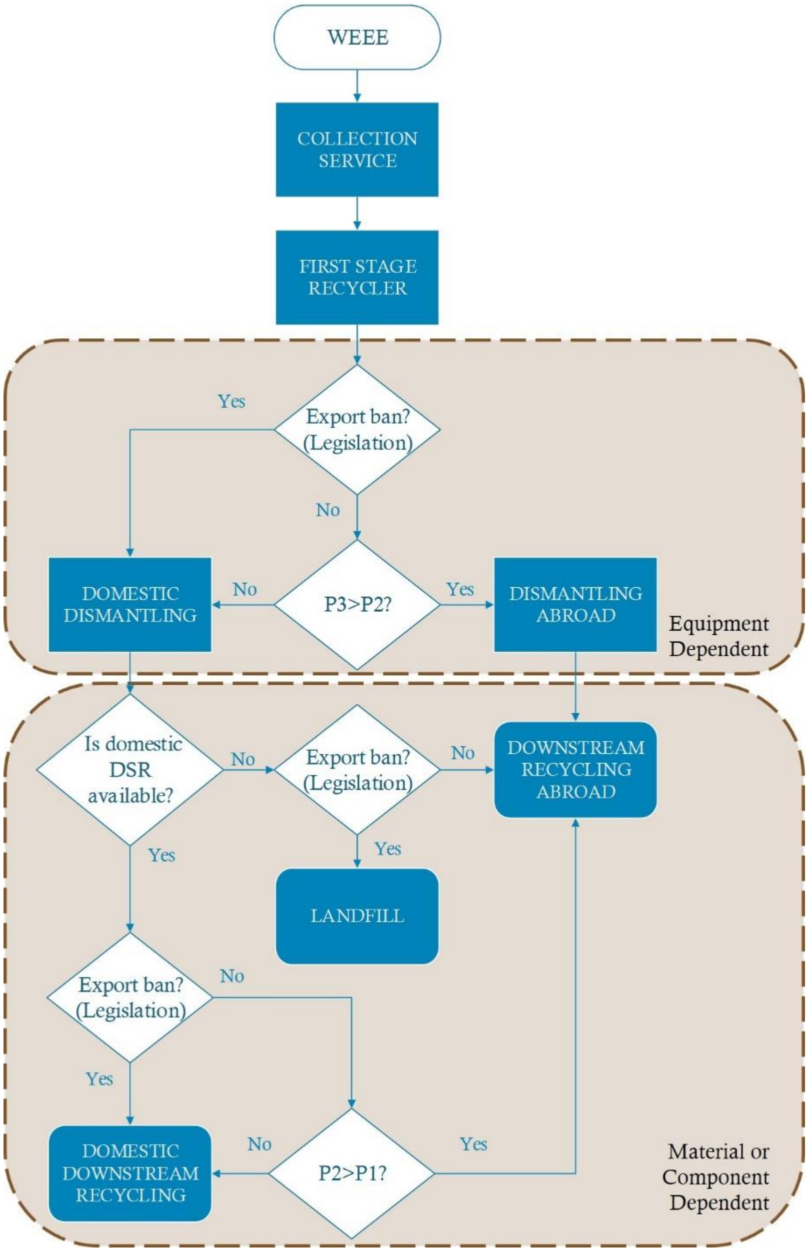

Figure 34: Decision making flowchart for the possible e-waste recycling routes in Australia. P1 = profit for scenario 1; P2 = profit for scenario 2; P3 = profit for scenario 3; DSR = downstream recycling.

In Australia, e-waste is never exported for international first stage recycling then imported for domestic downstream recycling (e.g. a batch of computers is exported to be dismantled abroad and the dismantled components are imported to be processed in Australia). This limits the possible outcomes for the scenarios and the decision can be made by relating P1, P2 and P3.

$$\frac{\boldsymbol{P3}}{\boldsymbol{m}} - \frac{\boldsymbol{P2}}{\boldsymbol{m}} = \pm \boldsymbol{ve} \tag{5}$$

$$\frac{P2}{m} - \frac{P1}{m} = \pm ve \qquad (6)$$

Where m is mass of waste, P1, P2 and P3 are the profits obtained in scenario 1, 2 and 3 respectively. Therefore, if equation (5) is positive, then scenario III is favored, if it is negative, then scenario II is favored. Similarly, if equation (6) is positive, scenario II is favored, if it is negative, then scenario I is favored. Equation (5) can be combined with equation (3) and (4) to generate equation (7), which has already been subtracted and simplified.

$$\frac{P3 - P2}{m} = (C' - C) + [E + H(1 - e)] \qquad (7)$$

Equation (7) can be broken down into two categories: i) the sale price difference between a dismantled equipment and an equipment as is (or an equipment with minimum dismantling) $(C' - C)$ and ii) the cost of domestic first stage processing (E) and disposal $[H(1 + e)]$.

Similarly, equation (6) can be combined with the profit equations for P1 equation (2) and P2 equation (3) to generate equation (8), which has already been subtracted and simplified.

$$\frac{P2 - P1}{m} = (C - B) + (F - F') \qquad (8)$$

As shown in Figure 34, equation (8) defines whether scenario I or scenario II will prevail, for the case in which scenario III has already been discarded using equation (7). Equation (8) highlights that the difference in the price paid between the international and domestic offer $(C - B)$ and the difference between national and international freight $(F - F')$ determine whether scenario I will occur or not.

5.4.3 Determining the unknowns

In order to determine the unknowns in equation (7) and (8), 15 out of 31 (48.4%) companies working as first stage recyclers under the NTCRS were visited. During visits, the processes used were observed and the following data were collected

(a) Processes used by facility to recycle e-waste;
(b) Equipment used;
(c) Power requirement of every equipment used;
(d) Amount of waste processed monthly/yearly;
(e) Fuel used in the recycling process;
(f) Number of employees working in the recycling;
(g) Type of employee's contract (permanent, casual, disability);
(h) Working hours of the facility;
(i) Time taken to process e-waste;
(j) Average time a certain equipment operates in a day;
(k) Average lifespan of the machinery used.

These data were used to calculate the cost of the processes undertaken by FRS (Unknown E in Table 12). The calculations required the cost of electricity and fuel paid by the FSR, which were obtained directly with some FSR and averaged with tailored quotations from electricity and fuel suppliers, respectively. The quotations took into account type of activity, state and usage. The process calculations also assumed the following

- Minimum wage in Australia is 843 AUD per week for full-time worker and 27.75 AUD per hour for casual worker within recycling sector in 2017 (Fair Work, 2017).
- In 2017, 248 (about 68%) of the 365 days were working days;

The cost of machinery amortization was calculated by contacting machinery suppliers to obtain quotes, which were averaged and diluted over their lifespan.

To determine the price paid by domestic DSR (Unknown B in Table 12) and the price paid by international DSR (Unknowns C and C'), offers from twelve buyers were averaged using online market websites. Furthermore, eleven direct quotation via email were obtained and six FSR informed the prices they received for their products. The prices were collected for non-dismantled equipment ("as is equipment") and e-waste components/commodities. The international offers covered North America, Europe and Asia. The prices in the recycling market vary according to supply and demand, prices of materials made from primary resources and behavior of markets and its stakeholders (Worrell and Reuter, 2014a). All the currency conversions (AUD, USD, EUR, CNY, JPY, KWR, MYR) were made using Bloomberg (Bloomberg, 2018), taking into account the mean rates of every month from April 2017 to March 2018 to create a yearly average for the financial year of 2017-2018.

The price of e-waste (B and C) can be understood as the price per commodity or the price per post-consumed equipment. In order to compare C and C' (equation (7), C also needs to be calculated per equipment. Therefore, the breakdown of each equipment was also obtained during the visits by observing the process and taking note of all the different components dismantled for a certain equipment. Later, component breakdown spreadsheets of three recyclers were used to obtain an average distribution of component per equipment. These data were combined with the market prices of every component/commodity in the market according to equation (9).

$$\sum_{i}^{n} \boldsymbol{Xi} * \boldsymbol{Pi} \tag{9}$$

Where *n* is the amount of *i* components in a given equipment (computer, printer, CRT monitor, flat screen, etc.), X_i is the given mass percentage (component/equipment) of component *i* and P_i is the given average market price for component *i* (in AUD/weight). Equation (9) was used to calculate the total market value of a given dismantled equipment.

To determine the shipping costs (Unknowns F and F' in Table 12), a combination of data from the FSR and direct quotations from two different Australian logistics companies was used. The quotations aimed to cover all possible shipping scenarios including domestic and international freights (Table 13). The international routes covered the main countries currently receiving NTCRS components/commodities reported in previous studies (Dias et al., 2018a) and, within these countries, the main ports. The domestic freights covered the shipping amongst the primary centers in the country assuming a scenario in which WEEE was collected in one location, but downstream was available in another (e.g. WEEE collected and dismantled in Melbourne but shipped to Sydney for downstream recycling).

Table 13: Possible shipping scenarios quoted for international and domestic freights.

	Port of loading	Port of discharge (country)	Commodity
International Freight	Sydney	Busan (South Korea)	Baled plastics (PVC, ABS)
	Melbourne	Jakarta (Indonesia)	Hard disc drives (HDD)
	Brisbane	Osaka/Yokohama (Japan)	Printed circuit boards (PCB)
	Adelaide	Port Klang (Malaysia)	Cables
		Shanghai (China)	
	Sending Location	**Receiving Location**	**Commodity**
Domestic Freight	Sydney	Sydney	Any non-hazardous e-waste
	Melbourne	Melbourne	
	Brisbane	Brisbane	
	Adelaide	Adelaide	

Triangulation concept was applied to the gathered data to increase the reproducibility of this study and provide a realistic average for the current market setup (2017-2018). A summary of the sources used in the triangulation is displayed in Table 14.

Table 14: Summary of triangulations used to validate data obtained.

Data	Data source			Relevant to[a]
Energy used in recycling process	FRS electric consumption spreadsheet	Calculated from data obtained during visits	Informed by equipment manufacturer	Processing (E)
Price of commodities (domestic and international)	Obtained during visits to FSR	Website of buyers displaying prices	Direct quotation from commodities buyers	Material sale (B and C)
Electricity cost	Obtained during visits to FSR	Direct quote from energy company A	Direct quote from energy company B	Processing (E)
Fuel cost	Obtained during visits to FSR	Direct quote from supplier A	Direct quote from energy company B	Processing (E)
International shipping cost (freight)	Obtained during visits to FSR	Direct quote from logistics company A	Direct quote from logistics company B	Shipping (F')
Domestic shipping cost (freight)	Obtained during visits to FSR	Direct quote from logistics company A	Direct quote from logistics company B	Shipping (F)

[a] All the information in this column is related to the revenues and costs presented in Table 12.

5.5 Results

5.5.1 First Stage Recycling in Australia

The observation of the processes used and the visit to the recyclers allowed breaking down the first stage recycling cost (Unknown E in Table 12) into the following items

- Electric energy (used to power equipment/machinery, lighting, fans, air conditioner, some forklifts, etc.)
- Fuel (either diesel, gasoline or LPG - liquefied petroleum gas – used to run generators, forklifts and/or trucks)
- Machinery (amortization of the initial investment to purchase or lease the machinery/equipment used)
- Labor (wages/salary of the workforce responsible for the manual dismantling of WEEE).

The total cost of processing equals to the sum of these items divided by the processed e-waste output, given in mass. It was found that first stage recycling consumes 39.7 kW per ton of e-waste in average in Australia. Facilities that are more automated, process, in average, 3840 tons of e-waste per year, while the facilities where dismantling is mostly manual, process, in average, 1361 tons of e-waste per year. The latter figure is increased to 1742 tons of e-waste per year if the Australian Disability Enterprises (ADEs) are disregarded in the average.

The cost of first stage recycling is highly dependent on the cost of labor, which represents, in average, 23.5 (±7.5) times the cost of energy and fuel combined (Figure 35). The cost of fuel is mainly related to LPG (about two times greater than diesel and gasoline), which is used in most forklifts at the facilities. Diesel powers some forklifts, some internally used trucks, compressors, generators and a few other pieces of equipment. The cost of water is negligible for the operation as it accounts for about 0.09% of the total processing cost. The following main cost is the investment in machinery, which includes leasing (or buying) trucks/forklifts and purchasing electric screwdrivers, compressors, balers, pallet stretch wrapping machines, etc. It also includes importing or ordering larger pieces of equipment such as automated separation lines, cable shredder-sorters and specific tailor-made machines. The total average processing cost for first stage e-waste recycling in Australia is approximately 483 Australian dollars per ton (E = 483 AUD/ton).

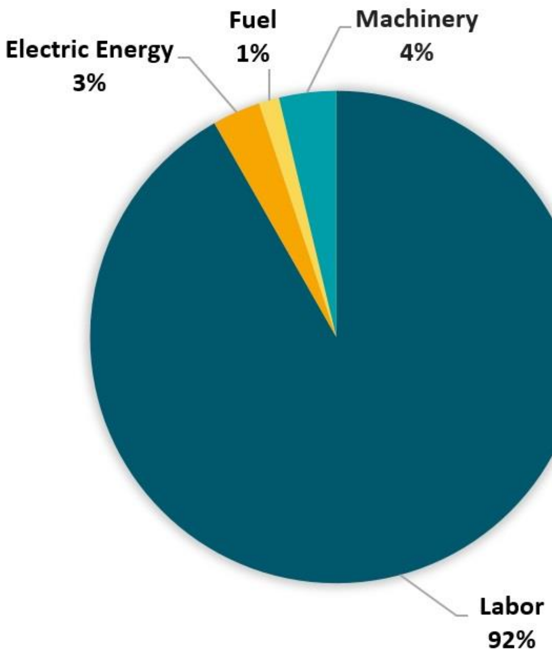

Figure 35: Breakdown of first stage recycling cost in Australia.

Furthermore, it was found that the cost of landfilling (Unknown H in Table 12) is negligible because the vast majority (more than 90%) of the first stage recyclers has an efficiency of 95% or higher, i.e. they forward to downstream processing at least 95% in weight of all waste they receive. In addition, the waste produced is limited to timber products, polystyrene (PS), polyvinyl chloride (PVC) and small bits and pieces that may be lost during disassembly (bolts, fragments of PCBs, etc.), all of which are not considered hazardous materials. Therefore, the cost of disposal is minimal. Most of these materials are gathered and disposed of as general waste (also known as household waste). Therefore, the efficiency term, (1-e) is considerably small (0.05 or less) as well as the landfilling cost, which allows the term H(1-e) in equation (7) to be neglected and rewritten as equation (10).

$$\boldsymbol{\frac{P3 - P2}{m} = (C' - C) + 483\ \frac{AUD}{ton}} \tag{10}$$

Where $P3 - P2$ is the profit difference between scenario 3 and 2, m is mass of waste and $(C' - C)$ is the sale price difference between a dismantled equipment and an equipment as is. The domestic dismantling of a certain equipment will only be economically advantageous if the profit of scenario II is superior to the one in scenario III (Figure 34). This can be expressed mathematically as having P2 > P3 or the difference between P3 and P2 smaller than zero. Therefore, equation (10) can be rearranged to these conditions, which generates equation (11).

$$\boldsymbol{C - C' > E \quad or \quad C - C' > 483\,\frac{AUD}{ton}} \tag{11}$$

Equation (11) indicates that the dismantling of a certain item will be economically feasible in Australia if the value added by dismantling the equipment is greater than the cost of domestic dismantling, which is about 483 AUD per ton of waste. According the findings, C is always greater than C' (C>C'), i.e., dismantled WEEE is more valuable than WEEE "as is". However, the difference between C and C' is equipment dependent, i.e., varies according to the e-waste in question. Among the equipment encompassed by the NTCRS (desktop/laptop computers, CRT monitors/televisions, flat screen monitors/television, printers and peripherals), computers have the highest material value (Table 15) and are the only type of equipment that can satisfy equation (11). Both C and C' fluctuate according to balance of supply and demand. For the current financial year (2017-2018), the difference for computers (C-C') varies from 174 to 682 AUD per ton, which means that this market fluctuation will determine whether its profitable to dismantle this type of e-waste domestically or not.

Table 15: Material value for dismantled e-waste calculated relating material breakdown and material pricing for financial year of 2017-2018.

	Average of C (AUD/ton)[a]	C – E (AUD/ton)[b]	Profitable Domestic Dismantling?
Notebooks	1150	>0	Possibly
Desktops	867	>0	Possibly
Flat Screens	366	<0	No
CRTs	141	<0	No

[a]C is determined as a range because prices for commodities are given as a range; displayed value is the mean of the range for the purpose of comparison. [b]Given C' is always greater than zero, if C-E is smaller than zero, then equation (11) will not be satisfied.

These results highlight the importance of the subsidy (or "gate fee") paid by the liable parties in schemes like the NTCRS. Furthermore, they highlight the importance of clear regulations that state the material needs to be processed domestically, since, in general, it is more profitable for companies to collect the waste and forward it to international recyclers than to process it domestically. This is especially true in Australia, given its high wages in comparison to neighbor countries (Table 16) and the importance of these wages in the first stage recycling cost (Figure 35). Finally, it shows that for items with an intrinsic value smaller than 483 AUD per ton, such as flat screens and CRTs, the subsidy is crucial to allow domestic recycling; and for CRTs – which generally cannot be exported - the subsidy is crucial for recycling to happen at all.

Table 16: Comparison of minimum wage in countries involved in the recycling of Australian e-waste.

Country	Wage	Unit	Year of reference	USD per hour	Australia/ Others	Reference
Australia	18.29	USD/ Hour	2018	14.18	1.00	(Fair Work, 2018a)
Japan	8	USD/ Hour	2016	8	1.77	(ILO, 2018a)
Korea	5	USD/ Hour	2015	5	2.84	(ILO, 2018a)
Hong Kong	4	USD/ Hour	2016	4	3.54	(ILO, 2018a)
China[a]	13.93	CNY/ Hour	2016	2.14	6.63	(Wage Indicator, 2018a)
Thailand	8.68	THB/ Day	2017	1.09	13.07	(The Maptics, 2017)
Indonesia[b]	9288.23	IDR/ Hour	2018	0.89	15.98	(Wage Indicator, 2018b)
Singapore	No Minimum Wage	-	-	-	-	(ILO, 2018b)

[a] Minimum wage calculated using simple average of all provinces. [b] Minimum wage calculated using simple average of all regions.

5.5.2 Downstream Recycling

Data concerning the domestic and international freight cost (unknowns F and F' in Table 12) revealed that it is about 50% more expensive to transport the dismantled goods domestically than it is to export it to the main countries that receive this type of material. Thus, the term F – F' in equation (8) can be rewritten as approximately 0.5F'. Moreover, for all scenarios of shipping explored, F is always greater than F'.

Data comparing domestic and international offer show that, with the exception of steel, the international market offers higher revenue than the domestic market for dismantled e-waste goods (Figure 36). In addition to steel, platinum, gold and some circuit boards can have a greater domestic offer, but, as shown in Figure 36, it requires specific market conditions. This trend has also been observed in other developed countries, such as Japan, where international offer for mixed-metal scrap from e-waste is about four fold greater than domestic (Sugimura and Murakami, 2016b).

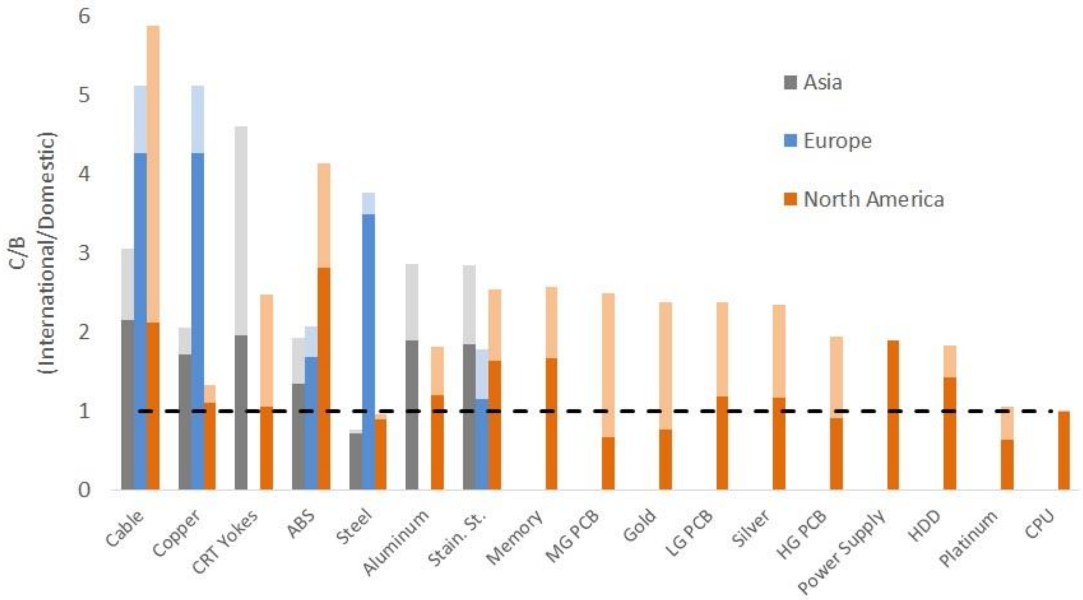

Figure 36: Comparison of international and domestic offer for the same components/materials for financial year of 2017-2018. Values above one (highlighted) indicate that international offer is greater than domestic. Stacked bars indicate bottom and top values considering bottom and top market prices proportions.

International downstream recycling is favored over domestic if the profit of scenario II is superior to the one in scenario I (Figure 34). This can be expressed mathematically as having P2 > P1 or the difference between P2 and P1 greater than zero. Therefore, equation (8) can be rearranged to these conditions and take into account the finding for freights, which generates equation (12).

$$\frac{\boldsymbol{P2-P1}}{\boldsymbol{m}} = (\boldsymbol{C}-\boldsymbol{B}) + \left(\frac{\boldsymbol{F'}}{\boldsymbol{2}}\right) > \boldsymbol{0} \quad \boldsymbol{or} \quad \left(\frac{\boldsymbol{F'}}{\boldsymbol{2}}\right) > \boldsymbol{B}-\boldsymbol{C} \tag{12}$$

Equation (12) shows that the domestic downstream recycling is unlikely to happen when taking into account economic factors. It will only be profitable when the difference between domestic and international offer exceeds half the cost of international freights, and, as shown, this can only happen for a handful of materials (Figure 36).

5.6 Discussion

Because first stage recyclers are autonomous in deciding what to do with the waste, the greater profit tends to be preferred. In this study, it was shown that, in Australia, it is economically advantageous to outsource both first stage recycling (i.e., dismantling and sorting) and downstream recycling to countries overseas.

The international first stage recycling is favored because the cost of processing is greater in Australia as compared to its neighboring countries. This is mainly because of the labor cost, which accounts for more than 90% of the total first stage recycling cost. Close range countries such as Thailand and Indonesia have a contrasting wage reality in comparison to Australia, where the minimum wage is 13-fold greater than that of these east-Asian countries (Table 16). In this sense, the cost of first stage recycling could potentially be reduced by seven times by outsourcing the process to Indonesia, for instance. This is the reality of most developed countries, where the minimum wage is comparable to that of Australia. Therefore, if there is no legislation in place to regulate the exchange of e-waste, it tends to be exported to countries where the labor is cheap. As shown in the introduction of this work, these countries commonly compromise environmental standards in exchange of financial gains, which incur in detrimental health impacts to e-waste workforce, environmental contamination and loss of scarce and critical materials. Moreover, when waste is processed abroad, it falls under the legislation of that specific country and out of the legislation of the country of origin. Thus, it is hard to maintain the standard required by the Australian regulation once the waste leaves the country. To achieve this, a great effort of monitoring is necessary.

The international downstream recycling is favored because international freights (shipping) is cheaper than domestic freights and because the international offer for dismantled goods is generally higher than the domestic offer. Furthermore, there is the limitation of technology, structure and consumer market reported in previous works (Dias et al., 2018a). The downstream recycling structure in Australia is virtually non-existent for a vast range of commodities. While the export option may present the best outcome for the FSR, it is a loss for the country, which could potentially benefit from the US$ 120 million that the

NTCRS materials have in recovery value (Golev and Corder, 2017) and ensure sound e-waste processing - as defined in its legislation. The country also loses several potential jobs generated by a downstream industry, which has been reported to create 5.4 full time equivalents jobs for every 1000 ton of e-waste processed (ADEME, 2014). Moreover, Toffolet (2016) claims that innovation is a crucial element in e-waste management systems and is necessary to gradually structure the recycling industry. The search for innovation is embedded in the National Waste Policy, the core of the regulatory framework around the NTCRS (Environment Protection and Heritage Council, 2009). What innovation can be expected in the current export setup? What could drive innovation in the country if the system in place outsources the majority of the recycling processes abroad?

Generally, most of the costs in e-waste recycling is related to collection logistics, sorting and the transport of these products to recycling centers (Toffolet, 2016). Australia currently undertakes all of these major costs and then exports the goods before final recycling phase. In a way, it currently applies the 'best of two worlds' model backwards (Wang et al., 2012).

Since the international recycling (both first stage and downstream) is economically preferable over the domestic, the Australian scheme has two options to maintain the standards established in its regulatory framework:

i) Monitoring: Invest in monitoring for both first stage and downstream recycling to minimize both improper WEEE handling abroad and environmental damage, and maximize the safety of the recycling sector's labor force. This involves constant monitoring from independent auditors to ensure that the companies receiving the waste abroad are compliant with the safety regulations and standards proposed by Australia. Toffolet (2016) argues that such auditors must be specially trained and have no connections with operators or take-back systems. Furthermore, Australia (or any e-waste source country) needs to be accountable for the negative impacts this kind of transboundary movement can promote. This can be achieved by regularly (and randomly) using GPS (geographical position system) devices in discarded e-waste to check their end-of-life destination and by imposing severe fines to the institutions whose waste are identified in irregular sites.

ii) Domestic recycling: The second option is to invest in domestic downstream recycling and gradually ban the export of waste to ensure there is a minimal volume for recycling. This would naturally generate more jobs within the sector and possibly result in economic gains for the country, given it would stop exporting low value commodities and begin to produce high value ones, such as gold, silver, copper, etc. Furthermore, the domestic downstream recycling requires the development of technology capable of processing smaller volumes of waste in relation to the current technologies. This would also assist with the cost of logistics within the country. Domestic freights are more expensive than international freights, so Australia would benefit from the development of local downstream recycling by avoiding the domestic transportation of goods. The simulation and quotes considered the transport between the main cities in Australia, but this transportation cost is eliminated if downstream facilities are available in all these main cities, for instance. If all the waste within a state is combined into a downstream recycling hub of that state, the transport cost could potentially be reduced. Government and private initiative should work together to develop this industry: Government can limit the amount of exports through regulation, while also assisting companies financially with machinery acquisition; given the high initial cost, unachievable by most companies currently operating. The private initiative can take advantage of the export limitation to invest in research and development of small plant downstream recycling – allowing a cost-efficient recycling with a lower volume threshold. This is particularly important because big machinery investments would require constant high volumes of e-waste input, which is not always a reality in the Australian scenario.

If a given process is not highly efficient, i.e., the percentage of non-recovered (and therefore landfilled) waste is not negligible, the environmental cost of exporting is higher than that of processing domestically due to the environmental impact of transport. This also argues in favor of domestic first stage recycling: all non-recoverable material separated during international processing travels unnecessary distances to be landfilled.

5.7 Conclusions

The results obtained in this study show that in countries where labor is expensive (generally the "developed countries"), there is a need for regulations in the recycling system. Without regulations, economic factors override environmental factors, i.e. free market is not enough to ensure e-waste will be recycled in an environmentally sound manner or recycled at all, which runs against the primary policies established in several of these countries.

In Australia, the companies responsible for recycling e-waste under the NTCRS are autonomous in deciding what to do with the waste and therefore the greater profit is favored, which implies in outsourcing both first stage and downstream recycling internationally. This is due to the high difference in wages paid in developed and developing countries and to the fact that first stage recycling is a labor-intensive activity. Better monitoring tools need to be developed to ensure environmentally sound processes are being used once WEEE is exported to low income countries. The only e-waste components that are not exported are the ones with negative economic net value or those whose export is restricted by law. Moreover, this study highlights the need of funding from the liable parties (importers and manufacturers) for e-waste to be recycled in Australia, because the only NTCRS equipment that have positive market value capable of justifying their first stage recycling without subsidy are computers. This is, however, subject to market fluctuations and even computers may result in an economic liability. Furthermore, the decision-making process and the current setup shows the need for clarification on the regulations to ensure that first stage recycling will be fully undertaken domestically.

If developed countries like Australia wish to ensure the standards they have established are being followed (i.e., that safe e-waste management and recycling is taking place), they should either invest in national and international monitoring (first stage and downstream recycling processes) or invest in domestic downstream recycling. In the current setup, installing and expanding the domestic downstream recycling automatically encourages the domestic first stage recycling. To achieve this, government and private initiative should work together – especially during the installation stages. Finally, the insights presented in this paper can serve as valuable resources for future planning, policymaking and maximizing resource efficiency.

5.8 Acknowledgments

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CHAPTER SIX
CONCLUSIONS

6.1 Discussion of the findings

Australia and Brazil are two countries with recent regulations towards e-waste management and comparable territory size (Table 17), meaning they have great distances to overcome during collection and transportation of WEEE. This continental dimension has already been appointed as a major obstacle for WEEE collection in a previous studies in Brazil (Caiado et al., 2017) and in Australia (Corder et al., 2015). Furthermore, the e-waste generated per GDP (gross domestic product) in Brazil and Australia is 786.2 and 388.4 tons per USD, respectively. E-waste generation of a country is directly correlated to its GDP, but the little influenced by its population size (A. Kumar et al., 2017).

Table 17: Characteristics and comparisons of Brazil and Australia.

Feature	Brazil	Australia	Brazil/ Australia
Territorial Size	8,515,759 m² (IBGE, 2017)	7,692,024 m² (Australia, 2017)	1.1
Total population in 2018	208.5 million people (IBGE, 2018a)	24.9 million people (ADS, 2018)	8.4
E-waste generated in 2016	1534 ktons (Balde et al., 2017)	570 ktons (Balde et al., 2017)	2.7
GDP in 2017	2.056 trillion USD (World Bank, 2018b)	1.323 trillion USD (World Bank, 2018b)	1.5
EEE import in 2017	20.7 billion USD (10% of total imports) (UN COMTRADE, 2018)	23.3 billion USD (14% of total imports) (UN COMTRADE, 2018)	0.89

These similarities allow the comparison of the WEEE management system of these two countries, which can be done by combining the information and data presented in the three published papers. This chapter presents this comparison and discusses the differences found between the two systems. It aims to improve the understanding of the approaches developed and developing countries take towards e-waste management.

The resemblance between the recent regulatory frameworks towards WEEE of both countries is remarkable. Australia introduced the National Waste Policy in 2009, while Brazil introduced its National Solid Waste Policy in 2010. While the contents of these documents are expressively similar, the practical changes that occurred in the two countries were dramatically different. In Australia, further regulations to support the National Waste Policy were implemented, while keeping the Policy as a foundation. These regulations set standards, targets and held stakeholders accountable for waste they generated. In Brazil, however, the National Solid Waste Policy (PNRS) was left unsupported and unenforced, having little impact in the recycling practices of the country. As shown in the second chapter of this thesis (2.4.3, page 63), there was a call to write a sectoral agreement three years after implementing the Policy. The agreement aimed to implement the reverse logistic concept and product stewardship to WEEE in practical terms, holding accountable manufacturers, importers, distributors, merchants, consumers and the waste management workforce. This agreement, however, was never signed and continues to await its conclusion. Meanwhile, the Brazilian WEEE recyclers, during interviews, claimed that the lack of regulations weakens the sector because of the lack of monitoring (and/or inspection), the constant competition with informal recyclers and the “cascade tax” that they end up paying to acquire, collect, treat and sell e-waste and the commodities recovered from it.

The first phase in the recycling process of e-waste is the collection. It was found that the collection of WEEE in both countries varies greatly. In Australia, the National Scheme (NTCRS) sets a collection target for the co-regulatory arrangements. These agents organize the collection and may run the collection themselves or outsource it to either the e-waste recyclers or third-party logistic companies. The collection includes high density areas (metropolitan areas) and outer regional areas. Currently, all the co-regulatory arrangements must service all regions, including low density regions. In Brazil, due to the lack of enforcement of reverse logistics, the collection is regulated by free market. The recyclers are responsible for collecting the waste on their own. Public bidding and private auctions are used by large organizations with high volumes of WEEE to sell this waste. Table 18 compares the data from Brazil (paper 1, page 89) and Australia (paper 2, page 114) and shows that both countries rely heavily on private sector partnerships and direct individual consumer handover to recover WEEE, but Australia has the local councils (local government) as its main mean to collect WEEE, while in Brazil, a great number of recyclers need to use their own collection services to obtain their waste. This is most likely related to the structuring of the Australian scheme, where the lack of consumer drop off fee encourages the consumers to dispose of their WEEE correctly and to have the local councils as an important and reliable drop off point. Whereas in Brazil, the recyclers cannot rely on local government to collect WEEE on their behalf and need to set up private collection services.

Table 18: Comparison between the Brazilian and Australian WEEE collection system.

Main Collection Means	Recyclers using these means (%)	
	Australia	Brazil
Local council/city council/government	89%	43.2%
Private company/organizations	78%	81.8%
Individual consumers handover	67%	63.6%
Collection centers (retailers, supermarkets, etc.)	56%	43.2%
Private collection service	48%	68.2%
WEEE collection events	30%	20.5%
Hand pickers (waste scavengers)	19%	13.6%

If the recyclers are considered as waste collection organizations, Brazil has a smaller proportion of organizations per capita than Australia (about 0.6 and 1.4

organizations per million inhabitants, respectively), which certainly reflects on the comprehensives of the collection services provided.

The most significant difference between the two countries, however, is the discrepancy in wages paid to the labor force involved in the e-waste dismantling process. As shown in the first paper (paper 1, page 89) and then confirmed in the third paper (paper 3, page 149), manual labor is a step commonly undertaken in the e-waste recycling process and accounts for most of the cost of first stage recycling in Australia. While Australia has a minimum wage varying from 22.2 to 27.7 Australian dollars (AUD) per hour (Fair Work, 2018b), Brazil has a minimum wage of 954 Brazilian *reais* (BRL) per month, equivalent to 2.3 AUD per hour (considering a 39 hours per week journey) (IBGE, 2018b; Planalto, 2017). A more precise comparison considering the purchasing power parity is shown in Table 19, which shows the minimum wage in Australia was about 12.5 to 15.5-fold that of Brazil in 2018. A better comparison needs to take into account the “real” cost of an employee, accounting for taxes, training and applicable penalties associated with the e-waste dismantling activity. This wage gap, however, has important implications in the WEEE recycling cost, especially for the first stages of dismantling and sorting, which are mostly undertaken manually. If it were not for the regulations in place in Australia, free market would drive the first stages of recycling abroad or, as was the previous setup, allow e-waste to go to landfill with no/little processing (Ongondo et al., 2011), as this is a cheaper alternative. In Brazil, however, the low minimum wage in place creates a scenario in which free market dictates that first stage recycling will occur domestically.

Table 19: Minimum wage comparison between Brazil and Australia considering PPP.

Country	PPP (in 2017) [a]	Min. wage per hour in local currency	Wage in AUD	Wage considering PPP in AUD
Australia	1.472	22.2 – 27.7 AUD	22.2 – 27.7	15.1 – 18.8
Brazil	2.024	6.11 BRL [b]	2.45 [c]	1.21
Australia/ Brazil	0.727			12.5 – 15.5

[a] Source: OECD (2018). [b] Minimum wage in Brazil determined per month. Calculation multiplies minimum month's wage by 13 (twelve months plus thirteenth salary), divides it by 52 weeks and by 39 hours per week. [C] Conversion taking average from April 2017 to March 2018 from Bloomberg (2018).

Since both countries lack downstream recycling industry for complex components (shown in paper 1 for Brazil and paper 2 for Australia, page 89 and 114, respectively), the components separated in the first stage recycling are generally exported to be processed abroad. The export of e-waste goods, nevertheless, also contributes to maintaining the downstream recycling industry stagnant. Among the main countries that receive these materials presented in the two published papers (paper 1 and 2, page 89 and 114, respectively), only Japan and Singapore receive from both Brazil and Australia. The destination countries are in accordance with geographical placement and shipping costs for both countries: Australia favoring Asian countries, and Brazil favoring European and American countries. The developed countries (USA, Belgium, Japan, etc.) receive the high value commodities, such as printed circuit boards, processors and hard drives. The developing countries (China, Indonesia) receive mainly polymers (ABS, PS, etc.) and cables. The export to developing countries is only observed in Australia, since Brazil exports exclusively to developed countries. This is directly related to the regulations in place in both countries. Australia, as shown in the third paper (paper 3, page 149), exports all allowed components (components whose export are not prohibited) it can for two main reasons: the profit obtained by international sale is greater (greater offer and lower shipping cost) and because it needs to meet the material recovery rate stablished in the regulations. The target recovery rates force the country to find alternative solutions instead of dumping the waste in landfills. In Brazil, however, the lack of regulations leaves landfilling as an option for e-waste components whose recycling/recovery is not economically profitable. Thus, instead of developing a downstream industry or stockpiling material to sell it internationally, the companies responsible for managing waste may landfill the components that represent an economic liability. This is especially true in the case of Australia and Brazil given the huge area these countries have, which diminishes even further the cost of landfilling in comparison to other countries.

Developing and implementing a downstream recycling industry in these two countries would avoid the export of e-waste components and generate jobs and a source of valuable material. The alternative to this, is the monitoring of exported material, as suggested in paper 3 (page 149). This is mainly a concern of developed countries, given developing countries (such as Brazil) only exports high value material to developed nations. The shipping to developing countries, however, incurs in an environmental problems due to the less demanding regulations generally found in these countries (in environmental terms) (Toffolet, 2016). Currently, the stakeholders in Australia claim they do monitor the exported material and some even claim to audit international partners that receive waste. In a recent report, however, the Basel Action Network (BAN) has tracked down e-waste arising from Australia using GPS systems. They have discarded the items in a government sanctioned consumer drop-off location (part of a NTCRS drop-off point) and found that some of discarded items ended up in landfill and two were tracked off-shore in developing countries (Hong Kong's New Territories and Thailand) (BAN, 2018). In Thailand, the device ended up in a primitive acid stripping operation – exactly the type of activity that is mentioned in the literature and that the regulations from developed countries try to avoid. The report estimates that the findings, if extrapolated, could represent as much as 16 thousand tons of illegal export (or illegal end-of-life destination) per annum. BAN has reported this kind of mismanagement in several countries besides Australia, the most recent reports include the U.S.A. and Canada. The investigations carried out by BAN over the years advocate against the monitoring alternative and favor the alternative of installing domestic downstream recycling industries. While placing GPS trackers every so often and applying fines to the exporter responsible for the waste may seem as an option, the pattern of export tends to continue worldwide because of the market forces in place (as shown in paper 3, page 149).

The high value material export pattern observed in both Brazil and Australia appears to be a new global trend. While these exports could be found to some extent in the last decade, it was only recently that it acquired this level of organization and maturity. The Brazilian companies that specialized in exporting material shown in the first paper (paper 1 and 2, page 89) are an example of this market organization. Perhaps there is a new e-waste transboundary movement pattern in place today, in which the developed countries still send the unwanted equipment to developing nations, but these nations (and any other nation with no downstream recycling industry) send back high value components to the downstream industry in developed countries. This, in turn, creates a novel material flow scenario, in which manufacturing countries export the EEE, developed countries export WEEE, developing countries export high value components from WEEE and countries with downstream industry export refined high end material (supplying it back to the EEE manufacturers). However, more studies are necessary to confirm this trend, especially in developing nations where data about e-waste movement is scarce.

6.2 Conclusions

Both Brazil and Australia share various similarities, including geographical size and comparable e-waste generated per purchasing power. They also possess a recent policy framework towards e-waste, but while both countries implemented the general guidelines about one decade ago, only Australia followed up on them and continued to set and organize the framework to collect and recycle e-waste. The country was able to make e-waste generators accountable for their waste and to have them finance the collection and recycling of certain items. This has diverted thousands of e-waste from landfills and established a countrywide collection system. On the other hand, Brazil was not able to follow up on its general guidelines, which left the collection and recycling of e-waste to the free market. This has created a scenario in which WEEE (the fraction that is collected) is dismantled and the most valuable components are later exported for downstream processing. Interestingly, the Australian scenario, despite its collection system, is the same: the country gathers the waste, dismantles it and exports the high value components abroad.

The major differences found in the systems include the collection and the wages paid to the e-waste recycling workforce, while the main similarity are the processes used in the recycling of e-waste. These differences and similarities are briefly described hereafter. In Australia, the National Scheme sets a collection target to agents that must organize the collection and may run it themselves or outsource it to either the e-waste recyclers or to third party logistic companies. The collection includes high density areas (metropolitan areas) and outer regional areas. Currently, all the four active agents must service all regions, including low density regions, where the cost of collection is an economic liability. In Brazil, due to the lack of enforcement of reverse logistics, the collection is regulated by free market. The recyclers are responsible for collecting the waste on their own. The result is that the collection system in Brazil is unorganized and inefficient, in spite of its 134 recyclers countrywide. Perhaps the biggest difference between Australia and Brazil are the wages paid to the WEEE labor force, the former being significantly higher than the Brazilian. This has important implications in the WEEE recycling cost, especially for the first stages of dismantling and sorting, which are mostly undertaken manually. If it were not for the regulations in place in Australia, free market would drive the first stages of recycling abroad or, as was the previous setup, allow e-waste to go to landfill with no/little processing - as this is a cheaper alternative. In Brazil, however, the low minimum wage in place creates a scenario in which free market dictates that first stage recycling will occur domestically. In regard to the processes used, Australia and Brazil currently have WEEE recyclers that undertake the initial recycling processes such as dismantling, manual sorting and shredding. Moreover, they both lack a downstream recycling industry capable of absorbing the complex commodity output generated from the first stage recyclers. This incurs in the export of commodities/components - originated in the e-waste dismantling - to be processed abroad. Nevertheless, the export of e-waste goods also contributes to maintaining the downstream recycling industry stagnant. Both countries would benefit from a downstream recycling industry for different reasons: Brazil because of its low wages, which allow the first stage recycling to occur without the need for regulations, and Australia because it has already set up regulations that made possible the collection and domestic first stage recycling of e-waste (two major costs of the whole recycling process).

In summary, the Brazilian scenario combines a cheap workforce and the lack of regulatory framework to manage and recycle e-waste. This incurs in a poor collection system, which favors metropolitan areas and disregards low population areas (*cherry picking* e-waste collection). This scenario also incurs in the establishment of a first stage recycling industry, given its main processes are associated with manual labor (dismantling and sorting) and that this is a profitable activity throughout the country. Finally, the setup contributes to another *cherry picking* situation after the dismantling of e-waste is complete: the components that can generate a profit are sold (either domestically or internationally) and the components that represent a liability may be landfilled or, in the worst case scenario, dumped illegally.

In the Australian scenario, there is a combination of expensive workforce and regulatory framework that contributes to the recovery of e-waste material to an extent. This scenario incurs in a comprehensive collection system financed by the companies responsible for placing EEE in the market. It also favors the first stage recycling industry to an extent, given the regulations require a minimum dismantling of the waste equipment prior to selling it internationally.

The primary conclusion is that in countries where labor is cheap, economic factors (free market) will drive the e-waste recycling to an extent, but political regulations are needed to ensure best collection practices and to avoid high value material export. On the other hand, in countries where labor is expensive, regulations need to be in place to ensure the first stages of recycling, otherwise free market will favor landfilling or exportation. Economic factors will drive international downstream recycling, while a political framework is necessary to establish a collection system and domestic downstream recycling, given these are generally non-profitable activities in the short term. The first stage recycling is dependent on the cost of labor of the country: in countries where labor is inexpensive, economic factors should drive domestic first stage recycling, in countries where labor is expensive, regulations need to be in place to ensure domestic first stage recycling.

6.3 Limitations of this work

The limitations associated with this research are described hereafter. Firstly, all three publications used at same stage survey measures, which has its own limitations. Alwin (2010) claims that “the basic purpose of the survey method is to obtain information from a sample of persons or households on matters relevant to researcher or agency objectives” and that “many aspects of the information gathering process may be sources of measurement error: the survey questions themselves; cognitive mechanisms of information processing and retrieval; the motivational context of the setting for data collection; and the response framework in which respondents transmit the information”. While the interviewees had a motivation to assist in the research and improve the recycling system in their country, the reliability of the information collected in each interview and questionnaire cannot be assured. In the case of the interviews, the perspective from each individual (and the organization they represented) were taken into account. Their point of view, however, is not neutral, as they are part of the e-waste market and have their own objectives and necessities. While this study took into account multiple points of view, they were all from only two stakeholders of the market: the recyclers and the co-regulatory arrangements. Furthermore, the statistical limitation (or statistical error) associated with the responses given (due to sample size) were calculated and presented in the published papers. In Brazil, the error calculated was 9.73%, in Australia, 6.89%.

Another important consideration of this work is the period limitation. The quantitative analysis presented in this thesis is valid only for the period comprised between the financial year of 2017-2018 and 2018-2019. This is due to the variation to which commodity market price, shipping cost, shipping routes, wages, electricity, fuel and machinery cost are subjected. They all vary with time and will give different outputs for a different period. Furthermore, e-waste also varies with time, and changes at a high speed. Not only there will soon be new arrivals concerning the equipment that will later become e-waste, but there will be changes in the materials that comprise the equipment currently on the market.

Finally, the legislation and treaties (national and international) concerning e-waste also vary with time and shall create different scenarios and constraints on a different given period.

The last important limitation of this thesis is the cost of e-waste collection. While the main collection channels were presented and discussed for both Brazil and Australia, the actual cost has been disregarded. The collection is one of the main costs associated with WEEE management (Toffolet, 2016). It is also a crucial step in waste management, given it dictates the overall recycling efficiency (Graedel and Reck, 2014; Hagelüken, 2012). Therefore, while the cost of collection may be disregarded when comparing two recyclers in the same situation (country, laws, distances), determining the cost of collection, its efficiency and the factors that may influence collection is important when studying the e-waste management of a given country.

6.4 Suggestion for future studies

The main suggestion for future studies is repeating the methodology used in paper 3 (page 149) in Brazil. This would determine the cost of recycling in the country and enhance the comparison between Australia and Brazil. Furthermore, it would highlight the importance of manual labor in the cost of first stage recycling in developing countries and the difference between countries with high wages versus countries with low wages.

Future studies can also determine, as mentioned in the last session (session 6.3), the cost of collection in Australia and assess its management and to what extent it can be replicated in other countries with large dimensions. Moreover, the discussions and findings of this thesis open space for studies that calculate the environmental burden associated with the shipping of e-waste to be processed abroad (first stage recycling) and evaluate the burden of waste generated during the process and sent to landfills. These materials would have traveled unnecessary distances to be placed in a landfill. In possession of this information, evaluate the benefit of having local downstream recyclers capable of processing complex e-waste. Finally, compare the benefit of local recycling to the impact this global setup would have in large scale downstream recyclers of the world, as this setup will probably make these recyclers less economically efficient due to the smaller overall volume they would receive.

Another important research that should follow this thesis is confirming whether the new global e-waste exchange pattern proposed is happening in the world. For this, the methodology applied in this thesis (or similar valid methodology) should be replicated in other countries worldwide, especially in developing countries. This may confirm the high value commodity export happening from developing countries to developed countries. These replications should increase the understanding of the e-waste management, the movement of material around the world and the global economic situation.

6.5 Contribution and implications

This work contributes to the e-waste management literature and practice concomitantly. Firstly, it assists researchers and academics to understand the current e-waste management scenario in Brazil and Australia, two countries about which little research can be found. This thesis provides a comprehensive insight regarding the agents involved in e-waste recycling in both countries, as well as information about the processes used, the legislations in place, the collection methods used, and the destination of components post dismantling. Future research can use the findings presented here as a foundation to their works. Moreover, these findings can be compared against future e-waste management findings to evaluate whether the *status quo* has shifted or if there has been any improvement concerning processes, collection, destination or legislation.

The results of the three published papers along with the discussion and comparisons made in this thesis can also serve as a foundation for institutions that aim to regulate the e-waste market and/or to assist organizations that promote sustainable development such as the United Nations. The debate over transboundary movement of e-waste from developed to developing nations is a serious and global issue that requires well-grounded studies to ensure humankind is following the right path to avoid and diminish health related problems, environmental damage and to improve resource efficiency.

This thesis also had (and has) an impact on the practical e-waste management in both studied countries, provided the interviews and visits resulted in an exchange of knowledge both ways. The recyclers and organizations that participated in the study had access to information that assisted them in improving their processes while respecting confidentiality agreements. All the companies that took part on the energy evaluation received an individual feedback relating their data and comparing their results to the overall results found (and presented) in the study. This assisted companies in benchmarking their processes and in understanding more about the system they are subjected to. Finally, the research comprised in this thesis has been shared with governments and non-governmental organization which claimed they would take into account the findings of this research to enhance and modify the system/regulations in place. In Australia, specifically, the NTCRS (national recycling scheme) is going through a scheduled review. Therefore, this research, could have a direct impact on this new WEEE management scheme, which, as pointed out in the published manuscripts, has great features that could be adopted by many other countries.

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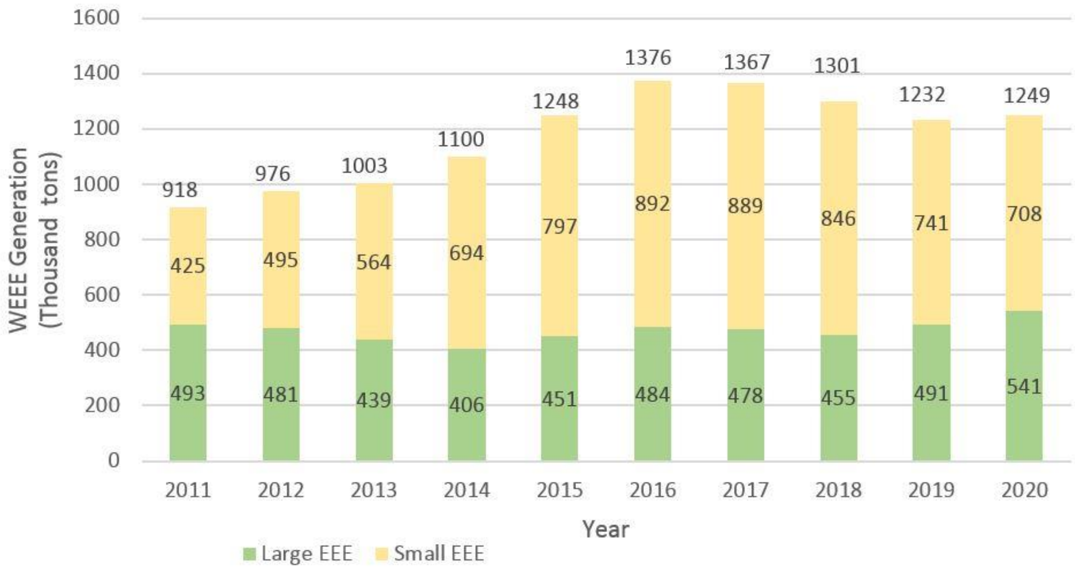
APENDIX A:

SUPPLEMENTARY DATA OF PAPER 1

Supplementary Figures:



Supplementary Figure A1: WEEE generation estimates in Brazil

Source: (ABDI, 2013)

Supplementary Tables:

Supplementary Table A1: Number of facilities in Brazil per state

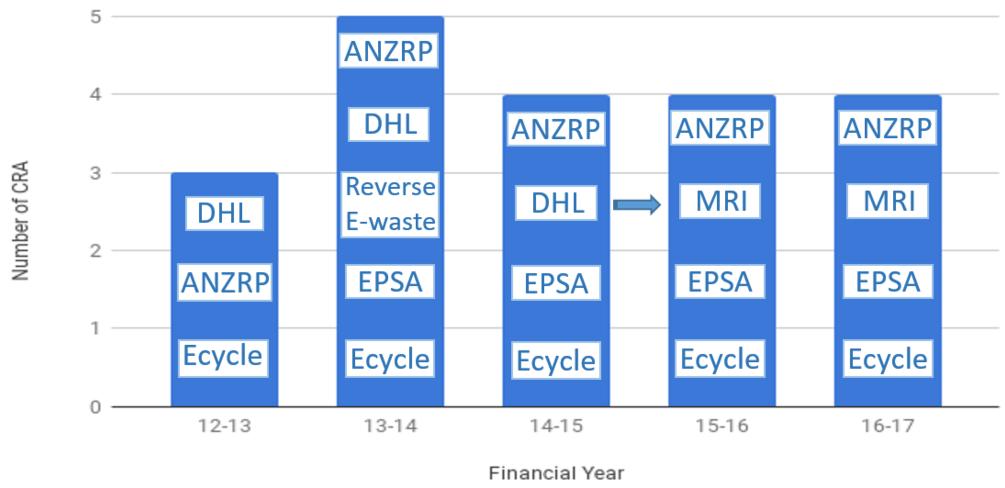
State	Region	Number of WEEE recycling facilities	Percentage	Density rank
Acre (AC)	North	0	0,0%	9°
Alagoas (AL)	Northeast	1	0,7%	8°
Amapá (AP)	North	0	0,0%	9°
Amazonas (AM)	North	1	0,7%	8°
Bahia (BA)	Northeast	5	3,7%	7°
Ceará (CE)	Northeast	1	0,7%	8°
Distrito Federal (DF)	Center-west	1	0,7%	8°
Espírito Santo (ES)	Southeast	1	0,7%	8°
Goiás (GO)	Center-west	5	3,7%	7°
Maranhão (MA)	Northeast	1	0,7%	8°
Mato Grosso (MT)	Center-west	1	0,7%	9°
Mato Grosso do Sul (MS)	Center-west	0	0,0%	8°
Minas Gerais (MG)	Southeast	7	5,2%	5°
Pará (PA)	North	0	0,0%	9°
Paraíba (PB)	Northeast	1	0,7%	8°
Paraná (PR)	South	16	11,9%	2°
Pernambuco (PE)	Northeast	0	0,0%	9°
Piauí (PI)	Northeast	1	0,7%	8°
Rio de Janeiro (RJ)	Southeast	9	6,7%	4°
Rio Grande do Norte (RN)	Northeast	1	0,7%	8°
Rio Grande do Sul (RS)	South	11	8,2%	3°
Rondônia (RO)	North	1	0,7%	8°
Roraima (RR)	North	0	0,0%	9°
Santa Catarina (SC)	South	8	6,0%	6°
São Paulo (SP)	Southeast	61	45,5%	1°
Sergipe (SE)	Northeast	0	0,0%	9°

Tocantins (TO)	North	1	0,7%	8°

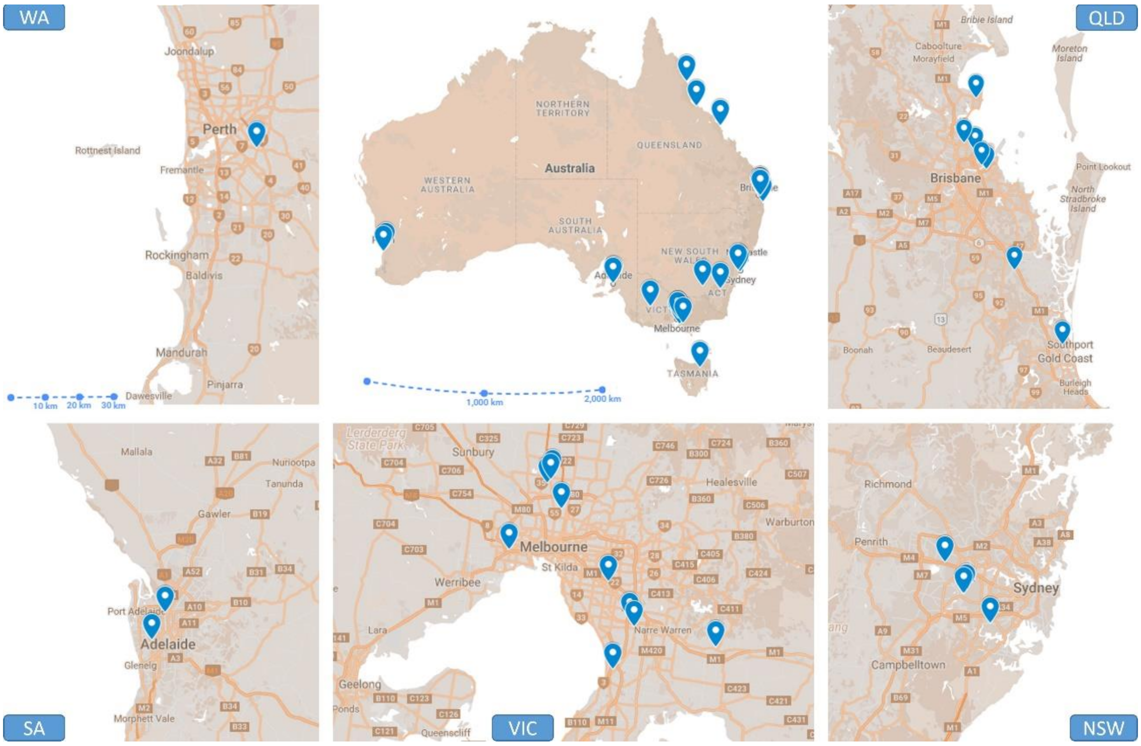
APENDIX B:

SUPPLEMENTARY DATA OF PAPER 2

Supplementary Figures:



Supplementary Figure B1: Number of CRA since the commencement of the NTCRS. Note: MRI-PSO took over DHL supply chain from FY 14-15 to 15-16



Supplementary Figure B2: Distribution of WEEE recyclers under the NTCRS in Australia. The scale provided in WA (left of the figure) is valid for all maps with the exception of the map of the country.

Supplementary Tables:

Supplementary Table B1: Questions included in the survey and in the interviews

Question	Type of response	Options
What is the size of your company? (number of employees and average of e-waste recycled monthly/yearly)	Free answer	-
Is the facility currently at full capacity? (i.e. The facility cannot take more waste to process at this stage)	Tick-box	Yes
		No
How do you collect WEEE? How does your company receive WEEE? Please check all that apply	Tick-box	Hand pickers
		Partnership with City Councils/Government
		Direct handover (consumer - company)
		Partnership with other companies (company - company)
		Delivery centers (or collection centers)
		Collection Fairs/Events
		Private collection service
Which machinery/equipment are used in your company? Please check all that apply	Tick-box	Electric screwdriver/Pneumatic screwdriver
		Fork-lift
		Circular saw

		Bench drill
		Shredder
		Balers (bale press)
		Magnetic conveyor
		Air Chisel
		BluBox™
		Other manual tools (screwdriver, wore cutters, socket sets, pliers, etc)
The company undertakes which of these processes? Please check all that apply	Tick-box	Manual dismantling
		Automated dismantling
		Manual sorting
		Automated sorting (sorting by color, weight, material)
		Grinding (Shredding)
		Sieving (size by particle size)
		Eddy current separation
		Magnetic separation
		Density separation
		Smelting
		Leaching (hydrometallurgy)
		Electrowining
What is the destination of the separate components?	Tick-box	Disposal in household waste
		Internal stocking

		Hazardous waste landfill
		Export
		Sale for partner recycler
Which changes did you notice after the NTCRS was implemented?[a]	Free answer	-
What is working in regard to the NTCRS? What should be improved?[a]	Free answer	-
Should the scheme be broadened to include other WEEE?[a]	Free answer	-
Do you export any materials? Which? Where to?[a]	Free answer	-

[a] Questions asked only in interviews, not on the online questionnaire.

Supplementary Table B2: List of materials recycled in Australia within the NTCRS (first stage recycling).

Component	Material(s)
Memory	Precious metals, copper
Processor	
Heat sinks	Aluminum
Copper wires	Copper
Cables	Polymer, copper
Fans/Coolers	Steel
Printed circuit boards	Precious metals (gold, platinum, silver, or palladium), copper
HDD	Steel, aluminum, neodymium, praseodymium, precious metals
Bolts	Steel
Speakers	Steel
CD/DVD Driver	Steel
External frame	Steel or polymer (usually ABS)
Power supply	Steel, copper, aluminum

Phosphorous powder	Phosphorous
Eyelets	Steel
Speakers	Steel
CRT tips	Nickel
Leaded glass	Glass
Unleaded glass	Glass
Yokes	Copper, steel
Flat screen display	Polymers
Inside frames	Steel
Flat screen lamps	Mercury
Batteries	*Depends on type of battery*

Supplementary Table B3: List of co-regulatory arrangements active in 2017.

Co-regulatory arrangement	Also known as	Comment
Australia & New Zealand Recycling Platform Limited (ANZRP)	Tech Collect	Tech Collect is the public facing program responsible for collecting e-waste for ANZRP
MRI PSO Proprietary Limited	MRI e-cycle solutions	MRI PSO is the product stewardship arm for MRI e-cycle solutions, which is a recycling service company dedicated to WEEE
	Drop Zone	Drop Zone is the public facing program responsible for collecting e-waste for MRI PSO
E-Cycle Solutions Proprietary Limited	QLS Group	E-Cycle Solutions is the product stewardship arm for the QLS Group, which is an Australian warehousing and logistics company
Electronics Product Stewardship Australasia (EPSA)	Sims Recycling Solutions or Sims E-Recycling Proprietary Limited	EPSA is the product stewardship arm for E-Recycling Proprietary Limited, which is the e-waste recycling arm of the metals recycler company Sims Metal Management Limited

APENDIX C:

BIBLIOGRAPHY SUMMARY TABLE

Supplementary Table C1: Summary of studies on Brazil and their main findings

Author	Title	Year	Main findings
Oliveira et al.	Collection and recycling of electronic scrap: A worldwide overview and comparison with the Brazilian situation	2012	No Latin American countries have a comprehensive e-waste management system; In Brazil, despite the existence of WEEE collection programs promoted by EEE manufacturers, most of the population does not know about them because there is not enough advertisement; In Brazil, with the exception of Sao Paulo, there is no specific national legislation governing the treatment of WEEE; Few companies specialize in recycling EEE, and the complete recycling of WEEE does not occur; PCBs are crushed and exported to countries such as Canada, Belgium and Singapore;
Araujo et al.	A model for estimation of potential generation of waste electrical and electronic equipment in Brazil	2012	The most important variable when determining WEEE generation is the product lifetime, which demands a comprehensive understanding of consumer behavior and the factors that affect the disposal decision (technological innovation, availability, cost of maintenance, etc.); The average lifetime chosen for mature market products of the model could be used for a total estimation for the country, but for specific regions or social strata, a different lifetime should be used; The penetration of devices in households varies for the different regions in Brazil. The same is likely true for the lifetime; The average generation per capita in 2008 was estimated to be 3.8 kg (considering TVs, fridges, freezers, washing machines, audio systems, computers and cellphones).
Araujo et al.	Cost Assessment and Benefits of Using RFID in Reverse Logistics of	2015	WEEE management in Brazil does not benefit from economies of scale and is very dependent on regulatory instruments; Implementation of radio frequency identification in WEEE could increase the control of potentially polluting activities and promote high-performance administrative structures for WEEE reverse logistics. However, there is a

	Waste Electrical & Electronic Equipment (WEEE)		lack of incentive to implement such technology and the management cost would rise for producers;
Guarnieri & Streit	Implications for waste pickers of Distrito Federal, Brazil arising from the obligation of reverse logistics by the National Policy of Solid Waste	2015	Few interviewed leaders seem to understand what it is the reverse logistics process and their role in this process; The inclusion of waste pickers in reverse logistics can lead to the increase in work safety, the reduction of the risk of disease and the creation of centers to segregate waste, but can also lead to the closure of landfills and to uncertainty concerning the decisions of local government; A reverse logistics obligation in the National Policy of Solid Waste could lead to better conditions of material collected, financial gains, better conditions of work, partnerships with private companies, but will not improve the knowledge of the workers, their visibility as a category, their recognition and respect from society.
Echegaray	Consumers' reactions to product obsolescence in emerging markets: the case of Brazil	2016	25% of computer owners and 20% of mobile phone and washing-machine owners have experienced problems with the functioning of their current devices; Pro-sustainability policy and grassroots actions would be wise to spotlight the issue of product longevity; 66% of Brazilians respondents feel product lifespan falls short of what they deem to be reasonable; 98.3% of the questioned Brazilians agreed they would do whatever they could to extend their appliances' lifespan; 85.9% express willingness to fix technical failures in devices; 60.5% prefer a reusable, non-disposable device over disposable ones; 41.9% disagrees with the idea that it is important to update their devices each year.
Bouzon et al.	Identification and analysis of reverse logistics barriers using fuzzy Delphi method and AHP	2016	The barriers in the implementation of reverse logistics for developed countries are different from the ones for developing countries; Especially in developing countries such as Brazil, there is a lack of skilled workers to perform reverse logistics activities; The misuse of environmental regulations and the lack of motivational laws are barriers in the implementation of reverse logistics in Brazil; Brazilian

			regulations have just started to include tax reductions for recycled materials or remanufactured products; Customers might think that remanufactured products or the use of recycled material results in lower quality standards; The financial burden of tax and the uncertainty related to economic issues appear to be major obstacles for reverse logistics implementation in the country.
de Souza et al.	Sustainability assessment and prioritisation of e-waste management options in Brazil	2016	WEEE collection and transport activities had little contribution to environmental impacts, in comparison to the recycling and treatment processes; The collection scheme with WEEE delivery only at EEE shops is environmentally better than the hybrid scheme with metro and neighborhood stations; Optimum result can be obtained using a hybrid WEEE collection system with delivery points (in EEE shops, metro stations and neighborhood centers), a pre-treatment phase (involving private companies, cooperatives and social enterprises), and full recycling of all components in the country.
Caiado et al.	A characterization of the Brazilian market of reverse logistic credits (RLC) and an analogy with the existing carbon credit market	2017	The paper reveals the uncertainty concerning the implementation of reverse logistics credits (RLC) in Brazil and discusses the reasons for it; RLC could act as a facilitator instrument and its benefits would be mostly social and economic, rather than environmental; The implementation, however, was not deemed feasible at the time of the study.
Moura et al.	Relation of Brazilian institutional users and technical assistances with electronics and	2017	The most common disposal reasons are related to equipment speed and hardware; The informal WEEE recycling market increased in Brazil; Users perceived a decrease in equipment useful life;

	their waste: What has changed?		
Echegaray & Hansstein	Assessing the intention-behavior gap in electronic waste recycling: the case of Brazil	2017	Most respondents hold a positive intention toward recycling WEEE; The intention toward recycling is related to social acceptance and positive views of recycling; Only a minority of respondents adopts adequate WEEE recycling practices; Respondents with a higher income are more likely to adequately dispose of WEEE.
de Oliveira Neto et al.	Economic and environmental assessment of recycling and reuse of electronic waste: Multiple case studies in Brazil and Switzerland	2017	WEEE reverse logistics for recycling and reuse resulted in reduction of the environmental impact in the abiotic, biotic, water and air compartments and economic gains for the manufactures and recyclers; The main barrier for adopting WEEE reverse logistics by manufacturers and recyclers is the lack of technology for PCB recycling and reuse; The main recycling activity in Brazil related to WEEE is that of polymers; The recycling process is decentralized in the country as waste like PCB, glass, and metals are sold to partner businesses; Simple recycling processes are used in the country mainly because PCB recycling requires a high investment by businesses;
Ghisolfi et al.	System dynamics applied to closed loop supply chains of desktops and laptops in Brazil: A perspective for social inclusion of waste pickers	2017	The study proposes a closed loop supply chain with the inclusion of waste pickers in the formal WEEE reverse logistics; Waste pickers need to increase their bargaining power by working with a varied portfolio of WEEE or by joining cooperative networks; Legal incentives are essential to integrate waste pickers to the formal process of waste recovery, but are not sufficient alone.

Supplementary Table C2: Summary of studies on Australia and their main findings

Author	Title	Year	Main findings
Davis & Herat	Electronic waste: The local government perspective in Queensland, Australia	2008	Limited audit data relating to the composition of general wastes (including e-wastes) within the domestic waste stream exists; There is a knowledge gap concerning WEEE across Local councils within Queensland, where there is also overwhelming support for the introduction of legislation to manage WEEE; There is an urgent need for more information and overall increase in the levels of awareness, both by policy makers and public.
Davis & Herat	Opportunities and constraints for developing a sustainable E-waste management system at local government level in Australia	2010	There are few facilities in Australia that can process e-waste making it difficult for those who live far away from these facilities and reinforcing the need for research in rural areas; There is insufficient data in terms of composition and extensions of issues to determine the full costs correlated with the e-waste management; Australia needs to control the influx of new unbranded electronic equipment to the market and reinforce regulations and other control measures for local producers; The survey also emphasized the need for legislative measures to manage e-waste with particular support for the introduction of a suitable funding mechanism and a consumer education program.

Lane	Understanding the Dynamic Character of Value in Recycling Metals from Australia	2014	While some sorting and reprocessing takes place in Australia, most of the NTCRS processes involving extraction of rare earth metals take place in factories in Singapore or Hong Kong in compliance with specified certification standards; Public support for materials recycling can increase government willingness to invest in waste collection and sorting facilities; The charity sector often extended product lifespans by donating unwanted goods to the needy; Australia lacks manufacturing expertise and infrastructure for reprocessing used products and materials; Australia lacks knowledge of the (i) size and characteristics of the potential resource, (ii) who are the actors and organizations that accumulate these materials and their current practices around disposal, (iii) which are the existing collection systems and how they work, and (iv) formal and informal institutional frameworks; Australia lacks the manufacturing expertise and infrastructure for reprocessing used products and materials;
Lane et al.	Mapping, Characterising and Evaluating Collection Systems and Organisations	2015	There are legitimate concerns about free riders and unauthorized export flows for product reuse overseas, which highlight the need for accurate modellings to better quantify e-waste stocks and flows; The e-waste "recyclers" in Australia are usually responsible for the collection and basic separation of the collected waste; Higher levels of material recovery can mean less domestic separation and recovery because overseas exports for reuse or recovery result in residual waste (after material recovery) being disposed of in unregulated circumstances overseas; There is a clear need for additional standards to regulate how unprocessed waste exported under the NTCRS is dealt with overseas; The incentive of capturing market value alone is not enough to motivate the entire commodity chain; The NTCRS ensured a level of disassembly takes place in Australia prior to export;

Corder et al.	"Wealth from metal waste": Translating global knowledge on industrial ecology to metals recycling in Australia	2015	The estimated potential for wealth from (metal) waste in Australia is of the order of 2 billion AUD per year, consisted of the value lost with landfilled metals and lost opportunities in domestic processing of collected metal scrap; Half the scrap metal collected in Australia is currently being transported overseas which potentially could be recycled in Australia if suitable technology were available; Australia's unique geographic location as a continent, long distances between major cities and industrial centers in regional areas, presents challenges from a metals recycling perspective;
Morris & Metternicht,	Assessing effectiveness of WEEE management policy in Australia	2016	Although successful in increasing the amount of WEEE recycled, major flaws were identified in the NTCRS; The Australian NTCRS lacks auditing compliance and reporting measures in all stages of the system; Councils suggest increasing the scheme's scope of WEEE categories, increasing the funding and increasing annual quotas as ways to improve the NTCRS; Ineffectiveness of the scheme is associated with five key issues: stakeholder roles, scope of WEEE categories legislated, public engagement and accessibility to services, recycling and material recovery targets and the auditing and compliance of material flows within the system, Local governments' effort appear to be directly related with the total amount of WEEE collected.
Golev et al.	Where next on e-waste in Australia?	2016	It is apparent that the environmental impacts and health hazards from WEEE can be mostly attributed to informal and improper metal recovery; The existing waste collection systems in Australia and other developed countries often fail to allow feasible material recovery within the domestic boarders, resulting in collected WEEE being exported to countries with less stringent regulation; In 2014, Australians purchased per person an average of 35 kg of EEE, disposed of 25 kg of WEEE, and possessed about 320 kg of EEE; The potential metal recovery value from PCBs in Australia has been estimated to peak in 2017;

			Efficient small scale recycling and stockpiling WEEE in properly conditioned landfills are possible solutions to the WEEE problem in the country.
Gumley	Using Environmental Taxation to Improve Outcomes for E-Waste in Australia, Critical Issues in Environmental Taxation	2016	The recycling task is commonly carried out by a wide range of sub-contractors, and much of the recovered material is then exported for re-processing overseas, where little further scrutiny is possible; There is clearly a need for better monitoring of e-waste that is exported, including quantitative information on the degree, location and type of processing and recovery; The NTCRS has appropriated much of the e-waste previously directed to the not-for-profit sector, and thereby increased the flow of used electronics that are dismantled and/or exported rather than re-used as second-hand products in Australia; The NTCRS lacks transparency concerning liable parties and local government spending; The NTCRS fails to impose individual responsibility upon manufacturers of electronic products for the ultimate life cycle impacts of all of their products; Taxation could be used to improve the e-waste management on a local level;
Golev & Corder	Quantifying metal values in e-waste in Australia: The value chain perspective	2017	Out of 65% of collected e-waste, about a quarter is further lost in recovery operations; The total estimated recovered materials accounts for about 48% of arising e-waste; The total economic losses across the metal value chain are assessed at about 170 million USD per year, which includes missed opportunities for domestic processing versus exporting metal scrap.
Lodhia et al.	Extended Producer Responsibility for waste televisions and computers: A regulatory evaluation of the Australian experience	2017	The NTCRS costs the industry about 364–437 AUD per ton of waste; Substantial volumes of WEEE are exported for downstream processing; Results suggest that exporting waste for downstream processing will continue in the future; The reasonable access provision can be met from the current collection networks; The meeting of recycling targets and optimizing collection costs tend to mediate the numbers of collections and recycling outcomes; It is important that NTCRS' regulations establish upstream and

downstream material recovery rate benchmarks, with further delineation between domestic and exported downstream recycling; The NTCRS' 37% upstream recovered materials export rate provides a positive comparative benchmark for WEEE export performance; Domestic downstream recycling lacks appropriate infrastructure to cope with growing volumes of upstream processed waste; The NTCRS is in the public interest.