ASSESSMENT OF A REVERSE LOGISTICS FRAMEWORK FOR WASTE PRINTED CIRCUIT BOARDS (WPCB) IN BRAZIL

.

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Dissertação de Mestrado apresentada ao Programa de Planejamento Energético, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Mestre em Planejamento Energético.

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“To see the world,
things dangerous to come to,
to see behind the walls, draw closer,
to find each other and to feel.
That is the purpose of life”.

-The Secret Life of Walter Mitty

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AVALIAÇÃO DE UM MODELO DE LOGÍSTICA REVERSA PARA RESÍDUOS DE PLACAS DE CIRCUITO IMPRESSO (WPCB) NO BRASIL

Marianna de Souza Oliveira Ottoni

Outubro/2021

Orientadores: Amaro Olimpio Pereira Junior

Lúcia Helena da Silva Maciel Xavier

Programa: Planejamento Energético

Os resíduos de equipamentos eletroeletrônicos (*e-waste*) possuem alto valor de mercado concentrado nas placas de circuito impresso (PCB, do inglês). No Brasil, a ausência de unidades de processamento industrial para recuperação de elementos de valor das PCB acarreta na exportação de grande parte desses resíduos, gerando perda de valor para o país e impactos ambientais. Nesse contexto, a presente dissertação visa quantificar esses impactos em termos econômicos, de emissões e energia demandada e propor um modelo logístico alternativo para possibilitar a recuperação de valor dos resíduos de PCB no Brasil. Para tal, o cenário base (exportação da fração formal de PCB residuais) e o cenário alternativo (instalação de unidades de processamento desses materiais no país) foram comparados com o suporte de ferramentas de geoprocessamento. Os principais resultados apontaram para as cidades de São Paulo, Salvador e Manaus como potenciais polos de processamento de PCB residuais. Ademais, as emissões, energia demandada e custos no cenário de base superam em 7,2, 31,9 e 4,5 vezes o cenário alternativo, respectivamente. A simulação indicou receitas do processamento de PCB residuais 24,7 vezes superiores aos custos totais no cenário alternativo, possibilitando cerca de 93.590 empregos para o país. Portanto, este estudo ressaltou que o processamento de PCB residuais no Brasil é mais vantajoso em termos econômicos, de emissões e energia demandada do que exportar esses materiais com alto valor agregado para recicladoras estrangeiras, o que se configura como uma possível tendência para os avanços na logística reversa de resíduos eletroeletrônicos no país.

Abstract of Dissertation presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

ASSESSMENT OF A REVERSE LOGISTICS FRAMEWORK FOR WASTE PRINTED CIRCUIT BOARDS (WPCB) IN BRAZIL

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Waste electrical and electronic equipment (e-waste) has a high market value concentrated in waste printed circuit boards (WPCB). In Brazil, the absence of industrial processing units to recover valuable elements from WPCBs leads to the export of a large part of this waste, generating a loss of value for the country and environmental impacts. In this context, this thesis aims to quantify these impacts in economic terms, emissions and demanded energy and propose an alternative reverse logistics model to enable the recovery of value from WPCB in Brazil. The baseline scenario (export of the formal fraction of WPCBs) and the alternative scenario (installation of processing units for these materials in the country) were compared with the support of geoprocessing tools. The main results pointed to the cities of São Paulo, Salvador and Manaus as potential clusters for WPCBs recycling. Furthermore, emissions, demand energy and costs in the baseline scenario exceeded by 7.2, 31.9 and 4.5 times the alternative scenario, respectively. The simulation indicated that the revenues from processing WPCBs were 24.7 times higher than the total costs in the alternative scenario, enabling around 93,590 jobs for the country. Therefore, this study highlighted that the WPCB processing in Brazil is more advantageous under economic and environmental perspectives than exporting these high added value materials to foreign recyclers, which might be a possible trend for advances in the e-waste reverse logistics in the country.

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LIST OF ABBREVIATIONS

ABNT - Brazilian Association of Technical Standards

ABREE - Brazilian Association for Recycling of Electronics and Household Appliances

ABS - Acrylonitrile butadiene styrene

ABS - Acrylonitrile butadiene styrene

AM – Amazonas state

AR - Action Research

BA – Bahia state

BBP - Butyl benzyl phthalate

BFR - Brominated flame retardants

BM - Base metals

BMO - Base metals operation

Bo2W- Best of 2 Worlds

BPSW - Brazilian Policy on Solid Waste

BRL – Brazilian coin

CE - Circular Economy

CETEM - Center of Mineral Technology

CFC - Chlorofluorocarbon

CNPJ - Brazilian legal person register

CONAMA - Brazilian National Council for the Environment

CRT - Cathode Ray Tube

DBP - Dibutyl phthalate

DEHP - Bis(2-Ethylhexyl) phthalate

DIBP - Diisobutyl phthalate

EC - Electronic components

EEE - Electrical or electronic equipment

EU - European Union

EWMS - E-waste management system

FRs - Flame retardants

GDP - Gross domestic product

GHG - Greenhouse gas

GIS - Geographic Information System

GO - Goias state

GPS - Global Positioning System

GWP - Global Warming Potential

HFO - Heavy Fuel Oil

HIPS - High Impact Polystyrene

HM - Hazardous metals

IE - Industrial Ecology

IT - Information technology

LCD - Liquid Crystal Screen

LED - Lighting emission diode

MA – Maranhão state

MCDA - Multicriteria Decision Analysis

MF - Metal fractions

MHDI - Municipal Human Development Index

NBR - Brazilian standard

NDC - Nationally Determined Contribution

NMF - Non-metal fractions

NSES - National Strategy for Electronics Stewardship

NTCRS - National Television and Computer Recycling Scheme

PA - Pará state

PAHs - Polycyclic aromatic hydrocarbons

PBB - Polybrominated biphenyls

PBDD/Fs - Polybrominated dibenzo-p-dioxins and dibenzofurans

PBDE - Polybrominated diphenyl ethers

PC - Personal computer

PCB - Printed circuit board

PCBs - polychlorinated biphenyls

PCDD/Fs - Polychlorinated dibenzo-p-dioxins and dibenzofurans)

PE - Pernambuco

PI – Piauí state

PM - Precious metals

PM - Precious metals

PMG - Platinum group metals

PMO - Precious metals operation

PoM - Put on market

PP - Polypropylene

PVC - Polyvinyl chloride

PWB - Printed wiring board

PXDD/Fs - mixed polybromochloro-dibenzo-p-dioxins and dibenzofurans

RFID - Radio Frequency Identification

RLC - Reverse logistics credits

RLS - Reverse logistics systems

RO - Retention option

RoHS - Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment

RS - Rio Grande do Sul state

SD - Sustainable Development

SDG - Sustainable Development Goals

SM - Scarce metals

SODA - Strategic Options Development Analysis

SP - São Paulo state

StEP - Solving the E-waste Problem

TSL - Top submerged lanced

UM - Urban Mining

UNEP - United Nations Environment Programme

UNSD - United Nations Statistics Division

UNU - United Nations University

UNU-IAS SCYCLE - Institute for the Advanced Study of Sustainability at UNU's

USA - United States of America

USD – American dollars

VDP - Voluntary delivery points

WPCB - Waste printed circuit board

WRU - WPCB recycling unit

WRU - WPCB recycling units

ZFM - Free Economic Zone of Manaus

1. INTRODUCTION

Waste electrical and electronic equipment (WEEE or e-waste) is the fastest-growing type of waste and represents the most hazardous streams worldwide (PETRIDIS, PETRIDIS, et al., 2020). This growth results from several trends, including the accelerated number of information technologies users and the progressive obsolescence of these electronic devices (XAVIER, LINS, 2018). Despite being composed of hazardous elements, the e-waste also contains strategic and critical raw materials, and, therefore, this waste emerges as an important supply of secondary resources (MARRA, CESARO, et al., 2018). Thus, the e-waste needs to be adequately processed to be used as a source of raw materials, to mitigate the mining impacts from virgin mines and to avoid the negative effects on the environment and human health of the inadequately disposed of e-waste (AWASTHI, LI, 2017).

Only about 17.4% of the e-waste amount generated worldwide was collected and recycled in 2019 (FORTI, BALDÉ, *et al.*, 2020). While the developed countries have a well-established system for e-waste collection and automatic processing technology, the developing countries have a significant contingent of collectors (or waste pickers) who begin to understand the value of technological waste and have not yet realized the risks involved in handling these products (XAVIER, LINS, 2018). Among these countries, Brazil can be highlighted as the greatest e-waste generation in Latin America, with 2,1 Mt in 2019 (FORTI, V, BALDÉ, *et al.*, 2020). Considering such quantities, Brazil is one of the biggest e-waste "mines" in the world, and, therefore, the electronics reverse supply chain has become a growing business in the country (SOUZA, Ricardo Gabbay, 2019).

The electronic industry is considered as one of the most polluting, especially due to the hazardous components and manufacturing processes, the material extraction from ores and energy requirements for production, use, and the reverse chain, besides the shortening of the lifespan of such products (DARBY, OBARA, 2005). E-waste is, then, a complex mixture composed of ferrous, nonferrous, plastic and ceramic materials (KHALIQ, RHAMDHANI, *et al.*, 2014). The main concerns about e-waste are related to its hazardous potential since these devices are often composed of toxic metals and other substances, such as Brominated flame retardants (BFR) (KAYA, 2020a), which might generate environmental impacts, besides health diseases to individuals when exposed to such inadequately disposed or handled e-waste (ILANKOON, GHORBANI, *et al.*, 2018, KIDDEE, NAIDU, *et al.*, 2013).

On the other hand, a large portion of e-waste contains precious metals (PM) that are especially concentrated in the printed circuit boards (PCB), found in practically all electrical and electronic devices (CANAL MARQUES, CABRERA, *et al.*, 2013). The PCB are laminated boards with circuit traces and connected to electrical components, which are usually composed of high added value elements, such as Au, Cu, Pd, Ag, among others (AWASTHI, ZENG, 2019). PM and strategic minerals account for about 80% of the e-waste intrinsic value, even though they do correspond to less than 1% of the total equipment weight (XAVIER, GIESE, *et al.*, 2019). The value of PM in waste PCB (WPCB) makes it more profitable to mine from e-waste than in mining ores (AWASTHI, ZENG, 2019), which emphasizes the economic and environmental importance of recycling.

In the Brazilian case, even though most e-waste components can be recycled, there is no large-scale technology installed to recover valuable metals from WPCB in the country (SOUZA, Ricardo Gabbay, 2019). As a result, the formal WPCB streams end up being exported to large plants overseas (mainly in Europe), thus transferring to other countries the highest aggregated value generated in the segment (DEMAJOROVIC, AUGUSTO, *et al.*, 2016). The literature points to the need for developing feasible technology for the recycling of a wider range of e-waste components, especially PCBs, in Brazil (SOUZA, Ricardo Gabbay, 2019). The recycling and other value recovery options contribute to reducing dependency on a permanent supply of essential resources, encouraging recycling companies, and minimizing environmental contamination derived from inadequate e-waste disposal (XAVIER, GIESE, *et al.*, 2019).

This responsibility becomes even more important when considering the climate changes and the goals for reducing greenhouse gas (GHG) emissions, especially CO2. The decarbonization of human activities is necessary to achieve the long-term goal of the COP21 climate change agreement in Paris: to keep the increase of the global average temperature to 1.5 °C maximum compared to pre-industrial levels by the end of the century (ZIS, PSARAFTIS, *et al.*, 2020). The current production, consumption and business models need to be completely rethought (XAVIER, GIESE, *et al.*, 2019) to align with the changes towards more circular, sustainable and carbon-neutral patterns, especially for sectors that generate high impacts, as the case of electronics.

Brazil has committed to the Climate Convention, with the presentation of the Nationally Determined Contribution (NDC) of the Paris Agreement, ratified by Brazil on September 12, 2016. The Federal Government has been articulating with the relevant actors the effective mitigation and adaptation to climate change through the implementation, improvement and revision of existing instruments (BRAZIL, 2016) to meet the challenge of reducing 37% of GHG emissions, i.e., achieving a limit of 1.76 GtCO2e (OBSERVATÓRIO DO CLIMA, 2020) for the Brazilian economy by 2025 when compared to the level of emissions in 2005 based on the Second National Inventory. In Brazil, the third-largest driver of GHG emissions, after deforestation and agriculture, are energy-related CO2 emissions from fuel combustion, and the transport sector is the largest contributor, with 47% of the share, followed by the industrial sector, with 27% (CLIMATE TRANSPARENCY, 2020).

The growing amounts of electronic devices will make it increasingly difficult to achieve the 2030 Sustainable Development Goals (SDGs), especially the SDGs related to environmental protection and public health safety (AWASTHI, LI, 2019). The study of FORTI, BALDÉ, *et al.* (2020) emphasized that e-waste management is closely related to many of the 17 SDGs, such as SDG 3 on good health and well-being, SDG 6 on clean waste and sanitation, SDG 8 on decent work and economic growth, SGD 12 on responsible production and consumption, SDG 13 on climate action, and SDG 14 on life below water.

A higher focus can be given to the SDGs 8, 12 and 13 in the matter of e-waste management, especially when considering the discussion of new anthropic models towards sustainability and the global climate in the future. Issues regarding material footprint (SDGs 8.4.1 and 12.1.1), domestic material consumption (SDGs 8.4.2 and 12.2.2), e-waste hazardousness (SDG 12.4.2), recycling rates in the countries (SDG 12.5.1), and the establishment of strategies to foster low GHG emissions development (SDG 13.2.1) can be monitored by their respective indicators and represent the boundaries between e-waste management and sustainable development. Both concepts can be aligned with the principles of the Circular Economy (CE), which engage businesses in sustainability urgencies, and, thus, CE may encourage the achievement of the SDG (XAVIER, GIESE, *et al.*, 2019).

Therefore, considering the attempt to implement low carbon patterns for the electronics segment, an analysis of the possibility of setting up recycling (or processing) plants to recover the strategic materials from e-waste (and, thus, reducing mining impacts) is of interest not only for Brazil but for neighbouring countries in Latin America, which, likewise, export this high value-added portion of their e-waste to refineries in developed countries. However, the maintenance of these large plants requires a guarantee of minimum waste volumes to justify the energy expenditure required by the recycling processes. In this regard, the adoption of such processing plants emphasizes the need for an efficient reverse logistics system in Brazil, which implies costs, given the country's territorial extension. Thus, the relevance of adopting WPCB value recovery through recycling processes in Brazil is reflected not only in the search for more environmentally adequate standards but also for more economic gains and social opportunities derived from a more circular e-waste management.

1.1 Objectives

This study aims at proposing a reverse logistics framework for promoting the value recovery of waste printed circuit boards (WPCB) in Brazil and assessing this model according to economic and environmental criteria when compared to the current scenario. For these purposes, a scenario analysis was developed with the support of geoprocessing tools and sustainability criteria for spatial and logistical analysis.

The specific objectives include:

- To indicate the main e-waste potential value recovery clusters to perform WPCB processing;
- To calculate the potential revenue, costs, emissions and demanded energy derived from the proposed framework (alternative scenario) for WPCB value recovery and compare it to the current status (baseline scenario);

At the end of this study, the answers for the following questions should be closer to a clarification:

- Where should be located the most strategic sites for the WPCB processing clusters in Brazil?
- Would processing WPCB in Brazil be more advantageous in terms of economics, emissions and energy than exporting these materials to foreign recycling industries?

1.2 Structure

This study is divided into five chapters. **Chapter 1** has described the context of the main problems and motivations for this study, besides the general and specific objectives and research questions.

Chapter 2 briefly addresses the main concepts for adequate e-waste management and value recovery, including notions of the Circular Economy approach and sustainable systems. This chapter also discusses topics related to e-waste and WPCB, considering definitions, types, composition, management stages, international and Brazilian legislations, as well as challenges, opportunities and main gaps in the related literature.

Chapter 3 presents the methodology, data and tools explored in this study. Details on the spatial analysis for identifying the current status of Brazilian e-waste generation, the criteria for siting the WPCB recycling units (WRU) in Brazil and the steps for the scenarios' comparative analysis were discussed.

Chapter 4 discusses the main results, including the spatial analysis of the Brazilian current scenario in terms of WPCB generation estimates, potential costs, emissions and demanded energy in the reverse logistics directed to the exportation of the WPCB formal fractions. Also, this chapter indicates the potentially most adequate WRU's locations in Brazil, followed by the calculation of the revenues, costs, emissions, and demanded energy in a scenario of WPCB value recovery in the country. The results of both scenarios were compared.

Finally, **Chapter 5** highlights the main conclusions and findings of this research, including the innovations, limitations, recommendations and proposition of future related studies.

2 LITERATURE REVIEW[1]

2.1 Sustainability and circularity in the anthropic systems

Sustainable systems are those that remain permanent along the time, considering the rates of natural resources usage equal to or smaller than the rates at which the resources are regenerated (FREEDMAN, 1998). The understanding of nature's mechanisms to survive in the long-term might indicate reasonable strategies for the anthropic models to become less destructive not only to the environment but also, consequently, for humanity itself. A circular economic system is a prerequisite for the maintenance of the sustainability of human life on Earth and demands that the economy and the environment have a circular relationship where everything is input into everything else (BOULDING, 1966).

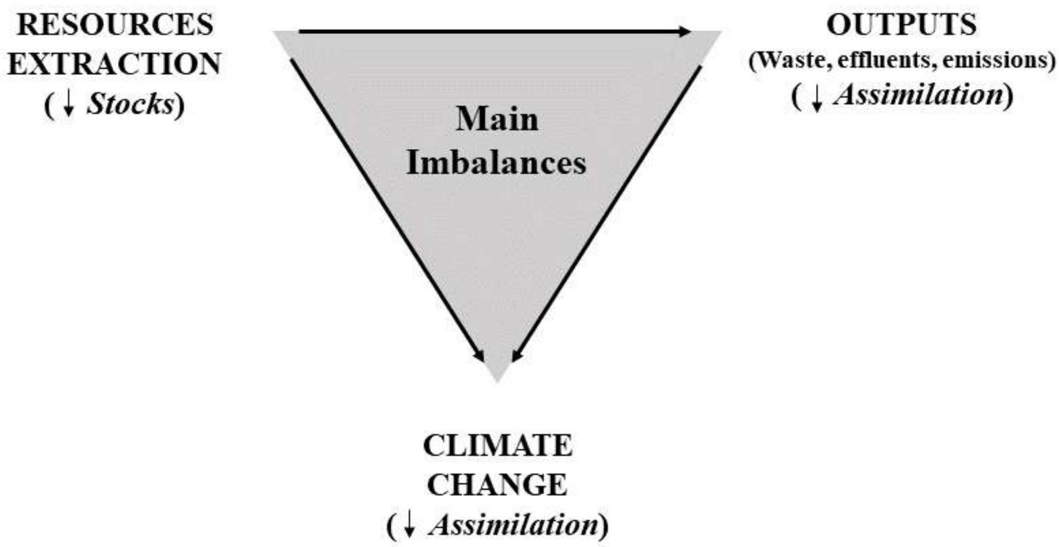
Sustainability does not mean constancy, especially after the understanding that all living systems are essentially changing systems. Therefore, the focus should not be on eliminating change, but on "avoid the destruction of the sources of renewal from which the system can recover from the unavoidable stresses and disturbances to which it is exposed because of its condition of being an open system" (GALLOPÍN, 2003). To be permanent, a system demands enough material stocks and fluid assimilation capacity of impacts. The problem arises when such renewal mechanisms (stocks and assimilation) are affected. In this regard, the current anthropic model and its increasingly larger production and consumption scales have resulted in imbalances that threaten, especially, the stocks of natural capital and the ability to assimilate the negative impacts (environmental, social and economic) across the planet. **Figure 1** presents the triangle with the main sources of imbalance derived from the anthropic systems that corroborate to reduce the regeneration capacity of the natural systems, and, hence, compromise their sustainability.

According to **Figure 1**, the accelerated pace of resources extraction of the last decades reduces the stocks of the natural capital (all resources and environmental services provided by nature), generate outputs (waste, effluents, emissions) – not only from extraction processes but also from other anthropogenic activities – and, therefore, contribute to climate change. These consequences reduce the assimilative capacity and,

[1] The contents of this chapter were incorporated to a chapter in Springer book and an article submitted to Ambiente & Sociedade Journal

hence, represent the main forms of pollution derived from human activities – even though natural processes also might contribute to this problem, but, generally on a much lower scale on a time basis, when compared to the anthropic processes. The climate crisis has been intrinsically connected to the excessive GHG emissions into the atmosphere from the industrial processes that started with the Industrial Revolution and much faster the present times (VIJAYAVENKATARAMAN, INIYAN, *et al.*, 2012).

Figure 1. Main environmental imbalances caused by anthropic systems that compromise resilience and sustainability.



Source: The Author

The solutions for such impacts can be found in the strategies for the human systems aiming at reducing the need for extraction of natural resources, avoiding waste (and hazardousness of materials) and investing in more efficient processes (less energy and material demands, and cleaner technologies). Considering such aspects, the Circular Economy (CE) encompasses a model of production which is restorative and regenerative by intention and design (ELLEN MACARTHUR FOUNDATION, 2013), and might be a way to achieve Sustainable Development (SD) and the three sustainability dimensions: social, economic and environmental (GEISSDOERFER, SAVAGET, *et al.*, 2017; KORHONEN, Jouni, HONKASALO, *et al.*, 2018, MILLAR, MCLAUGHLIN, *et al.*, 2019). For this purpose, some strategies can be adopted in the life cycles of products and materials to make them more circular (i.e., to achieve a greater degree of circularity).

The first strategy to avoid overloading natural systems would be to delay the disposal of products. To this end, the production system must value products with longer lifespans, that is, with greater durability, modularity, to facilitate the exchange of parts and not the entire product, in addition to adopting platforms that encourage the sharing of products between consumers, and business models that prioritize servitization - selling services, or renting for the time of using the products (KALMYKOVA, SADAGOPAN, *et al.*, 2018). Thus, the industry starts to demand higher quality products and more durable components to sell its services (SARIATLI, 2017), which eliminates the issue of programmed obsolescence of products. The circular systems prioritize quality over quantity, in opposition to what was expected in the Linear Economy model (OTTONI, DIAS, *et al.*, 2020).

The second strategy for circular production cycles is to increase the absorption capacity of substances in natural systems. The substitution of hazardous substances (e.g., toxic metals, dioxins, furans, among others) in the composition of products and, consequently, in the production cycles becomes an important step to preserve human health and the environment and, therefore, should be encouraged (GOLDBERG, 2017). The investment in more advanced treatment technologies for decontamination of materials would be a solution for the reduction of the hazardousness caused by post-consumer products with toxic elements in their composition.

The third strategy is to increase resource stocks to ensure their availability to future generations, obtained mainly through the reduction of both the extraction of natural resources and the exploration of non-renewable sources. Priority should be given to replacing materials with those that are more abundant and renewable, and reusing waste, making the production process more resistant to price fluctuations and resource scarcity (KALMYKOVA, SADAGOPAN, *et al.*, 2018).

In this regard, the Urban Mining (UM) approach has become a necessary tool to achieve the CE (XAVIER, LINS, 2018) since such processes provide the return and recovery of waste, used as a secondary raw material for new production cycles. From the business perspective, the earning potential through urban mining is broad, considering a diversity of productive segments and the focus on sustainability, especially in terms of: (i) Sustainable use of resources; (ii) Sustainable production, as it requires the development of technologies based on alternative inputs; and (iii) The efficient management of waste as a way of making it secondary raw materials (XAVIER, LINS, 2018). Together, the circular economy and closed-loop management concepts reinforce the concept of urban mining (COSSU, WILLIAMS, 2015).

Considering the emergency of natural resources depletion, the transition to a low-carbon economy with its new technologies (e.g., wind turbines, electric vehicles, solar panels) in the next years is predicted to demand crucially more metals and minerals than the fossil-fuel-based technologies that they replace (UPADHYAY, LAING, *et al.*, 2021). Thus, UM emerges as a promissory source of materials for the anthropic systems in this upcoming carbon-neutral model.

Especially in the case of e-waste, effective UM strategies have become even more urgent on a global scale. According to OTTONI, DIAS, *et al.* (2020), the CE applied to e-waste management considers the UM concept, reverse logistics, remanufacturing and redesigning as tools for implementing a circular pattern in terms of e-waste streams. The authors also pointed that the connected systems based on Industrial Ecology (IE) are one of the opportunities offered by the CE approach (OTTONI, DIAS, *et al.*, 2020).

Indeed, the literature has highlighted IE as a central tool to achieve SD (EHRENFELD, 2007, WALKER, VERMEULEN, *et al.*, 2021). The concept of IE is mainly focused on the understanding of how to integrate environmental concerns into economic activities by studying the flows of resources (materials and energy) in industrial and consumer activities and their effects on the environmental, economic, political, regulatory and social spheres (WHITE, 1994). ERKMAN (1997) suggested that the origin of IE in the literature was in the 1970s, and aimed at showing the potential symbiosis between the productive processes and the ecosystem of cities by reusing waste as raw material (XAVIER, GIESE, *et al.*, 2019). According to KORHONEN, J. (2002), in the industrial systems-oriented by IE, the actors involved cooperate by using each other’s waste material and waste (residual) energy flows. Despite the conceptual similarities between CE and IE, the first aims to generate a closed-loop economy by regenerative design strategies (SEHNEM, VAZQUEZ-BRUST, *et al.*, 2019, WALKER, VERMEULEN, *et al.*, 2021), whilst the second targets at modifying production and consumption systems to imitate natural ecosystems (FROSCH, GALLOPOULOS, 1989). Thus, systems based on CE, SD, UM and IE strategies are especially important for achieving sustainable e-waste management and higher value recovery rates.

2.2 E-waste management and value recovery options

E-waste processing is mainly motivated due to three general reasons:

environmental concerns (hazardous components), resource efficiency (value recovery potential) and energy savings (KHALIQ, RHAMDHANI, *et al.*, 2014). Such driving forces result from the e-waste particularities (**Subsection 2.2.1**) and are the basis for e-waste management (**Subsection 2.2.2** E-waste management) and the legislation (**Subsections 2.2.3** and **2.2.4**) that regulates the reverse supply chain of these post-consumption devices worldwide. The following subsections explain in more detail these characteristics.

2.2.1 E-waste particularities

The literature has pointed to various definitions for e-waste. The Directive 2012/19/EU designated the term "WEEE" (or e-waste) to electrical or electronic equipment (EEE) that is waste (EUROPEAN UNION, 2012), considering all components, subassemblies and consumables that are part of the product when discarded at the end-of-life. The Step Initiative understands that "e-waste" covers almost all types of EEE that have been discarded by the owner as waste without the intention of re-use, which includes almost any household or business item with circuitry or electrical components with power or a battery supply (STEP INITIATIVE, 2014).

FORTI, BALDÉ, *et al.* (2018) divided EEE into 54 different product-centric categories, referred to as the UNUKEYs. Given the varied EEE categories, functions, sizes and components, the classifications of e-waste are hence also diverse. **Table 1** presents the various e-waste categories proposed by the literature, bringing a comparison between one of the most accepted classifications internationally (Directive 2012/19/EU) and the one chosen for purposes of the Brazilian context and particularities for management, as proposed by XAVIER, OTTONI, *et al.*, (2020).

Globally, an important debate is found when classifying e-waste as hazardous or non-hazardous waste. According to the Basel Convention (UNEP - UN ENVIRONMENT PROGRAMME, [n.d.]), e-waste is categorized as hazardous waste given the presence of toxic materials. Almost the entire periodic table of elements is used in the electronic products given their complex and diverse functionalities (HUISMAN, STEVELS, *et al.*, 2019).

Table 1. E-waste classifications

Source	Category	Description
EUROPEAN UNION (2012)	**1. Temperature exchange equipment**	Refrigerators, freezers, air conditioners, and heat pumps.
	2. Screens and monitors (surface greater than 100 cm²)	Televisions, monitors, laptops, notebooks, and tablets.
	3. Lamps	Fluorescent lamps, high-intensity discharge lamps, and LED lamps.
	4. Large equipment	Washing machines, clothes dryers, dishwashing machines, electric stoves, large printing machines, copying equipment, and photovoltaic panels.
	5. Small equipment	Vacuum cleaners, microwaves, ventilation equipment, toasters, electric shavers, scales, calculators, radio sets, video cameras, electrical and electronic toys, small electrical and electronic tools, small medical devices, small monitoring, and control instruments.
	6. Small IT and Telecommunication equipment	Mobile phones, Global Positioning System (GPS) devices, pocket calculators, routers, personal computers, printers, and telephones.
(XAVIER, OTTONI, *et al.*, 2020)	**1. Large equipment**	Refrigerators, freezers, stoves, washers, electric ovens, microwave ovens, air conditioners, dishwashers, etc.
	2. Small equipment	Mixers, hairdryers, blenders, drills, vacuum cleaners, coffee makers, heaters, vaporizers, analogue cameras, fans, shavers, toasters, tools, toys, audio components, VHS, DVD, Blu-ray players, home-theatres, etc.
	3. Screens and monitors	Cathode Ray Tube (CRT), Liquid Crystal Screens (LCD), LED monitors and others.
	4. Information technology (IT) and Telecommunication equipment	Desktop computers, notebooks, tablets, printers, iPods, cell phones, printed circuit boards, hard drives, CD, DVD and VHS recorders, scanners, routers, ink cartridges, toners, keyboards, mouse, digital cameras, video games, microphones, calculators, headphones, etc
	5. Cables	Different types of cables found within discarded equipment
	6. Batteries	Alkaline (Zn/Alkaline/MnO_2) battery, Zinc – Carbon battery, Silver/Zinc (Zn/Ag_2O), Lithium/Solid Electrolyte, etc
	7. Lamps	Incandescent lamps, tungsten halogen lamps, fluorescent lamps, compact fluorescent lamps, mercury vapour lamps, etc.
	8. Photovoltaic panels	All types

The general composition of e-waste encompasses valuable substances, hazardous ones or even both, such as: (i) Base metals (BM) (e.g., Cu, Al, Ni, Sn, Zn, Fe, etc); (ii) Precious metals (PM) (e.g., Au, Ag, etc); (iii) Platinum group metals (PGMs) (Pd, Pt, Rh, Ir, Ru, etc); (iv) Scarce metals (SMs) (Te, Ga, Se, Ta, In and Ge); (v) Hazardous metals (HMs) (e.g., Pb, Hg, Be, Cr, As, Sb, Cd, etc); (vi) Halogens (e.g., bromine, fluorine, chlorine); (vii) Combustibles (Plastics, organic fluids, etc) (CHEN, OGUNSEITAN, *et al.*, 2016, HAGELUKEN C, 2006, KAYA, 2018, ZENG, YANG, *et al.*, 2017). For instance, 43% of the total production of gold in the world are used in the manufacturing of electronics, besides considering that the fabrication of mobile phones and personal computers (PC) demands significant fractions of Au, Ag and Pb obtained from mines on an annual basis (KAYA, 2016). **Table 2** lists the average composition of different EEE (and, hence, e-waste).

Table 2. Average material composition in some EEE and, hence, e-waste

EEE / E-waste	**Content**										
	(%w/w)								**(ppm)**		
	Fe	**Cu**	**Al**	**Pb**	**Ni**	**Sn**	**Plastics**	**Glass**	**Ag**	**Au**	**Pd**
TV boards	28	10	10	1.0	0.3	1.4	28	6	280	17	10
Computer boards	7	20	5	1.5	1.0	2.9	23	18	1000	250	110
Cellphone	5	13	1	0.3	0.1	0.5	57	2	1340	350	210
Portable audio	23	21	1	0.14	0.03	0.1	47	-	150	10	4
DVD	62	5	2	0.3	0.05	0.2	24	-	115	15	4
Calculator	3	3	5	0.1	0.5	0.2	61	13	260	50	5
TV scrap	-	3.4	1.2	0.2	0.038	-	-	-	20	<10	<6
PC scrap	-	14.3	2.8	2.2	1.1	-	-	-	639	566	-
PCB scrap	-	10	7	1.2	0.85	-	-	-	280	110	-

Note: “-“ means unavailable data

Source: Adapted from GHIMIRE, ARIYA (2020)

In case e-waste is not properly managed, it can impact the environment and threaten human health. However, many of the metallic pollutants present in e-waste are non-hazardous in their metallic forms and become hazardous only if ingested above certain concentrations in liquid, gaseous and dust/soot forms, and this happens when substances are leached out (solubilized) or released by burning processes from e-waste and achieve soil, ground, surface water and the atmosphere (ILANKOON, GHORBANI, *et al.*, 2018). Therefore, this contamination can occur mainly in two different ways (KIDDEE, NAIDU, *et al.*, 2013): (i) Through food chain, considering the contamination by toxic substances from disposal and primitive recycling processes that result in byproducts entering the food chain and thus transferring to humans; (ii) Through direct impact on workers who labour in primitive recycling areas from their occupational exposure to toxic substances (that may be added or formed), as in the case of the informal recycling chain.

The literature pointed to three main categories of contaminants related to e-waste (CAYUMIL, KHANNA, *et al.*, 2016, LUNDGREN, 2012, SCHLUEP, FORUM, *et al.*, 2009):

• **Primary contaminants:** hazardous substances (mostly metals and persistent and bioaccumulative organic substances) present initially within various types of e-waste, including heavy metals (lead, mercury, nickel and cadmium) and flame retardants present in polymers. These substances are generally released during pre-processing activities (e.g., manual dismantling, shredding, and crushing), end processing activities (e.g., open burning of e-waste or pyrometallurgical/ hydrometallurgical routes for extracting precious materials), incineration of e-waste (both integral and residual), and landfill leachates;

• **Secondary contaminants:** hazardous substances (mostly persistent and bioaccumulative organic substances) that derive from the combustion of primary contaminants, or during e-waste open burning, smelting or incinerating operations, resulting in volatile/toxic compounds, PAHs, spent acids, among others;

• **Tertiary contaminants:** hazardous substances (mostly acids and cyanides), emitted by leftover chemicals used during material recovery processing, such as the acids and cyanides reagents.

Table 3 shows the hazardous compounds present within e-waste (primary contaminants) and release during the e-waste processing (secondary and tertiary contaminants).

Table 3. Main primary, secondary and tertiary contaminants related to e-waste

Contaminant	Substance	Sources	Toxicity
Primary	Aluminium (Al)	WPCB, LED monitors, hard drivers, cables with inorganic FR, etc	Lung irritant, neurotoxic
	Antimony (Sb)	WPCB, CRT, LCD TVs, cables with inorganic FR, etc	Lung, eye and gastro-intestinal irritant
	Arsenic (As)	LCD monitors and TVs	Carcinogenic, hematotoxic, endocrine disrupter
	Beryllium (Be)	WPCB, power supply boxes	Berylliosis, carcinogenic
	Cadmium (Cd)	WPCB, batteries, toners, CRT, plasma TVs, cellphones	Carcinogenic, cardiotoxic, nephrotoxic, endocrine disrupter
	Copper (Cu)	WPCB, cables, plasma TVs, cellphones	Lung, eye and gastro-intestinal irritant
	Hexavalent chromium VI (Cr+6)	WPCB, plasma TVs	Carcinogenic (lung cancer), sensitizer, skin irritant
	Lead (Pb)	WPCB, TVs (CRT, LCD, plasma), flourescent tubes	Probably carcinogenic to humans, neurotoxic, cardiotoxic, nephrotoxic, endocrine disrupter
	Mercury (Hg)	Fluorescent tubes, fluorescent lamps, batteries, monitors, LCD TVs, laptops	Neurotoxic, skin, eye and gastrointestinal irritant, endocrine disrupter
	Nickel (Ni)	LCD, laptops, Ni-Cd batteries	Carcinogenic, sensitizer
	Silver (Ag)	Laptops, TVs and monitors (plasma, LCD, LED)	Nephrotoxic, reprotoxic
	Zink (Zn)	WPCB, CRT, plasma TVs, batteries, cellphones, cables with inorganic FR, etc	Neurotoxic, hematotoxic, gastric irritant, probably endocrine disrupter
	Halogenated flame retardants	WPCBs, plastics, condensers, transformers	Endocrine disrupter, neurotoxic, carcinogenic (chlorinated flame retardants)
	Halogen-free flame retardants	IT housing, plastics, epoxy resins in WPCBs	Organophosphorus: endocrine disrupter. Nitrogen-based: nephrotoxic, neurotoxic
	Polychlorinated biphenyls (PCBs)	Old capacitors and transformers, fluorescent lamps, electrical motors	Endocrine disrupter, hepatotoxic, carcinogenic
	Ozone-depleting substances (CFCs, HCFC, HFC, HCs)	Old refrigerators, freezers and air conditioning units, insulation foam	Neurotoxic, lung and eye irritants
	Phthalates	Plasticizers to soften plastics and rubber	Endocrine disrupter, reprotoxic, hepatotoxic
	Polyvinyl chloride (PVC)	Wiring and computer housing	Related to the toxicity of dioxins and furans generated during PVC burning
Secondary	PAHs (phenanthrene, anthracene, fluoranthene,	Combustion of e-waste containing PCBs, plastics and PVC (open burning activities, pyrometallurgical process in a furnace)	Carcinogenic, photosensitizer

	benzo[a]pyrene, benz[a]anthreacene)		
	PCDD/Fs PBDD/Fs PXDD/Fs	Incineration of e-waste residues as a disposal strategy	Immunotoxic, carcinogenic, reprotoxic, endocrine disrupters, may induce birth defects and also dermal damage (chloracne)
	Bisphenol A	Incineration of e-waste residues as disposal strategy (combustion of polycarbonate plastics)	Endocrine disrupter
	Gases (CO and CH4)	Incineration of e-waste residues as disposal strategy (generated during smelting process)	Asphyxia
	Acids	Incineration of e-waste residues as disposal strategy (hydrobromic acid from brominated FRs, hydrochloric acid from chlorinated FRs and incomplete combustion of PVC; phosphoric acid from organophosphorus FRs)	Induce from mild to severe burns to eyes and skin, sore throat, respiratory problems, corrosive injuries to lips, mouth, throat, etc., if swallowed
Tertiary	Acids (e.g., hydrochloric, nitric, sulphuric)	Pyrometallurgy for metal refining (acids used as electrolyte solutions for electrorefining) Hydrometallurgy for metal refining (acids used as leaching agents, for solvent extraction and electroextraction solutions)	
	Cyanides	Hydrometallurgy for metal refining (cyanides used as reagents)	Neurotoxic, cardiotoxic, may induce chest pain, breathing difficulties, increase in the size of the thyroid gland
	Thiourea	Hydrometallurgy for metal refining (thiourea used as reagents)	Photosensitizer, hematotoxic

Legend: *FRs (flame retardants); PBDD/Fs (polybrominated dibenzo-p-dioxins and dibenzofurans); PAHs (polycyclic aromatic hydrocarbons); PCBs (polychlorinated biphenyls); PCDD/Fs (polychlorinated dibenzo-p-dioxins and dibenzofurans); PVC (polyvinyl chloride); PXDD/Fs (mixed polybromochloro-dibenzo-p-dioxins and dibenzofurans).*

Source: Adapted from BAKHIYI, GRAVEL, *et al.* (2018)

The Global E-waste Monitor estimated that the value of raw materials in e-waste generated in 2019 was worth nearly $57 billion, even though only 10 billion USD worth of materials could be recovered in this year (FORTI, V, BALDÉ, *et al.*, 2020). This fact suggests e-waste as a promising source of resources from urban mining processes (i.e., resources recovery from waste) (GHIMIRE, ARIYA, 2020). **Table 4** presents the amount and potential value of selected raw materials contained in the e-waste generated in 2019.

Table 4. Global amount and potential value of some materials in e-waste in 2019

Material	Amount in e-waste (kt)	Potential value (million USD)
Iron/steel	20,466	24,645
Copper	1,808	10,960
Aluminium	3,046	6,062
Gold	0.2	9,481
Silver	1.2	579
Palladium	0.1	3,532
Antimony	76	644
Cobalt	13	1,036
Total	25,410	56,939

Source: (FORTI, V, BALDÉ, *et al.*, 2020, GHIMIRE, ARIYA, 2020)

Besides the economic advantages of recovering secondary materials from e-waste, as presented in **Table 4**, urban mining processes also corroborates energy savings when compared to the extraction of virgin materials (NING, LIN, *et al.*, 2017). **Table 5** shows the energy savings obtained with the use of recycled materials over virgin ones.

Table 5. Energy savings from the usage of recycled materials over virgin ones

Material	Energy savings (%)
Aluminum	95
Copper	85
Iron and steel	74
Lead	65
Zinc	60
Paper	64
Plastics	>80

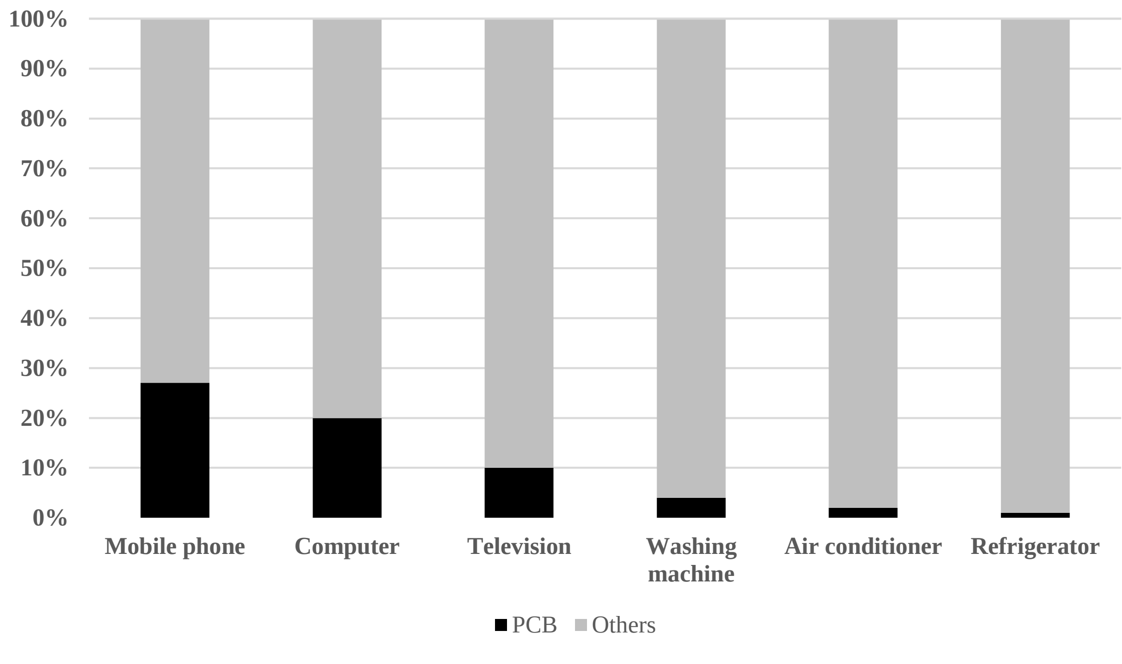
Source: (CUI, FORSSBERG, 2003)

The energy savings derived from e-waste value recovery are especially related to metals that exist at low concentrations in primary ores and consume significant energy during extraction, guaranteeing not only the preservation of scarce resources but also the reduced burden on mining ores for primary metals (KHALIQ, RHAMDHANI, *et al.*, 2014).

2.2.1.1 Waste printed circuit boards

In the particular case of the PCBs, the understanding of their composition might be strategic, especially because they represent one of the most valuable (also hazardous) fractions of e-waste (CANAL MARQUES, CABRERA, *et al.*, 2013), and are generally referred to as "urban mines" (LU, XU, 2016) or "secondary resources" (VERMEŞAN, TIUC, *et al.*, 2020). The PCB serves as a mechanical support and electrically connect electronic components in the devices (HAO, WANG, *et al.*, 2020) using conductive pathways, tracks, or signal traces etched from copper sheets laminated onto a non-conductive substrate. This component can be employed in business machines, computers, besides communication, control, and home entertainment equipment (AWASTHI, ZENG, 2019, KAYA, 2020a). In literature, a PCB is also referred to as a printed wiring board (PWB) or etched wiring board and it constitutes around 3wt% of all e-waste produced, even though this proportion varies for different devices (HADI, XU, *et al.*, 2015). **Figure 2** presents the proportion of PCB in some typical EEE.

Figure 2. The proportion of PCB in some typical EEE



Source: (WANG, ZHANG, *et al.*, 2017)

Three main types of PCBs can be found in the market according to the number of layers (AWASTHI, ZENG, 2019):

(i) **Single-sided:** when the electronic components (EC) are placed on just one side of the board, being easy to design and manufacture, and can be applied to televisions and household appliances;

(ii) **Double-sided:** with EC distributed along both sides of the board and connected by drilling holes filled with a conducting material through adequate locations in the substrate. Its applications can be in instrumentation, computers, LED lighting, etc;

(iii) **Multilayered:** 3-layers of printed wiring, with metallized holes connecting different layers, in which the substrate is made of layers of printed circuits placed between insulation layers, and the EC on the surface connect through plated holes drilled down to the proper circuit layer. It can be applied to complicated designs like medical equipment, satellite systems, etc.

Considering the board forms, the PCB can be classified as rigid, flexible and flex-rigid PCB, as described in **Table 6**.

Table 6. Types of PCB according to their board forms and their applications

Types	Characteristics	Applications
Rigid	With rigid substrate preventing the board from twisting	With single, double or multi-layer, same application
Flexible	Free bending, folding and easily coiled	With single, double or multi-layer, used for special requirements, e.g. complicated shape
Flex-rigid	Suitable for streamlined design, reducing overall board size and weight	Using in the case when space or weight are prime concerns, e.g. cellphone, digital cameras

Source: (HAO, WANG, *et al.*, 2020)

In terms of the properties of flame retardancy, the literature points to some types of PCB, as the case of FR-2 to FR-6, CEM-1 to CEM-8, G-10 and G-11, differing from each other concerning the resin composition and reinforcement materials (KUMAR, HOLUSZKO, *et al.*, 2018), as presented in **Table 7**. FR stands for flame retardant and denotes the flammability safety of the fibreglass-reinforced epoxy laminates (HADI, XU, *et al.*, 2015). The types FR-2 and FR-4 are normally used in PCs and mobile phones, and FR-4 is the most valuable type (HAO, WANG, *et al.*, 2020, KAYA, 2016, WEIL, LEVCHIK, 2004).

Table 7. Types of PCB according to flame retardancy and their applications

PCB Type	Colour	Description	Properties	Applications	Value
FR-2	Yellow/brown	Cellulose reinforced with phenolic resin	Flame retardancy	Televisions, radios, PC	Low
FR-3	-	Cotton paper reinforced with epoxy resin	Insulation resistance	-	-
FR-4	Green	Fibreglass reinforced with epoxy resin	Flame retardancy	Cellphones, laptops	High
FR-5	-	Fibreglass reinforced with epoxy resin	Thermal stability	-	-
FR-6	-	Mat glass reinforced with polyester resin	High-impact applications	-	-

Source: (KAYA, 2016, KUMAR, HOLUSZKO, *et al.*, 2018)

As illustrated by **Figure 3**, the PCBs consists of:

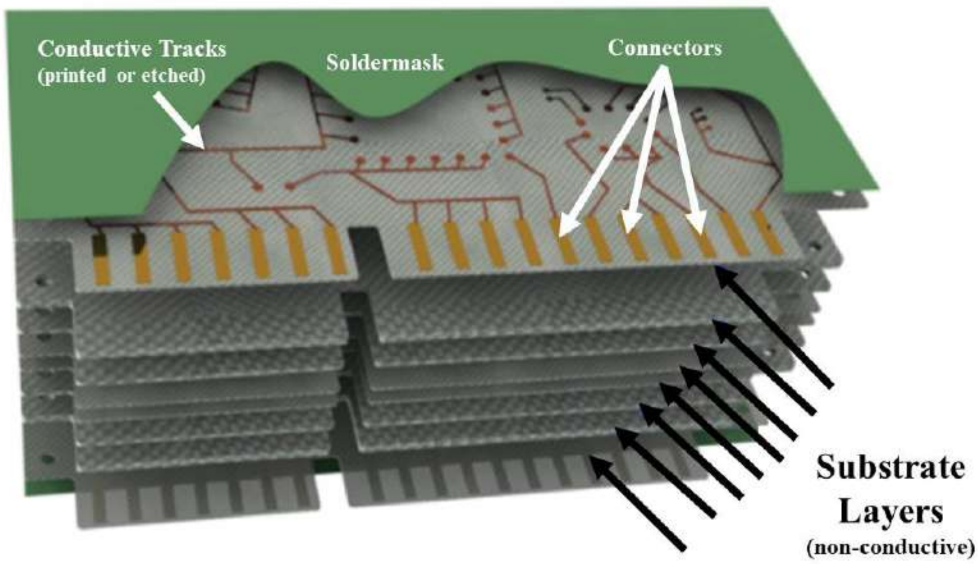
(i) **Insulating non-metallic polymer substrate or laminate (non-conductive):** thermosetting resins (epoxy, cyanate ester resin or phenolic resin) and reinforcement materials (cellulose, fibreglass, cloth, and ceramics) (KUMAR, HOLUSZKO, *et al.*, 2018, WANG, Huaidong, ZHANG, *et al.*, 2017). The choice of manufacturing materials used for PCBs depends on the application (LI, ZENG, 2012);

(ii) **A metal foil laminated layer inside, printed or etched on the surface of the substrate (conductive):** The conductive circuit is generally copper, although aluminium, nickel, chrome and other metals are sometimes used (LI, ZENG, 2012). Various etch-resistant materials such as gold, nickel, silver, tin, tin-lead are used to protect the copper during etching (GHOSH, GHOSH, *et al.*, 2015). Precious metals (mainly gold and Palladium) are used as contact materials in joints (KAYA, 2016). Some boards require the use of gold for sensitive, low-voltage applications or lead-free compliance. Copper traces usually demand the use of a nickel barrier layer before gold-plating. This is to prevent gold from migrating into the copper (AWASTHI, ZENG, 2019);

(iii) **Electronic components attached to the substrate:** chips, connectors, capacitors, etc., which can contain different metallic values (e.g., Ga, In, Ti, Si, Ge, As, Sb, Se, Te and Ta) (KAYA, 2016);

(iv) **Solder:** the materials and metals along with electronic parts are attached to the board by a solder containing lead and tin (LI, ZENG, 2012).

Figure 3. General structure of a printed circuit board



Source: Adapted from YOUSEF, TATARIANTS, *et al.* (2018)

Table 8 indicates the main composition of populated WPCB, or WPCB with electronic components (ECs), considering both metal fractions (MF) and non-metal fractions (NMF). PCBs without ECs contain about 30% metals and 70% nonmetals by weight (KAYA, 2016, NING, LIN, *et al.*, 2017). The literature has pointed that the NMF consists of glass fibre (65% by wt.), cured epoxy resin (32% by wt.) and impurities (mixed copper: <3%, soldering alloys: <0.1%) with the highest glass fibre and copper concentration in the fine fraction, and the highest resin concentration in the coarse fraction (KUMAR, HOLUSZKO, *et al.*, 2018).

Table 8. Main composition of populated WPCB

Metals (~40%)	**%**	**Ceramics (~30%)**	**%**	**Plastics (~30%)**	**%**
Cu	6-27	**SiO_2**	15-30	**PE**	10-16
Fe	1.2-8.0	**Al_2O_3**	6.0-9.4	**PP**	4.8
Al	2.0-7.2	**Alkali-earth oxides**	6.0	**PS**	4.8

Sn	1.0-5.6	**Titanates-micas**	3.0	**Epoxy**	4.8
Pb	1.0-4.2			**PVC**	2.4
Ni	0.3-5.4			**PTPE**	2.4
Zn	0.2-2.2			**Nylon**	0.9
Sb	0.1-0.4				
Au (ppm)	250-2050				
Ag (ppm)	110-4500				
Pd (ppm)	50-4000				
Pt (ppm)	5-30				
Co (ppm)	1-4000				

Source: (KAYA, 2016, LI, ZENG, 2012)

According to LI, ZENG, (2012), Au, Cu, Pd and Ag account for nearly all of the economic material value in WPCBs, and, therefore, PCB recycling focuses on recovering these metals above all else. **Table 9** describes the main metals present in PCB and the EC, which reinforces the importance of separating EC from WPCB (or unpopulated WPCB) for the recovery of EC metals. The concentrations of precious metals in WPCBs are richer than in natural ores, which makes their recycling important from both economic and environmental perspectives (KAYA, 2016, LI, ZENG, 2012).

Table 9. Main metals present in PCB and EC

Component	**Cu**	**Sn**	**Pb**	**Al**	**Fe**	**Zn**	**Ni**	**Cr**	**Sb**	**Ag**	**Au**	**Cd**
	(%)									**(g/t)**		
PCB	21.62	10.12	3.20	1.36	0.21	0.056	0.036	0.027	0.001	194.91	-	0.53
ECs	13.80	3.20	0.68	6.91	19.49	5.66	0.65	0.53	6.11	112.68	40.76	14.45
Total	16.9	6.0	1.7	4.7	11.8	3.4	0.4	0.3	3.7	145.70	24.4	8.9

Source: (AWASTHI, ZENG, 2019)

Even though an average composition of PCB can be obtained from the literature, KAYA (2016) highlighted that these elements proportions are continuously changing, which represents a challenge to obtain a stable material composition. YANG, SUN, *et al.* (2021) described the metal content in PCB of different e-wastes, as shown in **Table 10**.

Table 10. Printed circuit board metal content (kg/ton) of 22 kinds of e-waste

Equipment type	**Al**	**Cu**	**Fe**	**Pb**	**Zn**	**Ag**	**Au**	**Pd**
Air conditioner	6.90	70.0	20.0	5.80	4.90	0.06	0.02	/
Camcorder	29.0	210	45.0	0.05	13.0	5.00	0.53	0.97
Cathode ray tube television	4.18-62.0	40.9-72.0	34.0	14.0-82.3	0.54-5.30	0.12	5×10^{-3}	0.02
Digital camera	24.0	270	30.0	0.03	8.80	3.20	0.78	0.20
Digital versatile disc player	54.0	220	11.0	0.12	26.0	0.71	0.15	0.02
Liquid crystal display television	18.0-63.0	51.4-200	13.0-49.0	17.0-23.0	2.70-20.0	0.03-0.60	0.007-0.24	0.003-0.15
Laptop	18.0	190	37.0	9.80	16.00	1.10	0.63	0.20
LCD notebooks	/	51.7	/	2.03	2×10^{-3}	0.10	0.08	0.02
Light-emitting diodes television	/	51.7	/	2.03	2×10^{-3}	0.10	0.08	0.02
Mobile phone	15.0	330	18.0	0.02	5.00	3.80	1.50	0.30
Plasma display panel television	38.0	210	20.0	7.10	12.00	0.40	0.30	/
Phone	17.8-73.8	86.2-160	/	3.69-6.15	6.15-24.6	1.50-6.15	0.15-0.23	0.06-0.09
Portable compact disc player	68.0	200	46.0	0.05	20.0	3700	0.37	0.01
Portable mini-disc player	27.0	330	45.0	0.05	11.0	3400	0.94	0.55
Printer	180	140	17.0	0.01	4.20	0.07	0.04	0.02
Radio cassette recorder	61.0	140	58.0	0.02	11.0	0.17	0.03	0.03
Refrigerator	16.0	170	21.0	21.0	17.0	0.04	0.04	/
Stereo system	29.0	150	12.0	0.19	14.0	0.06	6×10^{-3}	/
Telephone	67.0	96.0	150	0.01	8.60	2.40	/	/
Video cassette recorder	35.0	160	38.0	0.02	16.0	0.21	0.02	0.05
Video game	40.0	190	77.0	0.08	12.0	740	0.23	0.04
Washing machine	1.00	70.0	95.0	2.20	2.40	0.05	0.02	/

Source: (YANG, SUN, *et al.*, 2021)

2.2.2 E-waste management

ZENG, YANG, *et al.* (2017) proposed that e-waste management should cover three main scales: (i) macroscopic (product and component); (ii) mesoscopic (material); and (iii) microscopic (substance). The products (cellphones, computers, TVs, refrigerators, etc.) are made of components (PCB, mouse, batteries, etc.) and have an economic value assigned by the market. The components are a mixture of materials (plastics, metals, etc.), which are composed of different substances or elements (Fe, Ag, Al, etc.). Each of these levels requires specific conditions and demand different procedures, or strategies, for value recovery (OTTONI, DIAS, *et al.*, 2020).

This approach can be related to the circular economy concept, especially when considering the upstream (before discard) and downstream (after discard) stages for e-waste management. LEPAWSKY (2012, 2018), on the other hand, considered that downstream stages start after production and not discard. Bakhiyi et al. (2018) highlighted the urgent need of considering both upstream and downstream solutions for the electronics industry. Ottoni et al. (2020) pointed that e-waste valorization in a circular model for all economic stages must consider some options for resource value retention, or retention option (RO), defined by Reike et al. (2018) as the conservation of resources closest to their original state. **Table 11** presented the correlations of the RO's with the upstream and downstream solutions, prepare for reuse strategies for the electronics chain and the e-waste management scales in terms of product, component, material and substance.

The upstream solutions are related to consumer habits and the commitment of manufacturers to use less hazardous substances and increase e-waste recyclability (BAKHIYI, GRAVEL, *et al.*, 2018, FIORE, IBANESCU, *et al.*, 2019). Therefore, as presented in **Table 11**, these alternatives can be applied into some stages, such as the extraction, transport, storage, sorting, designing and processing of new products, and the usage phase (BAKHIYI, GRAVEL, *et al.*, 2018, SHAIKH, THOMAS, *et al.*, 2020, XAVIER, OTTONI, *et al.*, 2021). The negative impacts are more significant at the upstream stage, especially due to raw-material extraction and production, which usually require significant energy and material inputs (XAVIER, GIESE, *et al.*, 2019, XAVIER, OTTONI, *et al.*, 2021). In this stage, the solutions target the macroscale since they recover value in form of products.

Table 11. Solutions based on value retention options of the circular approach

Stage	Strategies	Retention option	Description	Scale
Production / Usage phase	Upstream	R0 – Refuse	Avoid buying.	Product
		R1 – Reduce	Use longer, share the use of products, increase efficiency in manufacture or use by consuming fewer natural resources and materials.	Product
	Preparing for reuse	R2 – Reuse/Resell	Buy second hand, find a buyer for your non-used produced/possibly some cleaning, minor repairs.	Product
		R3 – Repair	Make the product work again by repairing or replacing deteriorated parts.	Product
Post-consumer phase		R4 – Refurbishment	Restore an old product and bring it up to date.	Product
		R5 – Remanufacturing	Use parts of a discarded product in a new product with the same function.	Component
		R6 – Repurpose/Rethink	Buy a new product with a new function.	Product
	Downstream	R7 – Recycling	Process materials to obtain the same (high grade) or lower (low grade) quality.	Product, component, material, substance
		R8 – Recovery (energy)	Energy production as a by-product of waste treatment.	Material, substance
		R9 – Remine	Buy and use secondary materials from landfills.	Component, material

Source: The authors, adapted from Kirchherr *et al.* (2017), Reike *et al.* (2018) and Ottoni *et al.* (2020)

One of the main targets considered for the EU's transition to a circular economy refers to the goals to prepare for reuse (EUROPEAN ENVIRONMENTAL BUREAU, 2018), which might also consider the strategies of repairing (R3), refurbishing (R4), remanufacturing (R5) and repurposing (R6). Under this perspective, the possible solutions might be adopted both in the production/usage phase and post-consumer stage.

The downstream solutions involve the reverse fluxes for recovering value from e-waste, considering the processes of collection, transport, processing and environmentally sound disposal (XAVIER, OTTONI, *et al.*, 2021). Hence, such options emphasize the enforcement of laws to progressively reduce the illegal waste trade, the integration of the informal sector into official recycling systems in developing countries, strengthening of reverse logistics, cleaner processing technologies, among others

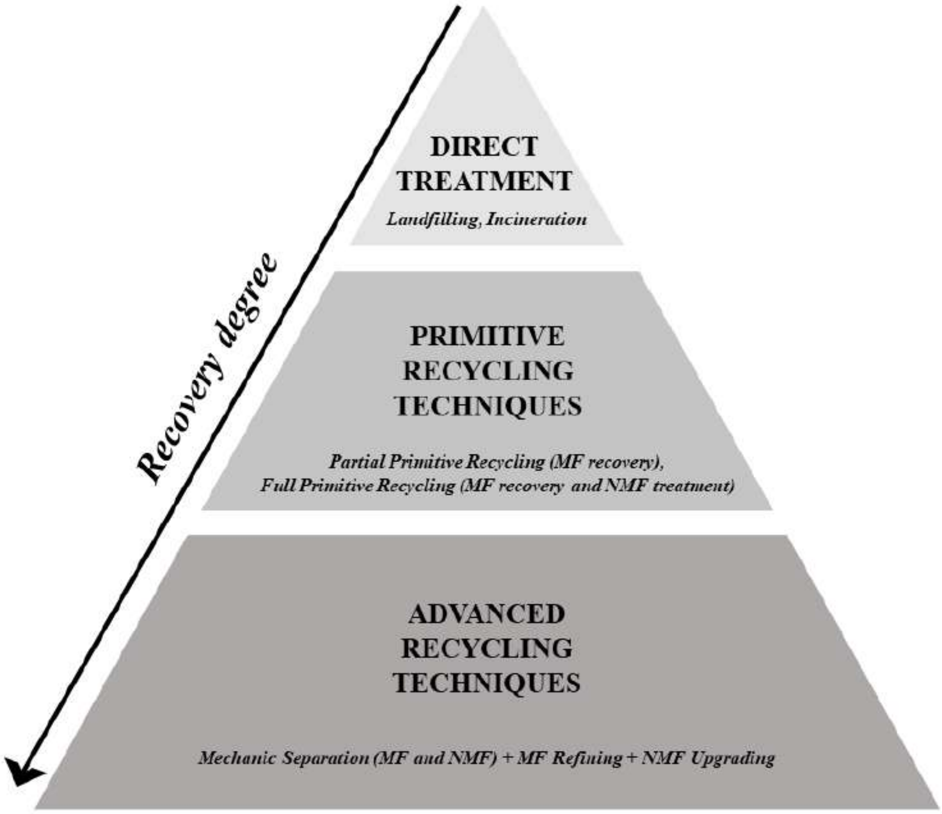
(BAKHIYI, GRAVEL, *et al.*, 2018, FIORE, IBANESCU, *et al.*, 2019, XAVIER, OTTONI, *et al.*, 2021). This stage encompasses the macroscale, mesoscale and microscale for returning products, components, materials and substances to new cycles in the industry.

E-waste collection can be performed through drop-off systems or pick-up systems (GREGORY, MAGALINI, *et al.*, 2009). The first considers that the consumer takes their e-wastes to the collection points (in fixed facilities or sporadic collection campaigns). The fixed take-back points can also be called Voluntary Delivery Points (VDP) (ARAUJO, OTTONI, *et al.*, 2020, ARAUJO, CUGULA, *et al.*, 2020, CUGULA, APOLONIO, *et al.*, 2020, OTTONI, DIAS, *et al.*, 2020). The second refers to the municipal or private agency being responsible for removing the discarded waste directly from the consumers' doors (ARDI, 2016). The adoption of a specific collection model depends on the responsible stakeholder (government, retail, commercial entity or producer) (GREGORY, MAGALINI, *et al.*, 2009). The collection and transport are reported as the most expensive stages in the e-waste reverse logistics, and, therefore, it is crucial to set up an efficient collection system (YLÄ-MELLA, POIKELA, *et al.*, 2014).

E-waste processing includes treatment and different value recovery procedures. NING, LIN, et al. (2017) described the options for e-waste treatment according to their material and energetic recovery degree, using the case of waste printed circuit boards (WPCB), which are present in practically all e-wastes (CANAL MARQUES, CABRERA, *et al.*, 2013). These processing technologies and their classification according to their recovery degree are described in **Figure 4**.

The recovery degree is directly related to the capacity of recycling both metals fractions (MF) and non-metals fractions (NMF). According to **Figure 4**, the first stages techniques (fewer recovery levels) correspond to the alternatives of direct treatment (also understood as end-of-pipe techniques), such as landfilling, in which neither material nor energy is recovered, and incineration, with the recovery of just the energy from e-waste. In the first case, the main problem consists of the toxic leachate formation and the evaporation of the hazardous substances, especially composed of heavy metals and brominated compounds present in the WPCB and other e-wastes, in the landfill sites (NING, LIN, *et al.*, 2017). In the case of incineration, the issue is that this process, which aims at reducing NMF volume through its combustion, generates toxic emissions (heavy metals, fly ash, PCDD/Fs and PBDD/Fs) directly to the atmosphere when a postpurification stage is not performed (NING, LIN, *et al.*, 2017). Besides, incineration corroborates to wasting of the recycling potential presented in the incinerated WPCB, which also enforces the extraction of raw material from traditional mining routes.

Figure 4. E-waste/WPCB treatment and recycling techniques according to the recovery degree capacity



Source: Adapted from NING, LIN, *et al.* (2017)

The second level techniques (or primitive recycling technologies) consider the simple recycling of MF (incorporating the most valuable fractions), as a partial recycling route. If the safe disposal of NMF is also considered, this is the full recycling route (NING, LIN, *et al.*, 2017). Both paths correspond to the loss of value of NMF, even though the pollution is controlled in the full route. Examples of MF recycling would be through metallurgical processes, such as: (i) Pyrometallurgical, in which the separation of valuable metals happens by smelting in furnaces at high temperatures (>800°C) and inert atmosphere, and this process produces dusty and toxic gases pollutants (HAO, WANG, *et al.*, 2020, KHALIQ, RHAMDHANI, *et al.*, 2014, NING, LIN, *et al.*, 2017); (ii) Hydrometallurgical, based on the usage of solvent leaching (using aqua regia, cyanide, thiourea, thiosulfate, halide, among others) for MF (mainly copper and gold) recycling (HAO, WANG, *et al.*, 2020, NING, LIN, *et al.*, 2017); (iii) Biohydrometallurgical, that considers using microorganisms, such as bacteria or fungi, to treat WPCB (NING, LIN, *et al.*, 2017); and (iv) Electrometallurgical, that refine de MF according to their difference of theoretical deposition potential of the metal ions (GUO, QIN, *et al.*, 2020). The hydrometallurgical and pyrometallurgical processes are the major routes for processing of e-waste, while only limited laboratory studies for e-waste processing through biohydrometallurgical routes and such processes may be followed by electrometallurgical/electrochemical processes (electrorefining or electrowinning) for selected metal separation and recovery (KHALIQ, RHAMDHANI, *et al.*, 2014). As for the NMF treatment techniques, the most used include supercritical fluid extraction, plasma treatment and hydrothermal methods, that, even though guarantee the safe disposal, demand high energy and effort put into the process, which are not proportional to the output (only MF) (NING, LIN, *et al.*, 2017). Thus, in the case of the primitive recycling techniques considered in this topic, the recycling and upgrading of the NMF fraction is not performed.

For the advanced stages of resources recovery from e-waste, the effective separation of MF and NMF is indispensable for efficient recycling. Therefore, WPCB recycling includes (KAYA, 2020b, NING, LIN, *et al.*, 2017):

(i) **Pretreatment**, considering dismantling, disassembly, desoldering, etc, to remove hazardous and reusable components;

(ii) **Preprocessing**, including shredding, crushing, pulverizing (finner comminution), sieving, classification (screening), mechanical separation (size, density, etc) to reduce sizes and separate materials;

(iii) **Processing**, to recover MF and NMF;

(iv) **Refining**, to achieve high purity levels of the recovered materials (MF refining and NMF upgrading).

The mechanical separation can be performed by the physical properties of the e-waste components according to their density, magnetic potentials and electrical conductivity. The processing and refining processes can be achieved through pyrometallurgical, hydrometallurgical, electrometallurgical, biohydrometallurgical routes and/or a combination between them (KAMBEROVIĆ, RANITOVIĆ, *et al.*, 2018, KHALIQ, RHAMDHANI, *et al.*, 2014). The NMF upgrading consists of modifying such components so that the carbon can be recovered for potential reuse in more valuable applications (e.g., as a catalyst, adsorbent and filter support), which, finally, compensate the high costs from mechanical separation in the initial stages (NING, LIN, *et al.*, 2017) and reduce the CO2 emissions compared to the production of these NMF from ore (MGG - MÜLLER-GUTTENBRUNN GROUP, [S.d.]). As the NMF value recovery includes both polymers and ceramics, the considered recycling routes are distinct from each other. While the polymers can be directed to chemical, mechanical or even energetic recycling, the ceramic ones are sent to cleaning processes and can be refined through etching procedures, being, then, ready to be reused in new products (DIAS, MACHADO, *et al.*, 2018).

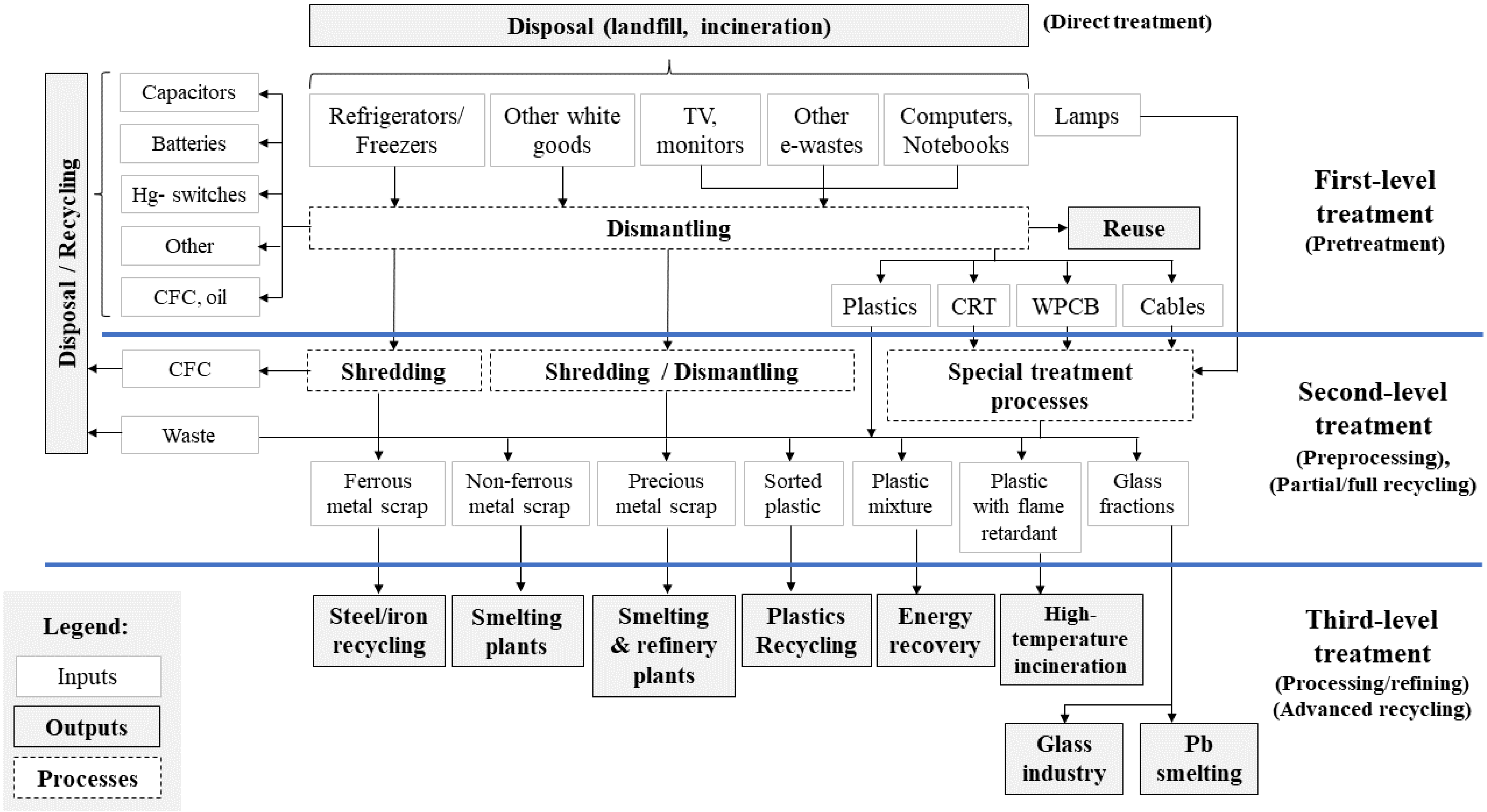
Currently, pyrometallurgical e-waste recycling routes are generally used globally (about 70%) with high investment cost, temperature and ecological problems. Compared with pyrometallurgical processing, the hydrometallurgical method is better, more predictable, and more easily controlled. New promising biological processes are now under development (KAYA, 2020b).

UNEP (2007) highlighted the three main scales or development levels for e-waste recycling. Such development levels are directly correlated to the recovery degree levels described by NING, LIN, et al. (2017) and the recycling stages proposed by KAYA (2020), and can be useful to determine the development degree of companies, cities and countries regarding e-waste treatment technology. The development levels for e-waste recycling were illustrated in **Figure 5**.

First-level recycling (or pretreatment) consists of data destruction in some devices (i.e., computers, cellphones, etc), sorting and dismantling of e-waste. Then, the e-waste components possible to be reused and the hazardous ones (oils, chlorofluorocarbons - CFCs, mercury switches, batteries, and capacitors) are separated from the main flux for treatment and safe disposal, as presented in **Figure 5**.

In the second-level recycling (or preprocessing), the previously separated CRT monitors, WPCB and cables from the first level are directed to special treatment processes (including disassembly for solder and other components removal, besides size reduction and separation of the MF and NMF), the plastics and other e-waste (i.e., refrigerators, freezers and others from the white line) follow to the comminution (shredding and pulverizing, for size reduction), classification and separation processes, and, when necessary, CFC removal and disposal. After this stage, fractions of plastics, ferrous, nonferrous metals (e.g., copper and aluminium) and precious (e.g., gold, silver, and palladium) are recovered to be further processed in the next level (LOPES DOS SANTOS, 2020, UNEP, 2007).

Figure 5. E-waste recycling/treatment development levels



Source: Based on (LOPES DOS SANTOS, 2020, NING, LIN, *et al.*, 2017, UNEP, 2007)

The third-level recycling (or advanced recycling, including metallurgical processing and refining) is based on more advanced technologies for recovering complex fractions with higher purity and refining elements. The ferrous metals fractions can be directed to steelmakers. The fractions with non-ferrous and precious metals are sent to specialized industries in some specific countries, such as Canada, Belgium, Germany, Japan, among others (DIAS, MACHADO, *et al.*, 2018, KAYA, 2019, KHALIQ, RHAMDHANI, *et al.*, 2014, LOPES DOS SANTOS, 2020), as presented in **Table 12**. Such industries use techniques of pyrometallurgy in foundry furnaces, hydrometallurgy and electro-metallurgical refining. The plastic fractions can be recovered in such plants as polymers or even as energy (**Figure 5**). After this level, the residues are disposed of either in a hazardous waste landfill or incinerated, and the efficiency of operations at the first and second levels determines the number of residues directed to a hazardous waste landfill site or incineration (UNEP, 2007).

Besides the adequate processes to be adopted, the design of a product is relevant when it comes to recycling or other value recovery options. The e-waste recycling potential might be significantly affected by the toxicity of the substance it contains, by its technical specifications, and by the country’s economic situation (DE ALBUQUERQUE, MELLO, *et al.*, 2020, ZENG, WANG, *et al.*, 2017). The recyclability potential of certain e-wastes is discussed by ZENG, LI (2016), which proposed a model based on the physical and chemical characteristics of the materials contained in the e-waste that classified e-wastes according to their recyclability. **Table 13** describes the categories of e-wastes according to their potential to be recycled.

Table 12. Main e-waste/WPCB recycling plants in the world

Recycling Plant (IRS)		Country	Processing Stages	Recovered Elements/Materials	Annual E-waste Input	Annual Recovered Output
1	Attero Recycling	India	1. Separation; 2. Pulverization; 3. Shredder	Cu, Pb, Ni, plastics	12 kt	N.I.
2	Aurubis	Germany	**1.** Smelting of Cu and e-waste in TSL reactor; **2.** Black copper processing; **3.** Electrorefining	Cu, Pb, Zn, Sn, PMs, plastics	N.I.	N.I.
3	Austrian Müller-Guttenbrunn Group (MGG)	Austria	**1.** Depollution (with smashers); **2.** Shredding; **3.** Separation (ferrous vs nonferrous metals); **4.** Plastic recycling; **5.** Smelter (ferrous metals and nonferrous materials)	Plastics: ABS, HIPS, PP; Metals: Cu, PMs (*precious metals*)	80 kt (total e-waste)	850 kt (metals, from e-waste and other materials)
4	Daimler Benz (Ulm)	Germany	**1.** Coarse-size reduction; **2.** Magnetic separation (NMF, MF); **3.** Low-temperature grinding stage; **4.** Hammermill fed with liquid nitrogen + grinding (inert atmosphere); **5.** Electrostatic separation	N.I.	N.I.	N.I.
5	DOWA Group	Japan	N.I.	Cu, Zn, Au, Ag	N.I.	N.I.
6	Elden Recycling	Spain	**1.** Shredder; **2.** Eddy current separator; **3.** Tumble back feeder; **4.** Multipurpose rasper; **5.** Eddy current separator; **6.** Heavy granulator; **7.** Separation table	Ferrous and stainless steel, Al, brass Cu, Pb, PM, Zn, plastic, rubber	N.I.	N.I.
7	Hellatron Recycling	Italy	**1.** Mechanical shredding; **2.** Separation techniques; **3.** Smelting processes	Ferrous metals, Cu, Al, plastics	N.I.	N.I.
8	NEC Group	Japan	**1.** EC and solder removal; **2.** Electrostatic separation	N.I.	N.I.	N.I.
9	Noranda / Xstrata / Glencore	Canada	N.I.	Cu	100 kt	N.I.
10	Rönnskar (Boliden)	Sweden	1. Smelters (furnaces); 2. Refining; 3. Gas cleaning; 4. Thermal energy recovery	Cu, Ag, Au, Pd, Ni, Se, Zn, Pb, In, Cd	100 kt (Cu)	N.I.
11	SDTI E-Waste Recycling Facility	Taiwan	N.I.	Cu, Sn, and PM, an only a small portion of NMF is recovered (6%-24%)	N.I.	N.I.
12	Sepro Minerals Systems Corp.	Canada	**1.** grinding, size separation, low-g gravity separation, and high-g gravity separation; **2.** The reject stream is nonhazardous (conventional landfill disposal or subsequent reuse)	Au, Cu, heavy metals	N.I.	N.I.
13	Shanghai Xinjinqiao Environmental Co., Ltd. & Yangzhou Ningda Precious Metal Co., Ltd.	China	**1.** Two-step crushing; **2.** Cyclone air separation-corona electrostatic separation; **3.** Dust collector; **4.** Vacuum distillation	Cu, Pb, Cd, Zn, Bi, NMF modification (asphalt, phenolic	5 kt	N.I.

				products, wood plastic		
14	SwissRTec AG	Switzerland	**1.** Shredder; **2.** Physical-mechanical separation (density)	Cu, Al, plastics, steel	N.I.	N.I.
15	Umicore Hoboken	Belgium	**1.** Sampling; **2.** PMO: Smelter; Leaching and electrowinning; PM Refinery **3.** BMO: Blast furnace; Lead refinery; SM refinery	Au, Ag, Pd, Pt, Rh, Ir, Ru, Cu, Pb, Zn, Ni, Sn, Bi, In, Se, Te, Sb, As, Co, REE	350 kt	50 t (PGM - *Platinum group metals*); 100 t (Au); 2400 t (Ag)
16	WEEE Metallica	France	**1.** Automated shredding; **2.** Magnetic separation (Fe); **3.** Eddy current separator; **4.** Pyrolysis furnace (plastics, resins); **5.** Gases treatment	Cu, PM	25 kt	N.I.

*N.I.: Not informed

Source: Based on (KHALIQ, RHAMDHANI, *et al.*, 2014) and (KAYA, 2019)

Table 13. E-waste recyclability classification

Category	**Examples**
Easy-to-recycle	Computers, washing machines, and some photocopiers
Moderately easy-to-recycle	Majority of electronic wastes, including air conditioners, refrigerators, toner cartridges, liquid-crystal display monitors, light-emitting diode monitors, printers and scanners
Difficult-to-recycle	PWB and cell phones

Source: The authors, based on information from (DE ALBUQUERQUE, MELLO, *et al.*, 2020, ZENG, LI, 2016)

The three recyclability levels of e-waste presented in **Table 13** imply diverse options for recycling technology. In the case of the "easy" recycling category, simple dismantling is the major approach, while in the "moderate" category needs a combined process of dismantling and simple mechanical recycling, and, finally, in the "difficult" category, intense physical treatment and chemical recovery are indispensable (ZENG, LI, 2016).

Thus, the knowledge of the respective treatment, recycling level as well as recyclability potential of e-waste in a certain country can help establish the stage of the e-waste management system (EWMS) in this nation. The EWMS involves a set of measures taken for establishing adequate e-waste management. Depending on the development level (not necessarily economic, but mainly in terms of e-waste management) of a certain country, there are three different stages (HUISMAN, STEVELS, *et al.*, 2019):

(i) **Starting countries:** inexistent EWMS or those starting to draft e-waste policies inspired by other countries. Such measures mainly aim to prevent disasters related to e-waste hazardousness, the basics of local pollution control, and initial infrastructure development as simple, practical and noncapital intensive as possible. Since the countries established in this development level are in their initial steps in the matter of adequate e-waste treatment, the usage of dumpsites, landfills and incineration techniques for e-waste can be more frequent than in the other levels, and the informal chains are dominant.

(ii) **Emerging countries:** in this level, e-waste policies are recently implemented or about to be enacted by decrees, laws or standardization. The main goal of this level is the improvement and expansion of the initial e-waste reverse logistics systems (collection and treatment). In this sense, pollution control is more developed than in the previous level, and there is the intention to upgrade the initial system in terms of efficiency (energy savings, material recovery, etc). However, more advanced technology for complex e-waste fractions is not a reality in these countries yet, and, therefore, exportation is still part of the EWMS business models of such nations to guarantee adequate treatment for their e-waste in the formal chains. Informal practices are still a reality at this level and represent one of the main challenges to the system. Therefore, even though dumpsites (mostly forbidden by law in these countries), inadequate/harmful recycling techniques, landfills and incineration are used informally by such actors, the second-level recycling technologies (as proposed by UNEP (2007)) can be already implemented by the formal e-waste industry. The challenges, in this case, are to improve the traceability systems, develop an inventory for a national database, increase the incentives to collection and adequate value recovery processes, explain some unclear topics in the implementation rules, establish basic standards to e-waste treatment, and, finally, to formalize and professionalize the informal actors.

(iii) **Established countries:** here, the e-waste policies are already implemented, in practice, and the efforts are to modernize some measures to refine the EWMS and include all e-waste flows into the national inventory and monitoring system. These countries already have high rates of pollution control and aim to improve the quality of the collected e-waste and the efficiency (energy savings, material recovery rates, etc) of the valorization processes. Therefore, innovation in the e-waste collections and recycling industry is encouraged, besides full deployment of standards and full monitoring system are targeted.

Table 14 illustrates the main e-waste systems' goals and main adopted techniques for e-waste processing in each EWMS. It is worth mentioning that, even though dumpsites are mostly forbidden in emerging and established countries, they are still a reality in the informal chains of the emerging nations, and, therefore, were considered in the second line in **Table 14**.

Table 14. Goals and main adopted techniques for e-waste processing in each EWMS

Development level	EWMS's main goals			Adopted techniques (recovery degree level)			
	Pollution control	Energy savings	Material recovery	Dumpsites/ landfills	Incineration	Primitive recycling	Advanced recycling
Starting countries	L / M	L	L	✓	✓		
Emerging countries	M	L / M	L / M	✓	✓	✓	
Established countries	H	M / H	M / H			✓	✓

*L = low; M = medium; H = high

Source: The authors, based on (HUISMAN, STEVELS, *et al.*, 2019, KHALIQ, RHAMDHANI, *et al.*, 2014, NING, LIN, *et al.*, 2017, UNEP, 2007)

Legislation is usually the first focus for starting countries to develop their EWMS and for emerging countries to improve their existing systems (HUISMAN, STEVELS, *et al.*, 2019). The next subsections briefly explain the evolution of the legal documents related to e-waste in the international and Brazilian scenarios.

2.2.3. International e-waste legislation

The first laws related to e-waste in the world started in the 1970s as an attempt to control the hazardous waste trades, including e-waste, from industrialized countries to less-developed nations in Asia, Africa, Central America and Eastern Europe (UNEP, 2010). Such transboundary movements were a result of strict legal measures against inadequate disposal of hazardous waste and its increasing costs in the developed nations, leading to the exportation of these materials to countries with less severe environmental laws. Also, cheaper labour costs and eventually bypassed taxes in the developing nations encourage these trades (legally or illegally) (SEPÚLVEDA, SCHLUEP, *et al.*, 2010).

This discussion resulted in the elaboration of the Basel Convention on the Control of the Transboundary Movements of Hazardous Wastes and their Disposal, which was adopted in 1989 and came into force in 1992 (BAKHIYI, GRAVEL, *et al.*, 2018). This document aimed at regulating the export of hazardous waste from industrialized countries to less-developed and vulnerable nations, therefore restricting hazardous waste exports unless the receiving country has confirmed the existence of environmentally sound practices for managing the imported waste (BAKHIYI, GRAVEL, *et al.*, 2018). E-waste was included in this document in 1998, in Annex VIII.

Since then, other laws and policies were implemented in the world to control and reduce toxicity, besides encouraging reuse and adequate processing through recycling and other value recovery options. The European Union (EU) is considered a leader in the implementation of e-waste management, legislation and best practices in the international scenario (ARAUJO, 2013), highlighting the Nordic countries' e-waste management systems as efficient models for e-waste recovery (YLÄ-MELLA, POIKELA, *et al.*, 2014). Switzerland was the first country in the world to develop and implement a well-organized, formal e-waste management system for the collection, transportation, recycling/treatment and disposal of e-waste (OLIVEIRA, C.R., BERNARDES, *et al.*, 2012).

In an attempt to both control the contamination caused by toxic substances and promote adequate management and recycling of increasingly generated e-waste in Europe, the EU adopted, in 2003, the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive (2002/95/EC) and the WEEE Directive (2002/96/EC in February 2003), respectively. The RoHS Directive restricted the use of ten toxic substances including heavy metals, flame retardants or plasticizers (i.e., lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE), bis(2-Ethylhexyl) phthalate (DEHP), butyl benzyl phthalate (BBP), dibutyl phthalate (DBP) and diisobutyl phthalate (DIBP)) (EUROPEAN UNION, [S.d.]). In 2011, a New RoHS Directive enters into force, and in 2017, the Commission adopted a legislative proposal adjusting the scope of the RoHS Directive. The WEEE Directive promoted e-waste collection, reuse and recycling, besides emphasizing the producers' responsibility for the collection and treatment of discarded devices. This legislative framework did not achieve the desired aims, and, therefore, a revised version of this Directive (2012/19/EU) became effective in February 2014.

In the Americas, the United States (USA) is the greatest e-waste producer, and the second in the world, only after China (FORTI, V, BALDÉ, *et al.*, 2020). However, the country allowed e-waste disposal in landfills and less strict environmental regulations for e-waste recycling in previous legislations (ILANKOON, GHORBANI, *et al.*, 2018). Hence, several states enacted regional laws to promote adequate e-waste management, and, currently, 25 states and the District of Columbia have enacted some form of related legislation, covering 75-80% of the USA population (FORTI, V, BALDÉ, *et al.*, 2020). In 2011, the federal government implemented the National

Strategy for Electronics Stewardship (NSES) as the basis for improving the design of electronic equipment and enhancing the management of used or discarded electronic devices (ILANKOON, GHORBANI, *et al.*, 2018).

Canada is one of the highest contributors to e-waste volume in the Americas (BAKHIYI, GRAVEL, *et al.*, 2018), even though the country does not have national legislation in effect on the management of e-waste, being regulated by the provinces (FORTI, V, BALDÉ, *et al.*, 2020, XAVIER, OTTONI, *et al.*, 2021). E-waste legislation has been introduced into each Canadian province since 2002, and today, all provinces and territories, except for Nunavut are covered by such regulations (FORTI, V, BALDÉ, *et al.*, 2020, XAVIER, OTTONI, *et al.*, 2021).

In Latin America, considerable progress in the promotion of specific e-waste regulations in the last years has been observed, even though this progress is limited only to a few countries (i.e., Brazil, Chile, Mexico, Costa Rica, Colombia and Peru). From them, only Brazil and Chile are establishing the bases to a formal regulatory framework for e-waste (FORTI, V, BALDÉ, *et al.*, 2020).

In the Asian continent, China is the major highlight as the greatest e-waste generator in the world. In 2006, the Chinese government has implemented regulations analogous to the European Union's RoHS directive: the China RoHS 1, with measures for the administration of pollution control of electronic information products. This document was revised in 2016, and this new version was entitled China RoHS 2, aiming at reducing the use of lead, mercury, cadmium, and hexavalent chromium and flame retardants in electronics (ILANKOON, GHORBANI, *et al.*, 2018). Since 2003, China has had national legislation ("Bulletin regarding strengthening environment management of WEEE") in force that regulates the collection and treatment of various types of e-waste (YU, HE, *et al.*, 2014). Other countries in East Asia (i.e., Japan and the Republic of Korea) have advanced e-waste regulation (FORTI, V, BALDÉ, *et al.*, 2020). India, the third-biggest e-waste generator worldwide, is the only country in Southern Asia with e-waste legislation, and laws to adequate e-waste management have been in place since 2011, in which only authorised dismantlers and recyclers can collect e-waste (FORTI, V, BALDÉ, *et al.*, 2020).

In the African continent, only 13 of the 54 countries have a national e-waste legislation/policy or regulation in place (e.g. Egypt, Ghana, Madagascar, Nigeria, Rwanda, South Africa, Cameroon, Côte D'Ivoire), even though enforcing the legislation is very challenging (FORTI, V, BALDÉ, *et al.*, 2020). The literature has reported that many countries (e.g., Nigeria, Kenya and South Africa) have poor regulatory frameworks and policing of the industry, resulting in unaccounted-for e-waste flows and a thriving illegal e-waste trade business. In general, even though these countries benefit from some of the international deals, they still do not have the infrastructure to ensure that the effects of participating in some of these treaties are felt at a grassroots level (ILANKOON, GHORBANI, *et al.*, 2018). In Nigeria and South Africa, institutional frameworks were developed to regulate and support the e-waste recycling industry. However, given the context of high informality, e-waste recycling became over-regulated and thus operators remained as informal and semi-legal agents (ILANKOON, GHORBANI, *et al.*, 2018).

From the 14 countries in Oceania, only Australia has national e-waste legislation in place: National Television and Computer Recycling Scheme (NTCRS), in force since 2011, providing Australian householders and small businesses with access to industry-funded collection and recycling services for televisions and computers (FORTI, V, BALDÉ, *et al.*, 2020). New Zealand is still considering the development of national regulation for e-waste management, especially taking into account that 98.2% of generated household e-waste ends up in landfills in the country (FORTI, V, BALDÉ, *et al.*, 2020).

Besides the regulations, some international initiatives can be highlighted, as the case of Solving the E-waste Problem (StEP), which is led by the Institute for the Advanced Study of Sustainability (UNU-IAS SCYCLE) at the United Nations University's (UNU). This multi-stakeholder program initiated research and discussion among these in tackling the e-waste problem (ILANKOON, GHORBANI, *et al.*, 2018, STEP INITIATIVE, [S.d.]).

2.2.4 Brazilian e-waste legislation

The Brazilian Environmental Policy (Law No. 6,938 of August 31, 1981) was a definitive milestone to environmental management in Brazil. However, the country has enacted its waste regulation at the federal level only in 2010, closing a cycle of environmental legislation in Brazil (ARAUJO, 2013).

Before the adoption of the Brazilian Policy on Solid Waste (BPSW), enacted by Law 12,305/2010, only some specific waste categories had management guidelines at the national level, such as construction (CONAMA 307 of 07/05/2002), pesticide packaging (CONAMA 334/2003 and Laws nº 7.802/89 and 9.974/2000), lubricating oils (CONAMA 362 of 06/23/2005 and 258/1999), batteries (CONAMA 401 of 04/11/2008 and tires (CONAMA 416 of 09/30/2009) (ARAUJO, 2013). In addition, the national standard ABNT NBR 10,004/2004 specifies the methods and tests for the characterization of waste that must be classified as "hazardous" or "non-hazardous", which can be "inert" and "non-inert". This standard is currently in the process of being revised and updated.

Before the enactment of the BPSW, some members of the Federation already regulated solid waste management, as illustrated in **Table 15**.

Table 15. Major Brazilian state regulations before BPSW related to post-consumer reverse logistics

Regulation	State	Year	Description
Decree No. 26,604, of May 16, 2002	Ceará	2002	Regulates Law No. 13,103/2001, which provides for the State Policy on Solid Waste in the state of Ceará.
Law No. 14,248 of July 29, 2002.	Goiás	2002	Provides for the State Policy on Solid Waste and other measures.
Law No. 7,862 of December 19, 2002	Mato Grosso	2002	Provides for the State Policy on Solid Waste and other measures
Law No. 4,191, of September 30, 2003	Rio de Janeiro	2003	Provides for the State Policy on Solid Waste and other measures.
Law No. 416 of January 14, 2004	Roraim a	2004	Provides for the State Policy for Integrated Solid Waste Management and other measures.
Law No. 5,857 of March 22, 2006	Sergipe	2006	Provides for the State Policy for Integrated Solid Waste Management and provides related measures.
Decree No. 54,645, of August 5, 2009	São Paulo	2009	Regulates provisions of Law No. 12,300 of 2006, which institutes the State Policy on Solid Waste, and amends item I of article 74 of the Regulation of Law No.

			997, of 1976, approved by Decree No. 8,468, of 1976.
Law No. 9,264 of July 15, 2009	Espírito Santo	2009	Establishes the State Policy on Solid Waste and other related measures
Law No. 18,031 of January 12, 2009	Minas Gerais	2009	Provides for the State Policy on Solid Waste
Decree No. 45,181 of September 25, 2009	Minas Gerais	2009	Regulates Law No. 18,031, of January 12, 2009, and other measures

Source: Adapted from FERNANDES DO NASCIMENTO, XAVIER (2018)

The waste regulation limited to the state or municipal levels imposed a problem to the policies of extended producer responsibility in some states (ARAUJO, 2013). This fact represented a challenge for some waste categories, as in the case of the post-consumption electronics, generated in a concentrated way in some specific states and in a dispersed way in others.

In 2010, the BPSW was enacted by Law 12,305/2010 (BRAZIL, 2010a) and regulated by Decree 7404/2010 (BRAZIL, 2010b) as the first national legislation that addressed the e-waste problem, among other waste categories. The BPSW established e-waste as one of the six waste categories considered in the reverse logistics systems (RLS) with procedures such as collection, transportation, processing and environmentally sound disposal of waste. The other waste categories in the RLS included: pesticides, their residues and packaging; batteries; tires; lubricating oils, their residues and packaging; fluorescent, sodium and mercury vapour and mixed light bulbs (BRAZIL, 2010a).

Despite being the main e-waste regulation in the country, the BPSW does not specify the quantitative goals and deadlines to environmental compliance (XAVIER, OTTONI, *et al.*, 2021). The implementation of such RLS at a national level was just conducted after the signature of the Sectoral Agreement (BRAZILIAN MINISTRY OF THE ENVIRONMENT, 2019), in 2019, and later in Federal Decree 10,240/2020 (BRAZIL, 2020), which officialized its terms at the level of federal law. The RLS includes household electrical and electronic products and their components, not considering nondomestic electronic waste of professional use, health services, batteries or lamps.

The goals considered in the RLS are related to collection and destination rate based on the total electronics products put on market (PoM) in Brazil for domestic use in the base year of 2018, varying, in weight, from 1% (in 2021), 3% (in 2022), 6% (in 2023), 12% (in 2024), and 17% (in 2025) (BRAZIL, 2020). **Table 16** details the main characteristics of the Brazilian e-waste legal framework and **Table 17** specifies the topics related to the e-waste RLS, as determined by Law.

Table 16. Brazilian legal framework in the EWMS

Legislation	BPSW (Law No. 12,305/2010 and Decree No. 7404/2010)	Established the obligation of implementing e-waste RLS
	Sectoral Agreement (2019)	Rules for household e-waste RLS
	Decree No. 10,240/2020	Rules for household e-waste RLS (officialized the Sectoral Agreement terms at the level of federal law)
Standards	ABNT NBR 16,156/2013	Electrical and electronic equipment's waste - requirements for reverse manufacturing activity
	ABNT NBR 15,833/2018	Reverse manufacturing - Refrigeration apparatus

Table 17. Main topics on the Brazilian e-waste RLS

Parameter	**Values/Types**	**Description**
E-waste RLS focus	Household e-waste	Included in the national RLS
	Other types	Can be collected via contracting between generators and product manufacturers, importers, distributors and merchants, with its final destination provided for in the Solid Waste Management Plans
Stakeholders' responsibilities	Producers, importers, distributors and traders	Implement RLS; Keep complete information updated and available to the competent municipal authorities regarding the actions under their responsibility
	Producers and importers	Provide environmentally adequate disposal of returned waste and its packaging
	Distributors and traders	Return products and packaging to producers or importers
	Consumers	Return of post-consumption products to the system
	Public urban cleaning services	Can be in charge of the responsibilities of agents in the direct chain upon remuneration agreed between the parties
	Waste pickers cooperatives/associations	Can be part of the RLS if legally constituted and qualified, and through a legal instrument
	Management entities (ABREE and Green Eletron)	Constituted by companies or associations of manufacturers and importers of electronic products to carry out the structuring,

		implementation, management and operation of the RLS
Financial responsibility	Producers and importers	Direct payment to management entities or by individual systems, in the proportion corresponding to their participation in the domestic use market
RLS processes	I - Disposal	Disposal, by consumers, of electronics at collection points
	II - Temporary storage	Receipt and temporary storage of electronics discarded at reception points or consolidation points
	III - Transportation	Transportation of discarded electronics from the collection points to the consolidation points
	IV – Final destination	Environmentally adequate final destination
RLS goals	Year 1 (2021)	**Collection & destination:** 1% by weight of PoM in 2018 **Attended cities:** 24
	Year 2 (2022)	**Collection & destination:** 3% by weight of PoM in 2018 **Attended cities:** 68
	Year 3 (2023)	**Collection & destination:** 6% by weight of PoM in 2018 **Attended cities:** 186
	Year 4 (2024)	**Collection & destination:** 12% by weight of PoM in 2018 **Attended cities:** 294
	Year 5 (2025)	**Collection & destination:** 17% by weight of PoM in 2018 **Attended cities:** 400

Producers, importers, retailers and distributors must implement the RLS, while the consumers are responsible for the return of post-consumption products to the system. This system is under the financial responsibility of the electronics producers and importers, which can be organized into associations. The producers and importers can also determine a managerial entity to control and implement the e-waste collection, transport, processing and adequate disposal.

2.2.5 Brazilian e-waste management system (EWMS)

The current status of the Brazilian EWMS can be illustrated in grey colour by **Table 18**, which indicates, according to an association of the E-waste Management Manual (UNEP, 2007) and the theory developed by HUISMAN, STEVELS, *et al.* (2019), some selected practices and corresponding levels of development. The five levels from low (1) to high (5) were converted into the three-scale method proposed by HUISMAN, STEVELS, et al. (2019): starting, emerging and established countries.

Table 18. Brazilian e-waste management status and development level in selected fields, in grey colour

Practice	Level				
	Starting country		Emerging country		Established country
	1 (Low)	2	3	4	5 (High)
Legal framework	There is no legal framework, strategy or norms	There is only a plan to develop a legal framework	The legal framework is being prepared and will be an issue/enforced n the very near future	Enforcement, but the legal framework is not well conducted	Full enforcement and model legal framework for other countries
Inventory	There is no inventory	There is an inventory for municipal solid waste, but no designated inventory for e-waste	E-waste inventory is being prepared	E-waste inventory is conducted, but lack of information and data	E-waste inventory is fully conducted and available on the website
Separate collection	There is no separate collection system	E-waste is locally collected by local recyclers, scavengers, etc, without any legal framework. Only recyclable e-waste is well conducted	E-waste collection is well conducted by local mechanisms. Pilot separation and collection systems have been set up	The collection system for e-waste is operational and includes environmentally sound disposal	Collection systems are fully operational. The collection system is recognized as a model for other countries
Recycling / other value recovery technology	There is no recycling / other value recovery mechanism	Only recyclable and reusable e-waste is recycled and reused by local stakeholders	There is a plan to set up an e-waste facility	There are e-waste recycling facilities, but not achieved full operation for all e-waste in the country	The e-waste recycling facility is fully operated for all e-waste in the country and is a model of a state-of-art recycling facility for other countries

Source: Based on UNEP (2007) and HUISMAN, STEVELS, *et al.* (2019)

Table 18 indicates the development stage of Brazil regarding e-waste management, highlighting its characteristics as an emerging country in terms of EWMS. Legal framework and existent recycling techniques are more developed, while formal data for inventory and the level of collection system are still in their beginning. Even though Brazil already established a national reverse logistics system for e-waste, the informal sector still takes part in this collection, and it is difficult to determine if environmentally sound disposal is performed in such chains. Therefore, in **Table 18**, Brazil was assessed in Level 3 in this topic.

The legal framework is in force, especially more recently, with the first-year implementation of the e-waste RLS at a national scale. However, considering the various challenges related to the legislation (fragile taxation system, double taxation, significant informal chains, among others discussed in this chapter), it was considered here as “not well conducted”.

The e-waste inventory is not a reality in the current status, given that the RLS is still in its first year. Only after this first year of RLS operation that the inventory will be disclosed. It is important to highlight that this inventory will cover only the household e-waste quantities collected by the system, excluding the other e-waste types, as those generated by corporations and institutions. This means that the e-waste national inventory is still far from being a complete and real representation of the generated and treated e-waste in the country.

The e-waste collection system was recently implemented (January 2021), but an infrastructure for collection and separation was already operational in more developed Brazilian regions, mostly stimulated by the legal framework in BPSW for pollution control and shared responsibility for product life cycle at company levels. However, given the relevant presence of the informal chains in the collection systems and the lack of traceability of e-waste flows, the environmental sound disposal of such collection cannot be determined in a current context. Only the formal collection system in the established RLS can have a guarantee of adequate disposal.

The national e-waste collection system is built upon take-back points (or voluntary delivery points - VDP) from both e-waste management entities, ABREE and Green Eletron, besides sporadic campaigns for e-waste collection promoted by such entities. **Figure 6** presents the details regarding the official collection system of the Brazilian e-waste RLS.

Figure 6. Official collection points of the Brazilian e-waste RLS: (a) ABREE collectors; (b) Green Eletron collectors

Management entity	**E-waste collection points**	**Attended cities**
(a) ABREE	1364 points	576 and the Federal District
(b) Green Eletron	215 points	77

Source: ABREE (2021) and GREEN ELETRON (2019)

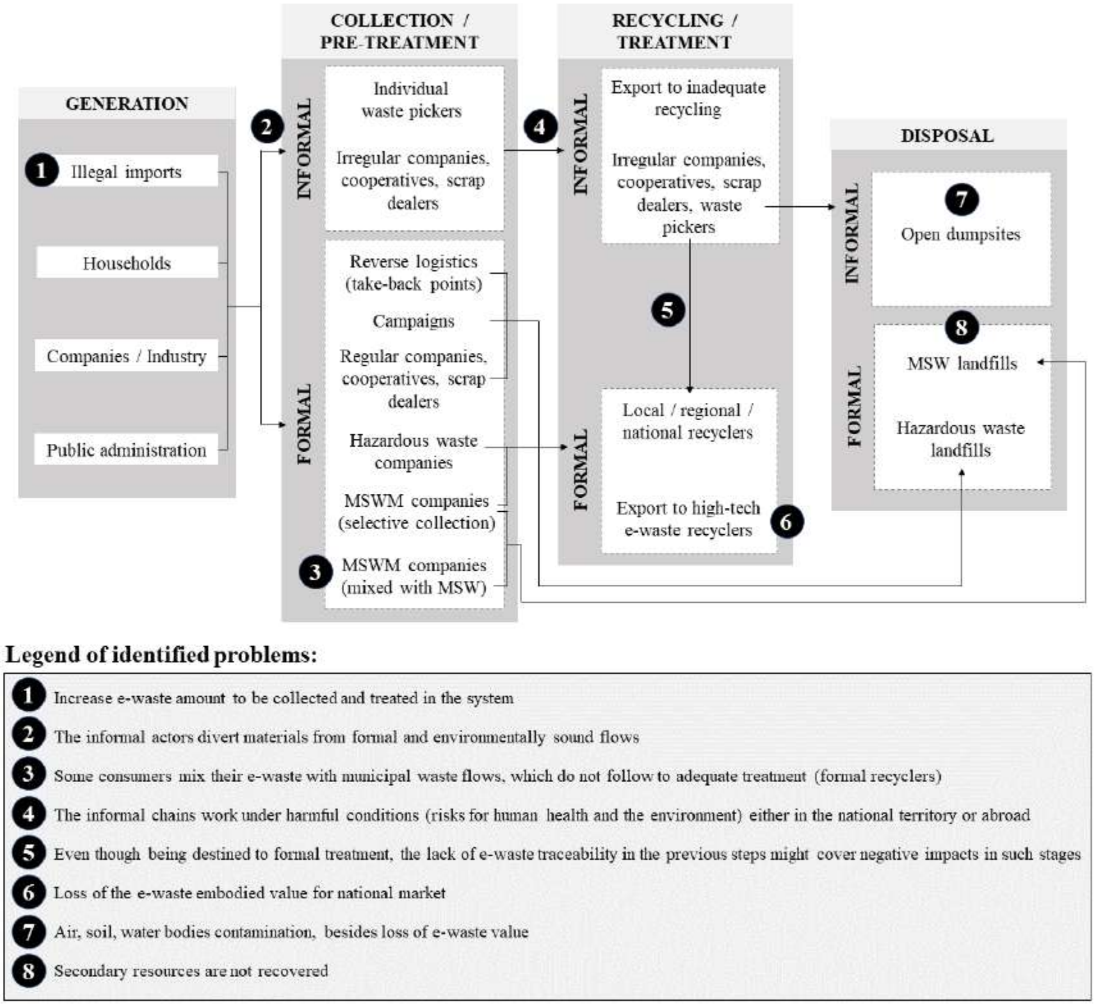
Besides the official collection system, the various recycling agents and some municipal governments also provide door-to-door collection for household e-waste under a certain fee (SOUZA, Ricardo Gabbay, 2019), which tends to migrate to the national system in the next years with its expansion to more cities.

Finally, as discussed in **Table 18**, Brazil already has e-waste recycling facilities, which operate only until an intermediate recycling level, as already verified by previous studies (AFONSO, 2018, DIAS, MACHADO, *et al.*, 2018, LOPES DOS SANTOS, 2020). Therefore, the valuable and most complex fractions collected by the formal chains are exported for adequate treatment and value recovery overseas.

Even in this transition from a starting to emerging country level in terms of EWMS, Brazil is known as a reference for e-waste management in Latin America given the established regulation (FORTI, V, BALDÉ, *et al.*, 2020) and recent national collection system implementation.

Figure 7 illustrates the general framework of the main e-waste fluxes within the Brazilian EWMS and some identified problems.

Figure 7. E-waste flows in the Brazilian EWMS and identified problems



Source: Based on flows frameworks in SOUZA (2019) and XAVIER, OTTONI, *et al.* (2021)

Figure 7 indicates eight main issues related to the flows in the Brazilian EWMS, in a way to complement the analysis of the current country status. This framework highlights that, besides the significant e-waste production from internal sources, e-waste generation is also influenced by illegal imports, which might contribute to overloading the downstream collection and treatment system in the country.

In the collection and pre-treatment step, the informal agents in this chain corroborate to divert e-waste fractions that should be directed to environmentally sound disposal options, which can increase the risks of human and environmental contamination downstream. Besides, there are several cases of inadequate e-waste disposal by consumers that discard their post-consumer devices mixed with municipal solid waste flows (OLIVEIRA, FRANCISCO, *et al.*, 2020), configuring this as one of the problems spots to the e-waste RLS since these materials end up in landfills and not in the e-waste value recovery destinations. The still embryonic consumers awareness regarding their responsibilities for adequate disposal must be faced as an important step to be addressed for increasing the development level of the Brazilian EWMS.

In the next phase of the e-waste flows, the techniques adopted in the informal chains to recover some valuable fractions of e-waste are mostly performed in harmful conditions. Most developing countries face environmental and health challenges from a prevalence of artisanal and informal recyclers (ILANKOON, GHORBANI, *et al.*, 2018), offering risks to the involved workers and the environment, even when performed abroad. These informal actors might also sell materials to some formal recycling/treatment companies, but even so, this alternative does not fix the possible negative impacts in previous stages. According to SOUZA (2019), the individual waste pickers collect e-waste, dismantle the devices, sell the most valuable components (usually to scrap dealers), and dispose of the less valuable parts at open dumps, like vacant lots, green areas, or public parks. The cooperatives or scrap dealers who are not formally licensed to process e-waste is very common in Brazil (SOUZA, Ricardo Gabbay, 2019).

The exportation of the most complex and valuable e-waste to developed countries is a better choice when compared to informal recycling, but it also represents the loss of these embodied valuable fractions of e-waste that could be incorporated into the national market if adequately treated and recovered inside the country. Most of these foreign companies pay reduced values for the preprocessed valuable materials, which decreases the profitability of the Brazilian market (NETO, J.F.O., SILVA, *et al.*, 2019).

The options for final disposal in the country should be the least adopted. However, many scholars still report the usage of landfills and even open dumps for e-waste disposal from both formal and informal chains (SOUZA, R.G., CLÍMACO, *et al.*, 2016, SOUZA, Ricardo Gabbay, 2019, XAVIER, OTTONI, *et al.*, 2021), not only represents a loss of embodied value, but also possible contamination spots. As observed in **Figure 7**, some of the main obstacles to the advance of this current system are informality and lack of traceability since reliable information is one important condition for efficient and transparent system monitoring.

Another challenge directly related to information is the lack of knowledge regarding the real value of the number of electronics placed on the Brazilian market (PoM) in 2018. Therefore, these goals are, in the current status, merely estimated and not properly disclosed by the producers, importers and management entities yet.

The still unclear taxes for the e-waste transport and processing industry at a national scale are other challenges for full implementation of the e-waste value recovery in the country, and this scenario becomes possible for only bigger companies to survive in the market, excluding smaller formal businesses that cannot afford the high taxes. This fact also encourages an informal market in the country. The cases of double taxation (when the taxes are incurred to that same equipment both in the phases before discard and after it) are another vulnerability of the system, especially for recycling agents. An alternative taxation system to promote the e-waste recycling process without incurring double taxation is fundamental to avoid the problems of the current legislation in Brazil (DEMAJOROVIC, AUGUSTO, *et al.*, 2016). A clearer taxes system and financial incentives and subsidies from the Government could change this context. Therefore, although there is a legal framework for e-waste implemented in Brazil, this system still faces many challenges to operate more efficiently, mainly related to lack of information, spread informality, developing consumer awareness and still incipient financial measures to encourage recycling. A plan to address these issues corroborates to increase in the formally collected volumes of e-waste and favours the adoption of more efficient technologies for e-waste value recovery in the country.

2.3 Previous studies related e-waste management in Brazil

The analysis of the e-waste management in Brazil can be understood through the optic of the evolution of the Brazilian regulation on e-waste management, especially after 2010, when the Brazilian Policy on Solid Waste (BPSW) was enacted. The assessment of previous studies related to e-waste in Brazil is another way to complement this comprehension. Therefore, this section presents a literature review of previous studies considering the keywords “e-waste” AND “WEEE” AND “Brazil” in the Scopus Database, in a total of 72 papers. The search was conducted in July 2021 and the first relevant papers started in 2010, as illustrated in **Figure 8**.

Figure 8. Evolution of previous studies and the main regulatory milestones regarding e-waste management in Brazil

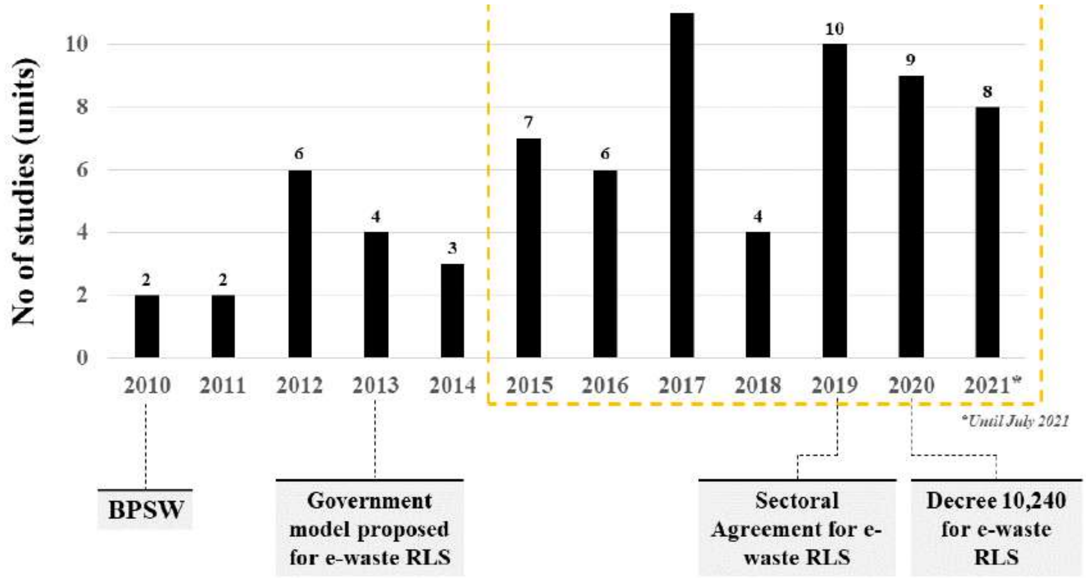
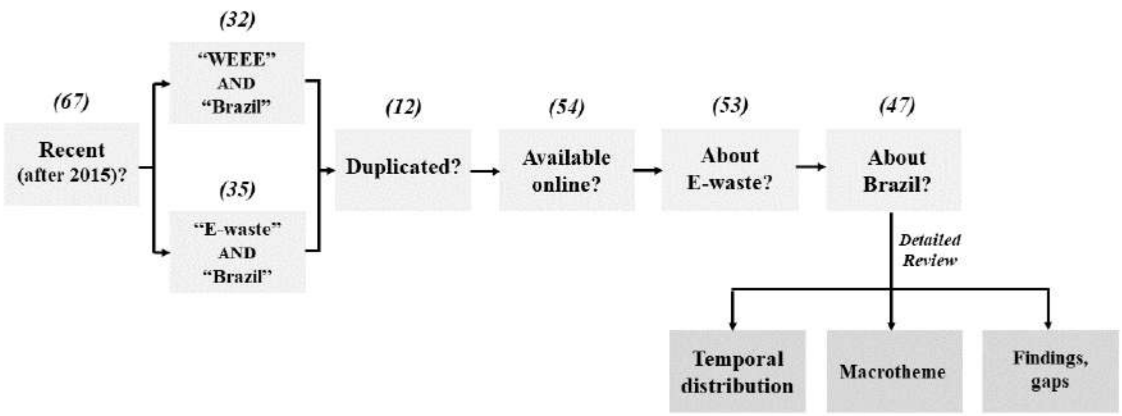


Figure 8 presents the temporal evolution of the studies related to e-waste in Brazil and contrasts it with the main regulatory milestones for e-waste management in the country. In 2010, BPSW established that the Reverse Logistics Systems (RLS) would be mandatory for electrical and electronic products, among others. However, by that year, no EWMS was implemented yet. In 2013, the Brazilian Government proposed a model for EWMS (ABDI, 2013), but since e-waste RLS was just officialized in 2019, this period between 2013 and 2019 the Brazilian EWMS was one of the main debated themes regarding e-waste management in Brazil. From 2019 on, with the Sectoral Agreement followed by the Decree 10,240/2020, the e-waste RLS was officially implemented in the country. These last regulations might explain the boom in the number of papers in 2019 and 2020.

The most recent studies were selected to be assessed in more detail. For this purpose, the chosen sample encompassed the studies published from 2015 until July 2021 (67 articles). Also, the duplicated papers with both "WEEE" and "E-waste" keywords (12 articles) and unavailable papers (1 article) were excluded, besides those that did not address e-waste issues (1 article) in Brazil (6 articles), totalizing 47 articles to be further assessed. **Figure 9** presents the steps for defining the studies to be analyzed according to their temporal distribution, macrothemes, findings and identified gaps.

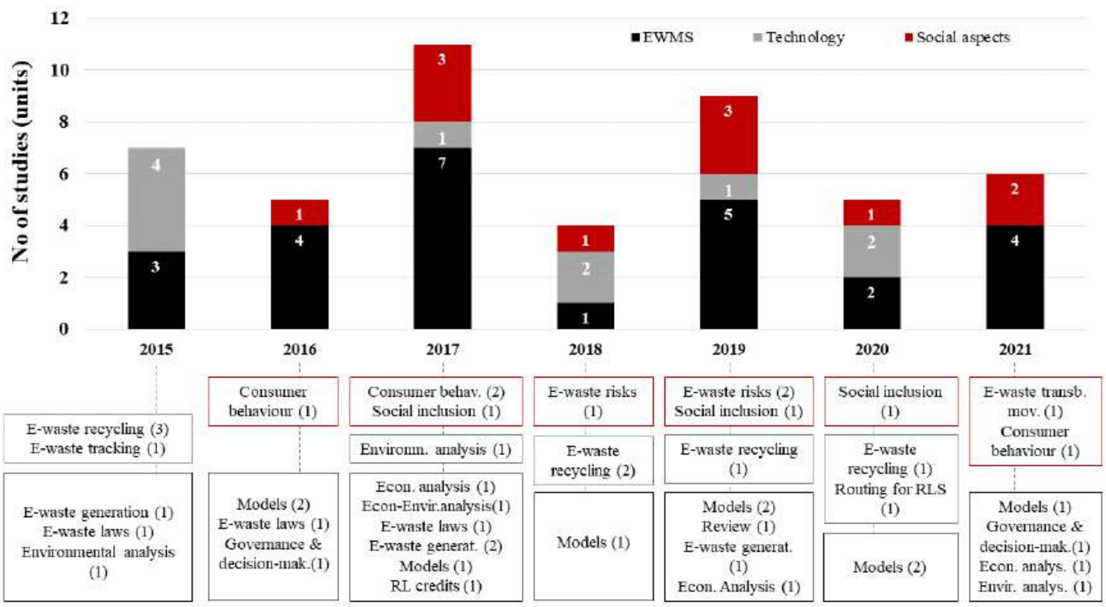
Figure 9. Steps for defining the studies to be assessed



2.3.1. Analysis by macrothemes

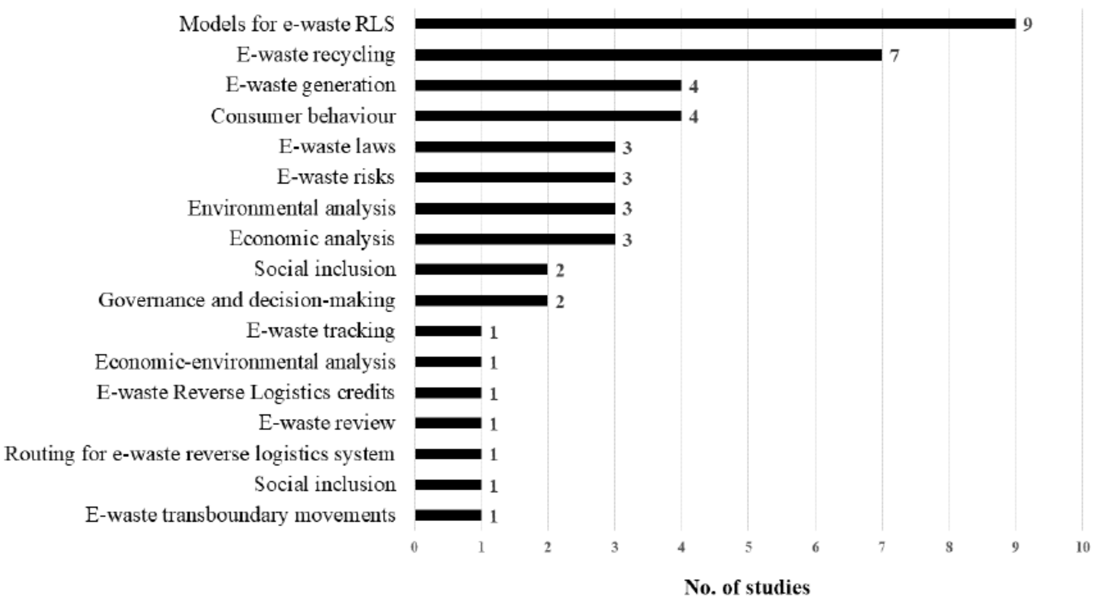
A more detailed assessment of each study was performed to indicate the distribution of the main theme groups (EWMS, Technologies, Social aspects), as illustrated in **Figure 10**.

Figure 10. Temporal distribution of the main theme groups in this review



As described in **Figure 10**, the most studied themes regarding e-waste management in Brazil were related to the macrotheme EWMS (26 studies), followed by Social aspects (11 studies) and Technology (10 studies). **Figure 11** illustrates the most addressed themes within this review: Models for e-waste RLS, e-waste recycling, e-waste generation and consumer behaviour. These main themes have been emphasized by the scientific community in Brazil especially because of the still lacking efficient structure for e-waste collection and value recovery through recycling. The volume of collected e-waste cannot be defined, but the literature estimated that e-waste corresponds to 2% of all waste collected by recyclables collection schemes in 2018 (CEMPRE, 2018). Also, the e-waste recycling rate in Brazil is estimated at 2% (ARAÚJO, MAGRINI, *et al.*, 2012), which is still very far from a solid and efficient infrastructure for value recovery in the country.

Figure 11. Main theme groups identified in this review



Sections 2.3.1.1, 2.3.1.2 and 2.3.1.3 presented the main assessed studies of EWMS, Technology and Social aspects macrotheme groups, highlighting their findings and gaps, which considered limitations indicated in each study and gaps highlighted by the respective authors concerning the Brazilian e-waste management system. **Appendix A** summarizes the most recent and relevant studies regarding e-waste management in Brazil assessed in this study.

2.3.1.1. EWMS macrotheme

Most of the relevant published papers related to e-waste management in Brazil were classified into the EWMS macrotheme, divided into nine themes: Governance and decision-making, models for e-waste RLS, e-waste laws, e-waste generation, environmental analysis, environmental-economic analysis, economic analysis, e-waste reverse logistics credits and e-waste review.

PEDRO, GIGLIO, *et al.* (2021) assessed the constructed governance as an alternative to e-waste recycling management, using the city of São Paulo, Brazil, as a case study. According to the authors, constructed governance could be a competent way to bring actors together to decide about collective rules and obtain a high volume of recycled material, compared with the actual numbers since most e-waste management models are based on control, hierarchical governance, and the prohibition of commercial actions, which seems not to be successful (PEDRO, GIGLIO, *et al.*, 2021).

GUARNIERI, E SILVA, *et al.* (2016) proposed the usage of a specific Problem Structuring Method, the Strategic Options Development Analysis (SODA), for developing strategic analysis based on the decision-makers viewpoints for the e-waste reverse logistics system (RLS) in Brazil. Four categories of actions to be implemented were found and developed: strategic, environmental, economic and social. The authors verified that some aspects still must be improved, such as: i) environmental education; ii) the urgency for greater involvement by producers; iii) the installation of collection points of e-waste in retail channels (e.g., retail stores, shopping malls, supermarkets, etc.); iv) the creation of government policies related to tax incentives; v) the use and adaptation of technologies and systems to register and control the return of e-waste and, vi) the implementation of procedures for effective control by the Government to ensure the effectiveness of the BPSW (GUARNIERI, E SILVA, *et al.*, 2016). It is important to highlight that by the time this paper was published, the country still lacked an e-waste RLS at a national scale.

DEMAJOROVIC, AUGUSTO, *et al.* (2016) have reviewed international examples of e-waste management systems, as the case of two developed countries (Switzerland and Sweden), and two developing countries (China and India), to, finally, compare them with the Brazilian case. The authors pointed out the Best of 2 Worlds (Bo2W) philosophy, discussed in the study of WANG, HUISMAN, *et al.* (2012). In this approach, it was suggested the creation of a consortium to create the ideal e-waste large scale recycling model in the developing nations with the support of developed countries. However, (WANG, Feng, HUISMAN, *et al.*, 2012) demonstrate that the large scale recycling system implemented in China, despite the amount of technical knowledge generated, was not efficient, especially due to the lack of sufficient e-waste volumes at reasonable prices to sustain the daily operation of the plant. It was a result of the absence of e-waste treatment laws in the country, and, therefore, the informal sector dominated waste collection and negotiations, making this project economically unfeasible (DEMAJOROVIC, AUGUSTO, *et al.*, 2016). Thus, implementing a Bo2W recycling infrastructure on a large scale in China can only be successful when adequate laws are in effect (WANG, Feng, HUISMAN, *et al.*, 2012), which could also be considered in the case of other developing countries, as the case of Brazil.

DEMAJOROVIC, AUGUSTO, *et al.* (2016) also indicated some challenges to a large scale implementation of e-waste reverse logistics in developing countries, such as collection volumes insufficient to sustain the operation financially; technological gaps; illegal exports of e-waste; taxation issues are also identified as barriers to companies joining the programs; the resistance by self-employed waste pickers and informal sector companies to supplying e-waste to organized, well-equipped recycling centres; and finally, low awareness of e-waste potential risks to health and the environment, which encourages disassembling and recycling processes without safety equipment and environmental controls.

SOUZA, CLÍMACO, *et al.* (2016) proposed an e-waste take-back system to be applied into the metropolitan region of Rio de Janeiro, considering, by that time, the absence of a national-basis reverse logistics system. The system recommended in the study consisted of a hybrid e-waste collection scheme with delivery points at shops, metro stations and neighbourhood centres; a pre-treatment phase with the involvement of private companies, cooperatives and social enterprises; and full recycling of all components in the country (SOUZA, CLÍMACO, *et al.*, 2016). The authors highlighted the need to integrate Geographic Information System (GIS) with the methodology in search of logistics optimisation (routing and siting).

AUGUSTO, DEMAJOROVIC, *et al.* (2018) evaluated the impact of the cooperation on the implementation of the ‘descarte ON’ e-waste reverse logistics (RL) pilot project in Brazil, considering that the elements of cooperation between the actors can partly explain the success of European countries within their e-waste reverse logistics models. A partnership between Brazil and the Japan International Cooperation Agency (JICA) to implement the ‘descarte ON’ project aimed at assisting in the drafting and implementation of the e-waste Sector Agreement in Brazil. The main results showed that e-waste RL can be effective in the country with the cooperation/partnership among the actors if the proposal presents opportunities for all actors and minimises risks. The participation of the retailers, which for many years rejected to join RL initiatives in Brazil, was positive. However, the e-waste collection was below the expected volumes, showing that cooperation has to occur among all RL members including the final consumer. Therefore, the authors highlighted that the need to encourage the consumer to be aware of the benefits of proper disposal, from the collection phase until the discussion and implementation of the project (AUGUSTO, DEMAJOROVIC, *et al.*, 2018).

SOUZA (2019) analyzed the Brazilian e-waste management scenario, highlighting that more specialized operations within the reverse logistics routes are concentrated in the Brazilian Southeast and South regions. The e-waste recyclers in these regions can only process some e-waste types at a limited capacity, and that informality plays a huge role in e-waste management recycling chains in the country.

DIESTE, VIAGI, *et al.* (2019) proposed a framework to indicate the most suitable scheme for e-waste reverse logistics for Brazil according to the models used in Europe. The European collective schemes can be divided into two main models: the National Collective scheme (NC) and Clearing House model (CH). In the first model, one or more schemes can operate and are in charge of the collection of diverse e-waste categories. This model tends to be more efficient as the schemes can manage the collection points in the best way to maximize logistics efficiency. In the second model, the schemes compete between them as they can gather the same e-waste categories, besides having low logistics efficiency and higher complexity than the NC. Considering the large extensions of the Brazilian territory and the socioeconomic differences between the states, the study suggested a three-level model for Brazil, in which the Federal Government should set the guidelines for e-waste management, states would decide the best model to be adopted and cities would be in charge of the effective e-waste collection. The study indicated that the most suitable model for Brazil is the National Collective model, the most adopted within the Brazilian states (DIESTE, VIAGI, *et al.*, 2019).

The study of VIEIRA, GUARNIERI, *et al.* (2020) was also related to the implementation of the e-waste RLS in Brazil, aiming to identify the main barriers to fully implementing RLS and prioritize it under a Multicriteria Decision Analysis approach (MCDA). According to the perception of the main stakeholders interviewed, the government, micro and small companies agreed that internal barriers with an organizational nature or related to infrastructure management are the main obstacles to the implementation of reverse logistics, while the consumers considered the managerial barriers as a priority (VIEIRA, GUARNIERI, *et al.*, 2020).

DE ALBUQUERQUE, MELLO, et al. (2020) analyzed the e-waste generation and treatment in Brazil and China. Especially regarding the Brazilian situation, the authors identified that Brazil is a great e-waste generator, but more than 90% of it receives inadequate destination. Besides the significant informality in the e-waste recycling sector, the reasons for such problem were highlighted as the lack of: (i) financial factors to support for waste collectors; (ii) a system that covers all stages of the e-waste treatment/processing; (iii) effective standards for collection systems; (iv) cooperation among waste stakeholders; (v) robust educational policy focused on the environment. Therefore, most e-waste in Brazil is separated, exported or landfilled (DE ALBUQUERQUE, MELLO, et al., 2020).

XAVIER, OTTONI, *et al.* (2021) analyzed and compared the e-waste generation patterns, fluxes and regulatory frameworks in Brazil and Canada, two of the biggest e-waste generators in the American continent. Even though Brazil and Canada have differentiated scope of regulation, both have an action agenda that seeks to prioritize the management of hazardous substances, as well as lack of harmonized regulation, low control of the e-waste illegal trade and traceability (XAVIER, OTTONI, *et al.*, 2021).

CORREIA, NETO, *et al.* (2015) performed a comparative analysis of regulatory instruments in reverse logistics for e-wastes in Brazil, Japan, European Union members, the USA, and China. The main findings indicated that the largest number of laws created for e-waste management was not decisive to improve the return index (or collection rates) and e-waste recycling. The countries with few regulatory instruments (as in the case of Japan and European Union members) stood out for their high return indexes and e-waste recycling. The USA, despite being a developed country and the largest e-waste generator on the planet, exported much of its e-waste to developing countries, which could be understood as a lack of consistent policies Nationwide to adequately tackle the e-waste issue. China has shown to have legislation for e-waste management, but structured reverse logistics and mapping recycling is still a challenge in the country, given the relevant informal segments without proper government control. The Brazilian e-waste law was considered relatively new for conclusive analysis with the researched data to demonstrate the collection and recycling rates, even though some goals for e-waste RLS had been already set by Law.

POLZER, PISANI, *et al.* (2016) analyzed the current situation of the reverse logistics schemes in Brazil (including e-waste) and the importance of the Brazilian Policy of Solid Waste (BPSW). The study showed that Brazilian cities can use the European extended producer responsibility (EPR) schemes as parameters to set up the guidelines in the short and long terms. Also, the EPR regulation and economic instruments can promote diverting of waste from landfills to reusing, recycling and recovering treatments. However, the lacking political will to implement aspects of the Law regarding waste management was observed, as well as the need for cities not only to increase the number of e-waste delivery points but also to help recycling companies being able to disassemble the e-waste components.

LIMA, ROCHA, *et al.* (2017) presented three Brazilian government's efforts to support e-waste recycling facilities to comply with environmental sound practices: a legal framework as an incentive, a technical standard as a tool and SIBRATEC as technological support, make up the structure of Brazilian government support for small and medium-sized recycling enterprises. Law 12.305/2010 (which enacted the Brazilian Policy on Solid Waste, BPSW) is a legal framework that determines the guidelines, goals, responsibilities and actions to achieve integrated solid waste management. The technical standard ABNT NBR 16156/2013 is a tool to discipline the best practices of organization and management of an enterprise that performs e-waste recycling. The SIBRATEC program (2015) provided technological support for small and medium-sized enterprises to suit the requirements of ABNT NBR 16156. Preliminary results of the SIBRATEC program has demonstrated the importance of ABNT NBR 16156 as an effective tool to make the technological evolution of enterprise by placing it at a new technological level and encouraging more efficient practices in the e-waste recycling market (LIMA, A.B., ROCHA, *et al.*, 2017).

RODRIGUES, GUNTHER, *et al.*, (2015) estimated the e-waste generation from households in the city of São Paulo. The study indicated a total amount of 71.9 million electrical and electronic equipment (EEE), 8.8 million of which (12.2%) are out of service and most of the households (72.6%) declared to store out of service EEE. Average annual disposal *per capita* resulted in 4.8 kg/inhabitant. Moreover, CRT TVs and monitors represent from 25 to 27% of the total weight, needing treatment due to the hazardous substances they contain. Reverse logistics systems must be prepared to primarily absorb this liability within the next few years (RODRIGUES, GUNTHER, *et* *al.*, 2015). The proposed method contributed to the estimates of important indicators for e-waste management in Brazil.

PANIZZON, REICHERT, *et al.* (2017) evaluated the e-waste generation in a private university in Brazil. The main e-waste generated by the institution was Information technology (IT) and telecommunications equipment (48.2%), large household appliances (14.4%), monitoring and control instruments (13.3%), electrical and electronic tools (10.9%) and consumer equipment (9.8%). The results also showed that the majority of e-waste was generated by the university administration (29.3%) and the computer classrooms (17.3%), whilst areas like Biology and Exact Sciences have EEEs with a longer lifespan, resulting in smaller waste generation. The authors highlighted the great complexity in e-waste management in higher education institutions, mostly due to the considerable diversity (PANIZZON, REICHERT, *et al.*, 2017).

PAES, BERNARDO, *et al.* (2017) also conducted a study on a University Campus by proposing an e-waste management model for public education institutions through Action Research. As indicated in the main findings, the action research is an adequate management tool for public institutions looking to deal with e-waste issues. Two improvement cycles were conducted: at the university warehouse and other sectors within the institution. The results pointed that 474 e-waste units were adequately treated and disposed of (PAES, BERNARDO, *et al.*, 2017).

ARAUJO, DE OLIVEIRA, *et al.* (2017) evaluated the e-waste generation on Fernando de Noronha Island in Brazil. The study estimated that 1.3 tons of e-waste were generated in one year. Also, mobile phones, televisions, computers in general, and refrigerators were the most found domestic equipment, and these goods are quickly exchanged due to the lack of technical assistance on the island. The study indicated that the population and government treated e-waste as ordinary waste, ignoring its contaminant potential (ARAUJO, Dhiego Raphael Rodrigues, DE OLIVEIRA, *et al.*, 2017).

ABBONDANZA, SOUZA (2019) aimed at developing and applying an e-waste estimation method in São José dos Campos, Brazil, using, therefore, primary data. The main results of the study suggested that the lifespan profiles in the city are considerably different than previous values adopted in other Brazilian studies. For instance, the variation in waste smartphones generation in the study of ABBONDANZA, SOUZA (2019) from 2014 to 2022 ranges from 2.4% to 9.1%, while the growth of waste mobile phones generation in Brazil estimated by (ARAÚJO, MAGRINI, et al., 2012) from 2000 to 2008 was around 0.35%. Also, the authors showed that there were significant variations of lifespan profiles for different e-waste types among the geographical zones of the city, reflecting the socioeconomic differences (ABBONDANZA, SOUZA, 2019). SOUZA (2019) discussed this same theme, highlighting that the e-waste generation in Brazil is based on estimation methods, which have uncertainties and adopted approaches.

SOUZA, ROSENHEAD, *et al.* (2015) developed a methodology for stakeholder consultation regarding the selection of impact categories and applied this method for the definition of a model for the Brazilian e-waste reverse logistics system (RLS). The main results revealed some potential innovative impact categories in the Brazilian e-waste RLS, especially driven by the causal mapping and the involvement of stakeholders. Also, the endpoint impact categories in the LCA reflected best the essential sustainability concerns, but their measurement was problematic, while the midpoint impact categories were more operational, even though they needed to be refined. The method has shown to be straightforward and effective, with no need for quantitative ratings and minor influence of the analysts' perspectives and had very positive feedback from stakeholders in its application in the Brazilian e-waste RLS modelling.

ROCHA, PENTEADO (2021) assessed the environmental benefits and burdens resulting from an e-waste reverse logistics system through life cycle assessment (LCA) in Campinas Area, Brazil. The results indicated that the benefits of reverse logistics outweigh its impacts due to the saving of metals and mineral resources recovered from recycling printed circuit boards and to the reduction of the potential environmental impact in human toxicity categories. Moreover, the material flow analysis showed that 85% of the e-waste materials (by mass) are effectively recovered, indicating a loss of 15% of all input material. In the case study, the reverse logistics of all small e-waste generated (52,206 tonnes) has the potential to avoid about 149,000 tonnes of CO2 eq. and 2000 TJ of fossil resources (ROCHA, PENTEADO, 2021).

AZEVEDO, ARAÚJO, *et al.* (2017) and estimated the costs of the proposed logistical model for e-waste RLS, indirectly assessed the main routes between the collection, screening centres and recycling industries in Minas Gerais state and Brazil, respectively. The first study indicated that the proposed logistical model in Minas Gerais is profitable. Also, the installation of industries for the processing of printed circuit boards in Brazil would increase earnings as legal export costs, environmental taxes, and charges would be replaced by environmental taxes in Brazil and maritime freight costs would be eliminated (AZEVEDO, ARAÚJO, *et al.*, 2017). The second study showed that 10,000–15,000 workers would be required to operate the entire RLS at full capacity, covering 100% of the national territory. Besides, if the producers/importers pay for the RLS and complete recycling for precious metals recovery, the entire system would become self-sustaining without demanding government investment and consumer charges (AZEVEDO, ARAÚJO, *et al.*, 2019).

NETO, CORREIA, *et al.* (2017) mapped the e-waste recycling processes in Brazil and evaluated the economic and environmental advantages of e-waste reverse logistics manufacturers and recyclers in Brazil, considering that some valuable e-waste components (i.e., WPCB) are exported to foreign countries to be recycled. The authors assessed the recycling processes in Brazilian companies and a Swiss recycling unit that receives WPCB from Brazil. The results showed that the main e-waste recycling activity in Brazil is that of polymers, which requires a simpler technology. Moreover, the e-waste reverse logistics resulted in the reduction of the environmental impact in the abiotic, biotic, water and air compartments and economic gains for the manufactures and recyclers in Brazil. The authors suggested that Brazil should invest in PCB recycling technology to increase its economic and environmental advantages in e-waste materials management (NETO, G.C.O., CORREIA, *et al.*, 2017).

VALENTE, GUABIROBA, *et al.* (2021) conducted an economic analysis of e-waste management in recycling cooperatives in Brazil in a way to determine whether it is attractive for recycling cooperatives in a determined Brazilian municipality to include a selective collection of e-waste in their operating systems. The case study in the municipality of Volta Redonda, in Rio de Janeiro state, was performed to test the method. The results indicated that e-waste inclusion is economically attractive when recycling cooperative receives support from scrap dealers and the government. Also, the distance between cooperatives and the recycling industry is generally long, which might compromise the economic sustainability of the e-waste value recovery. Another pointed challenge was that the large generators and recycling industries do not establish agreements directly with cooperatives, mainly because these cooperatives do not offer large volumes. The authors highlighted the importance of the participation of public authorities in the promotion and support of recycling cooperatives.

The study of CAIADO, GUARNIERI, *et al.* (2017) proposed the description of the Brazilian e-waste reverse logistics credits (RLC) market and an analogy with the carbon credit market. The main findings indicated that most of the stakeholders agree that the reverse logistics credit market is a possibility, but currently, the Brazilian RLC market still does not have any legal support to work on, no organization to control and audit the market, and no support from the government (CAIADO, GUARNIERI, *et al.*, 2017).

NETO, SILVA, *et al.* (2019) proposed a brief overview of e-waste management in Brazil, including technical aspects, scientific studies, and the challenges ahead. In this paper, 26 articles were analyzed until 2018. Most studies referred to “e-waste management strategies”, followed by “e-waste composition and recovering”, being published after 2012, probably motivated by the 2010 promulgation of the BPSW. After 2017, more articles focused on management strategies were developed, reflecting a trend to resolving e-waste management problems (NETO, SILVA, *et al.*, 2019). Only a few studies focused on e-waste’s production forecast, reflecting the difficulty of finding reliable data of certain types of electronic devices in the country (NETO, SILVA, *et al.*, 2019), same tendency observed in the present chapter.

2.3.1.2. Technology macrotheme

The Technology macrotheme was divided into four themes: E-waste tracking, e-waste recycling, environmental analysis and routing for e-waste RLS.

In 2015, a study for tracking e-waste was developed to incorporate Radio Frequency Identification (RFID) in e-e-waste reverse logistics in Brazil, and, to highlight the benefits of such technology, the authors performed a cost assessment study (ARAUJO, OLIVEIRA, *et al.*, 2015). The main findings indicated that the introduction of RFID technology in e-waste reverse logistics increases the potential for surveillance practices and contributes to better performance of administrative structures of e-waste, avoiding cases of government failure by damaging omission (ARAUJO, OLIVEIRA, *et al.*, 2015).

In this same year, all three studies related to e-waste recycling aimed at developing new routes or analyzing already existing processes for WPCB recycling. WPCB full or advanced recycling is not a reality in Brazil yet, which was highlighted as a gap in various previous studies (SILVA, AUGUSTO, *et al.*, 2015, DE ALBUQUERQUE, MELLO, *et al.*, 2020, GHISOLFI, DINIZ CHAVES, *et al.*, 2017, LOPES DOS SANTOS, 2020, NETO, SILVA, *et al.*, 2019, SCHROEDER, DE OLIVEIRA NETO, *et al.*, 2015).

Some studies on the recycling of WPCB in Brazil have been published in the last years, focusing on the details of laboratory-scale processes. SILVA, AUGUSTO, et al. (2015) suggested a route considering the mechanical processes followed by hydrometallurgical and biohydrometallurgical solutions since the country already has the basic competencies for the development of these technologies in other applications, as the case of primary mining. (SILVAS, JIMÉNEZ CORREA, *et al.*, 2015) developed a new combined route (physical and hydrometallurgical) to recycle printed circuit boards (PCBs) from printers to recover copper. The results indicated that at the end of the hydrometallurgical processing, 100% of copper extraction was obtained and the recovery factor was 98.46%, which corresponds to 32 kg of Cu in 100 kg of PCB (SILVAS, JIMÉNEZ CORREA, *et al.*, 2015).

SCHROEDER, DE OLIVEIRA NETO, *et al.* (2015) described all processes involving recycling and reuse of WPCB in Brazil and verified the available technology to so, by conducting semi-structured interviews in a PCB manufacturer company. The results indicated that e-waste recycling and reuse in Brazil are decentralized, so it becomes complex to develop general network cooperation, mainly for the metal recovery process of e-waste, which is made by foreign companies (SCHROEDER, DE OLIVEIRA NETO, *et al.*, 2015).

CAMPOLINA, SIGRIST, *et al.* (2017) assessed the environmental aspects of e-waste plastic recycling on large scale in a Brazilian company. The main findings indicated that, when compared to the production of virgin ABS and HIPS, the recycling processes reduced the energy consumption by approximately 90% for both plastics and CO2 emissions by approximately 84% for HIPS and 87% for ABS. Besides, the plastics recycled by the company retained over 90% of their virgin mechanical properties. Thus, recycling avoids environmental impacts since it prevents e-waste from being disposed of in landfills and the pellets of recycled plastics can be recovered as raw materials (CAMPOLINA, SIGRIST, *et al.*, 2017).

In 2018, two other studies discussed the recycling technologies for e-waste. AFONSO (2018) described the e-waste reverse manufacturing processes, starting from sorting and disassembly, highlighting that the initial focus is the housing, which, in general, is separated without much difficulty from the internal components, and the electrical wires/cables. The internal components can be separated into a few large groups: printed circuit boards (PCB), cathode ray tubes (CRT), liquid crystal display

(LCD) flat screens and lighting emission diode (LED), support elements and components according to the EEE considered (such as a scanner screen, printer cartridges, etc) (AFONSO, 2018). The author also explained the recycling processes of specific and complex e-waste components, such as the PCBs, CRT and LCD flat screens, and emphasized that e-waste recycling in Brazil is very incipient and not organized in scale, resulting in the export of items that have high added value (AFONSO, 2018).

This same problem is discussed by DIAS, MACHADO, *et al.* (2018), which presented an analysis of the e-waste market in Brazil, considering the analysis of e-waste processing based on 134 recycling companies active in Brazil, main e-waste fluxes/routes, and suggested that future studies could evaluate to which extent the country is unable to recycle complex components such as PCB. The study showed 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 it manually. Also, the revenue generated by the e-waste recycling market in Brazil can financially support up to five agents involved in the e-waste flow (DIAS, MACHADO, *et al.*, 2018).

In 2019, another study was developed for e-waste recycling technology, aiming to analyze a mechanical process route for WPCB to concentrate their metal content and reduce costs of the subsequent recovery of copper, tin, and lead (DA SILVA, M.F., DUTRA, *et al.*, 2019). The authors found out that 10.7% of the obsolete WPCB was comprised of magnetic materials, the content of the metals in the residue was 18.8% of copper, 3.4% of lead, and 1.3% of tin, and the enrichment of copper (from 43±11% to 68±5%), tin (from 10±3% to 17±1%), and lead (from 4±1% to 6.4±0.5%) were obtained by the developed process (DA SILVA, M.F., DUTRA, *et al.*, 2019).

LOPES DOS SANTOS (2020) analyzed the organisation of formal recyclers in São Paulo Macrometropolis (SPMM) and found out that most companies operate at different organizing levels and only have the technology to perform the initial (data destruction, sorting and dismantling) and intermediate levels (also operating with waste physical fragmentation), and none perform the advanced recycling level of the e-waste recycling process. Therefore, most of the partially recycled e-waste is sold to other industries that can use it as raw material (like steel mills) or to recyclers outside the country that have the most advanced technology (LOPES DOS SANTOS, 2020).

In terms of logistical studies aiming at routing for e-waste reverse logistics, OTTONI, DIAS, et al. (2020) assessed the best routes between e-waste hotspots and reverse logistics agents (those who work in the pretreatment and/or preprocessing stages) in the Metropolitan Region of Rio de Janeiro, Brazil. The authors identified thirty-five hotspots and divided them into five main routes according to the recycling industries nearby, the local roads and 12 indicators for circular e-waste management (OTTONI, DIAS, *et al.*, 2020). In a similar line, AZEVEDO, ARAÚJO, *et al.* (2019) and AZEVEDO, ARAÚJO, *et al.* (2017) also proposed a logistical model for e-waste RLS, indirectly assessed the main routes between the collection, screening centres and recycling industries, but with a focus on economic analysis.

2.3.1.3. Social aspects macrotheme

The Technology macrotheme was divided into four themes: Consumer behaviour, e-waste risks, e-waste transboundary movements and social inclusion.

ECHEGARAY (2016) evaluated the consumers' reactions to product obsolescence in emerging markets in Brazil. The main findings indicated that the consumers have experienced a shortened product lifespan over time, which trails expectations of product longevity, but even so, they did not demonstrate dissatisfaction. Also, the technical failure is far surpassed by subjective obsolescence as a motive for rapid product replacement. Therefore, Brazilians naturalize obsolescence by adjusting downwardly their product lifespan management behaviours. The research suggested that knowing how product longevity relates to consumer values may play a pivotal role in the success of public policy and initiatives that promote product longevity (ECHEGARAY, 2016).

In 2017, MOURA, GOHR PINHEIRO, *et al.* (2017) analyzed the relationships between institutional users (IU) and technical assistance (TA) regarding their electronics and e-wastes in Blumenau, Brazil, in the years of 2010 and 2015. The results showed a downward trend for the useful life perception of the equipment and the biggest reason for the exchange/disposal was related to the difficulty for adequate disposal. Therefore, some IUs and TAs chose to stock their waste in the workplace or dispose of them in the municipal solid waste collection. Also, the study identified increasingly informal e-waste recycling companies in Brazil and scarce knowledge about e-waste laws. The authors suggested the implementation of a reverse logistics system that included electronic institutional users and technical assistance.

The study of ECHEGARAY, HANSSTEIN (2017) discussed the determinants of consumer intentions and behaviour towards e-waste recycling in the major metropolitan areas of Brazil. Most respondents of the survey held by the authors demonstrated a positive intention towards e-waste recycling, particularly, female, middle-aged individuals from lower-income groups, and residents of the Southeast region. Only a minority of respondents adopts adequate recycling practices connected to e-waste, a behaviour that is socially skewed among the higher income echelons of Brazilian society (ECHEGARAY, Fabian, HANSSTEIN, 2017). According to the authors, e-waste legal arrangements remain largely unfamiliar to consumers and poorly enforced among both manufacturers and local authorities.

ALVES, FERREIRA, *et al.* (2021) conducted Action Research (AR) to create and implement an e-waste collection program in Brazil. The method was validated in the city of São João del Rei, in Minas Gerais state. The AR method proved to be highly efficient in dealing with e-waste reverse logistics and the consumers showed interest in participating and contributing to the proposed e-waste management program. The study also pointed that public awareness has led to a significant increase in the amount of collected waste by the assessed program in a total of 1710 kg of e-waste. The author indicated that the lack of infrastructure and hesitance of the public for implementing e-waste reverse logistics were complicating factors for the program (ALVES, FERREIRA, *et al.*, 2021).

The study of DIAS, DE OLIVEIRA, *et al.* (2018) focused on recycling technology and methods for mercury removal. DIAS, DE OLIVEIRA, *et al.* (2018) performed a natural leaching simulation (NBR10005) to determine the toxicity of CRT monitors in Brazil and verify how to reduce the hazardousness in its recycling methods. All assessed samples are hazardous due to lead leaching. The CRT panel was verified as lead-free, while the CRT funnel and neck have about 20% of lead oxide in their composition. The study indicated that a vacuum atmosphere and the addition of 5% carbon graphite as a reducing agent are optimum conditions to turn the CRT into a non-hazardous waste.

GOUVEIA, BUZZO, *et al.*, (2019) addressed the problem of the risks related to e-waste handling in waste pickers cooperatives in Brazil, with a case study in the metropolitan region of São Paulo. The study consisted of the assessment of the occupational exposure to mercury in four cooperatives, considering nine areas (recyclable materials pile, scale, baling press machine, e-waste room, cafeteria, office, forklift, conveyor, belt, and outside patio). The results showed that only 14.5% of the

83 samples had concentrations above the limit of quantification (LOQ) while 53% were between the LOD (limit of detection) and LOQ. Also, the Hg concentrations were low in areas of e-waste handling and storage, probably due to the small amount of material and way of processing. Since the samples presented the results below the occupational reference values, the workers were not exposed to Hg (GOUVEIA, BUZZO, *et al.*, 2019). However, the authors affirmed that the sampling performed did not reflect the actual worker exposure, and, therefore, the usage of personal protective equipment was recommended to prevent Hg exposure from broken light bulbs.

CAETANO, DE LEON, *et al.* (2019) developed a methodology to analyze environmental and occupational health risks in e-waste management organizations in Brazil. The main results indicated that the most significant environmental impacts and occupational risks are associated with e-waste sorting and disassembly. Also, some potential environmental impacts are associated with e-waste transportation and coproducts, and the accident risks represented 69% of the sum of all risk levels associated with occupational health. The study showed that e-waste management organizations in Brazil fail to recognize the importance of appropriately addressing risks associated with their processes and activities, and, therefore, there is a need to adopt control measures to protect workers in e-waste organizations (CAETANO, DE LEON, *et al.*, 2019).

The study of ABALANSA, MAHRAD, *et al.* (2021) addressed the e-waste transboundary movements and highlighted that one of the problems relies on the fact that waste management facilities should be installed closer to where the waste is generated. According to the main results, the developed countries are not assuming full responsibility for their environmental problems, opting for exporting their e-waste rather than treating it nationally. Also, the e-waste export to developing countries is driven by the need for novel sources of materials and for constant technological advancement. The authors highlighted that exporting e-waste (whether it comes from developed or developing countries) results in negative environmental impacts (ABALANSA, MAHRAD, *et al.*, 2021).

GHISOLFI, DINIZ CHAVES, *et al.* (2017) designed a closed cycle model to manage the reverse logistics of desktop and laptop waste and assessment of the impact of Brazilian public policies on social inclusion and formalization of waste pickers within EWMS. The main results showed that, even in the absence of bargaining power, the formalization of waste pickers occurs due to legal incentives, and that all the efforts made in the structure and the implementation of such incentive policies will be useless if the necessary raw recycling material is not collected in sufficient volume (GHISOLFI, DINIZ CHAVES, *et al.*, 2017). As suggested by the authors, the cooperatives should work with a varied e-waste portfolio to ensure bargaining power or to achieve this goal through membership in cooperative networks.

FERREIRA, GONÇALVES-DIAS, *et al.* (2019) assessed the inclusion of cooperatives of recyclable waste pickers in the e-waste market in Brazil. Through analyzing the Eco Eletro project, which focuses on the insertion of cooperatives into the Brazilian e-waste market, the study indicated that there is a clear barrier in the access of the waste pickers' cooperatives in the market. Moreover, the government envisioned the inclusion of waste pickers in reverse logistics but did not promote concrete actions for such inclusion to occur. The main challenges faced by e-waste pickers cooperatives were based on achieving a partnership with companies, the competition with companies in the area, the need to achieve minimal e-waste volumes to negotiate good selling prices and, finally, the lack of knowledge about the Brazilian e-waste regulation (FERREIRA, GONÇALVES-DIAS, *et al.*, 2019).

OLIVEIRA, J.D., FRANCISCO, *et al.*, 2020) developed a characterization study of e-waste sent to two waste picker cooperatives that receive e-waste in the city of Recife, Brazil. The authors concluded that the e-waste in cooperatives tends to decrease, being associated with a probable loss of family purchasing power due to the economic crisis, or the removal of e-waste by street waste pickers before the municipal selective collection. The adopted framework considered the monitoring and the e-waste stream analysis phases. During monitoring, no cell phones were found, despite being one of the most frequently replaced electronic devices in Brazil, which can be justified by high retention index of obsolete or broken appliances at home for repair or use in emergencies; and the preference for selling, exchanging or reselling of obsolete or broken appliances. According to (OLIVEIRA, José Diego De, FRANCISCO, *et al.*, 2020), the proposed framework for monitoring and analyzing e-waste streams can be applied and replicated in other situations and contexts. This approach also contributed to reflections regarding the potential business opportunity for cooperatives if the recovery of materials is carried out efficiently and in an environmentally friendly manner. According to the authors, this issue will require the municipality to integrate this new activity into the municipal solid waste management system to minimize environmental and public health risks and to boost the income of cooperatives

(OLIVEIRA, José Diego De, FRANCISCO, *et al.*, 2020).

2.3.2. Main identified gaps

The main gaps identified in each macrotheme were listed to configure a broader vision of the next steps for future research within e-waste management in Brazil (**Table 19**).

Based on the presented information in **Table 19**, the main limitations cited in the literature for effective e-waste management in Brazil are related to:

- **Governance and laws:** Lack of control of authorities over the current distribution of existent e-waste actors, besides the fragile coordinated cooperation between the involved agents and difficulties in adjusting taxation for e-waste within the Brazilian states;
- **E-waste reverse logistics:** Lack of consistent data and a structured system with capillarity;
- **E-waste generation:** Uncertainties related to e-waste estimation methods and few studies focused on e-waste hotspots at the municipal level;
- **E-waste collection:** Irregular flow of collected e-waste, and not organized in scale, lack of effective standards for the collection and the cooperation of involved actors, difficulties in transporting e-waste due to the continental proportions of the country and insufficient collections points for e-waste reverse logistics;
- **E-waste recycling:** Lack of technology for processing the most complex and valuable fraction of e-waste (i.e., WPCB), which is exported. Also, the limited capacity of the recycling industry to process e-waste components in the country mostly concentrated in the Southeast and South regions;
- **Risks:** Mostly presented in the pickers cooperatives, which are unaware of many of the negative effects of e-waste. Potential environmental impacts are associated with e-waste transportation, sorting and disassembly;
- **Informality:** There is an increasing trend for informal e-waste recycling companies, which can result in the illegal extraction of precious metals and generate negative impacts;
- **Social inclusion of cooperatives:** There is a clear barrier in the access of the waste pickers' cooperatives in the market, with a lack of concrete governmental

actions for such inclusion to occur. These organizations face competition with companies and need minimal e-waste volumes to negotiate good selling prices;

- **Consumer behaviour:** Low consciousness of the Brazilian population about proper disposal and often discards e-waste along with the common recyclable waste. Also, the consumers have experienced a shortened product lifespan over time and this fails to fuel consumer dissatisfaction.

This Master's thesis addresses one of these identified gaps in the literature, related to the lack of recycling processes of one of the most complex and valuable fractions of e-waste: the WPCBs. As discussed in this section, the literature indicated several reverse logistics agents acting in the electronics industry in Brazil (DIAS, MACHADO, *et al.*, 2018, SOUZA, 2019), especially numerous small units and few large companies. According to some studies (AZEVEDO, DA SILVA ARAÚJO, *et al.*, 2017, DIAS, MACHADO, *et al.*, 2018, LOPES DOS SANTOS, 2020, SCHROEDER, DE OLIVEIRA NETO, *et al.*, 2015, SOUZA, 2019), these larger recyclers in Brazil purchase valuable e-waste components, or offer treatment and disposal of hazardous fractions, and separate and shred the WPCB to export to large recyclers in the international market – mostly the European ones. Besides the lack of adequate technology, the main difficulty for implementing e-waste recycling processes in Brazil is structuring efficient the e-waste collection system (AZEVEDO, L.P., DA SILVA ARAÚJO, *et al.*, 2017).

As observed in this review, only three studies (AZEVEDO, L.P., ARAÚJO, *et al.*, 2019, AZEVEDO, L.P., DA SILVA ARAÚJO, *et al.*, 2017, OTTONI, DIAS, *et al.*, 2020) addressed the logistical approach in case studies to connect e-waste generation hotspots to recyclers for enabling the implementation of e-waste/WPCB advanced recycling units in Brazil by indicating efficient routes for guaranteeing minimal volumes of collected e-waste. Therefore, this literature gap in determining the main e-waste hotspots and more efficient routes for the recently implemented EWMS in the country (January 2021) to recover the material value of WPCB was one of the reasons for developing this thesis.

Table 19. Main identified gaps in the Brazilian e-waste management

Macrotheme	Theme	Gaps	Sources
EWMS	**Governance and laws**	Most e-waste management models are based on hierarchical governance, and the prohibition of commercial actions, which seems not to be successful	(PEDRO, GIGLIO, *et al.*, 2021)
		Some developed countries are not assuming full responsibility for their environmental problems, opting for exporting their e-waste rather than treating it nationally	(ABALANSA, MAHRAD, *et al.*, 2021)
		E-waste legal arrangements remain largely unfamiliar to consumers and poorly enforced among both manufacturers and local authorities. Lack of formal and continuous feedback instruments to provide all stakeholders with information about their respective roles and possible sanctions	(ECHEGARAY, Fabian, HANSSTEIN, 2017)
		Lack of cooperation among e-waste stakeholders	(AUGUSTO, DEMAJOROVIC, *et al.*, 2018, AZEVEDO, ARAÚJO, *et al.*, 2017, DE ALBUQUERQUE, MELLO, *et al.*, 2020, NETO, CORREIA, *et al.*, 2017)
		Conflicts and the low willingness of manufacturers and retailers with costs sharing	(DEMAJOROVIC, AUGUSTO, *et al.*, 2016)
		Differentiated taxation by Brazilian states for e-waste. Difficulties in adjusting taxation and the possibility of double taxation represents a political cost	(DEMAJOROVIC, AUGUSTO, *et al.*, 2016, NETO, J.F.O., SILVA, *et al.*, 2019)
		The Brazilian government is active in defining incentives, but not in inspecting the industry	(DEMAJOROVIC, AUGUSTO, *et al.*, 2016)
		The government does not have control over the number of active e-waste recycling companies in Brazil	(DIAS, MACHADO, *et al.*, 2018)
		Great complexity in e-waste management in higher education institutions, mostly due to the considerable diversity, increasing the recycling complexity	(PANIZZON, REICHERT, *et al.*, 2017)
	E-waste reverse logistics	Absence of consistent data related to e-waste management and reverse logistics for MERCOSUR countries	(XAVIER, OTTONI, *et al.*, 2021)
		The biggest challenge is the efficient e-waste reverse logistics system with high capillarity and formalizing the informal chain	(AFONSO, 2018)
	E-waste generation	Few studies focused on e-waste's production forecast, especially at the municipal level, and the uncertainties related to these e-waste estimation methods	(NETO, J.F.O., SILVA, *et al.*, 2019, SOUZA, Ricardo Gabbay, 2019, VALENTE, GUABIROBA, *et al.*, 2021)
		High e-waste generation and the inefficient recycling system are critical issues in Brazil	(DIAS, MACHADO, *et al.*, 2018)
		Lack of effective standards for collection systems	(DE ALBUQUERQUE, MELLO, *et al.*, 2020)

	E-waste collection	The main difficulty for implementing e-waste recycling processes in Brazil is the collection system (dependent on the cooperation of consumers, industry, distributors, and the government)	(AZEVEDO, ARAÚJO, *et al.*, 2017)
		Brazil´s huge territory makes collecting waste even more difficult outside big urban areas	(DEMAJOROVIC, AUGUSTO, *et al.*, 2016)
		Difficulties in transporting e-waste from distant areas to recycling centres	(NETO, J.F.O., SILVA, *et al.*, 2019)
		The cities need not only to increase the number of e-waste delivery points for collection but also to help recycling companies being able to disassemble the components	(POLZER, PISANI, *et al.*, 2016)
Technology	**E-waste recycling**	The Brazilian e-waste companies only have the technology to perform the initial and intermediate levels of the e-waste recycling process and the most complex and valuable fraction of e-waste is sold to recyclers abroad that have advanced recycling technology	(AFONSO, 2018, DE ALBUQUERQUE, MELLO, *et al.*, 2020, DIAS, MACHADO, *et al.*, 2018, GHISOLFI, DINIZ CHAVES, *et al.*, 2017, LOPES DOS SANTOS, 2020, NETO, G.C.O., CORREIA, *et al.*, 2017, SCHROEDER, DE OLIVEIRA NETO, *et al.*, 2015, VIEIRA, GUARNIERI, *et al.*, 2020)
		E-waste recycling and reuse processes in Brazil are decentralized and the development of a cooperation network is complex	(NETO, G.C.O., CORREIA, *et al.*, 2017, SCHROEDER, DE OLIVEIRA NETO, *et al.*, 2015)
		Waste management facilities should be installed closer to where the waste is generated	(ABALANSA, MAHRAD, *et al.*, 2021)
		Southeast and South regions concentrate the infrastructure for more specialized operations for e-waste	(NETO, J.F.O., SILVA, *et al.*, 2019, SOUZA, 2019)
		E-waste recyclers can only process some e-waste types at a limited capacity in Brazil	(SOUZA, 2019)
		Brazil lacks proper facilities to extract precious metals from e-waste, and the formal market exports preprocessed waste abroad, reducing the profitability of the enterprise	(NETO, SILVA, *et al.*, 2019)
		WPCB recovery demands a structured plan of the entire network and it increases its complexity	(SCHROEDER, DE OLIVEIRA NETO, *et al.*, 2015)
		If the producers/importers pay for the RLS and complete recycling for precious metals recovery, the entire system will become self-sustaining (no government investment and consumer charges)	(AZEVEDO, ARAÚJO, *et al.*, 2019)
		The installation of industries for the processing of printed circuit boards in Brazil will increase earnings as legal export costs, environmental taxes, and charges will be replaced by environmental taxes and charges in Brazil and maritime freight costs are eliminated	(AZEVEDO, ARAÚJO, *et al.*, 2017)
		The revenue generated by the e-waste recycling market in Brazil can financially support up to five agents involved in the e-waste flow, creating job opportunities	(DA SILVA, AUGUSTO, *et al.*, 2015, DIAS, MACHADO, *et al.*, 2018)
		Recycling in Brazil is very incipient, with the low or irregular flow of collected e-waste, and not organized in scale, and only a very small portion of e-waste has been recycled	(AFONSO, 2018, DA SILVA, AUGUSTO, *et al.*, 2015, LOPES DOS SANTOS, 2020)
		Only one company in Brazil that operates e-waste plastic recycling on a large scale	(CAMPOLINA, SIGRIST, *et al.*, 2017)
		All recycling techniques have limitations, but mechanical preprocessing may increase metal recovery efficiency	(SILVA, DUTRA, *et al.*, 2019)
		The development of small local plants is a viable option, and hydrometallurgy/biohydrometallurgy technology for WPCB recycling supports a low volume of PCBs	(DA SILVA, AUGUSTO, *et al.*, 2015)

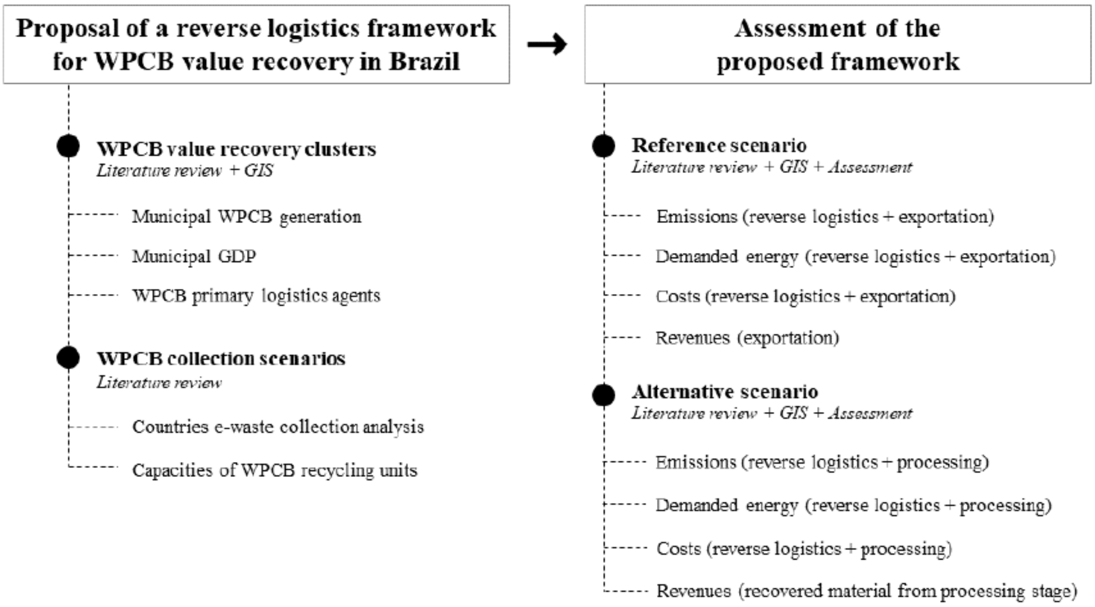
		The biometallurgical process has great potential to leach metals from PCBs. But there are only limited laboratory studies for PCBs processing through Biometallurgical routes	(DA SILVA, AUGUSTO, *et al.*, 2015)
Social	**Risks**	The most significant environmental impacts and occupational risks in the e-waste pickers cooperatives are associated with e-waste sorting and disassembly. Potential environmental impacts are associated with e-waste transportation and coproducts	(CAETANO, DE LEON, *et al.*, 2019)
		E-waste management organizations in Brazil fail to recognize the importance of appropriately addressing risks associated with their processes and activities	(CAETANO, DE LEON, *et al.*, 2019)
		Main suggestions for safety in the e-waste pickers cooperatives: need to adopt control measures to protect workers in e-waste organizations, such as the use of hoods as protection during equipment operation, staff training, and use of personal protective equipment (PPE) have to be adopted in such organizations	(CAETANO, DE LEON, *et al.*, 2019)
		Reducing risks in CRT recycling: CRT monitors are hazardous waste and should not be discarded in non-controlled landfills. The CRT panel is lead-free, while the CRT funnel and neck have about 20% of lead oxide in their composition. Vacuum atmosphere and the addition of 5% carbon graphite as a reducing agent are optimum conditions to turn the CRT into a non-hazardous waste	(DIAS, DE OLIVEIRA, *et al.*, 2018)
		Significant environmental impact reduction in abiotic, abiotic, water and air components with the adoption of e-waste reverse logistics	(NETO, CORREIA, *et al.*, 2017)
	Informality	There is an increasing trend for informal e-waste recycling companies	(MOURA, GOHR PINHEIRO, *et al.*, 2017)
		There is an economic hierarchy among e-waste workers which provides the basis for managing e-waste activities in the informal sector	(ABALANSA, MAHRAD, *et al.*, 2021)
		Informality plays a huge role in e-waste management recycling chains in Brazil	(DE ALBUQUERQUE, MELLO, *et al.*, 2020, SOUZA, 2019)
		An increase in costs of final products may stimulate consumers to purchase products in the grey market	(DEMAJOROVIC, AUGUSTO, *et al.*, 2016)
		Lack of control over the informal market has already begun to undertake the illegal extraction of precious metals from e-waste	(NETO, SILVA, *et al.*, 2019)
	Cooperatives	The participation of public authorities is necessary for the promotion and support of recycling cooperatives	(VALENTE, GUABIROBA, *et al.*, 2021)
		Lack of financial support for waste pickers	(DE ALBUQUERQUE, MELLO, *et al.*, 2020)
		Even in the absence of bargaining power, the formalization of waste pickers occurs due to legal incentives	(GHISOLFI, DINIZ CHAVES, *et al.*, 2017)
		Some Brazilian e-waste pickers cooperatives showed discontinuity of the e-waste processing and the unpredictable occurrence of fluorescent lamps mixed with recyclable materials	(GOUVEIA, BUZZO, *et al.*, 2019)
		Inefficient waste sorting and disputes with private companies that compete with cooperatives are some of the reasons for low efficiency in the e-waste collection process	(GHISOLFI, DINIZ CHAVES, *et al.*, 2017)
		Cooperatives should work with a varied e-waste portfolio to ensure bargaining power	(GHISOLFI, DINIZ CHAVES, *et al.*, 2017)
		There is a clear barrier in the access of the waste pickers' cooperatives in the market. The government envisioned the inclusion of waste pickers in the reverse logistics but did not promote concrete actions for such inclusion to occur	(FERREIRA, GONÇALVES-DIAS, *et al.*, 2019)

		Challenges faced by cooperatives within the e-waste market: the competition with companies in the area, achieving minimal e-waste volumes are needed to negotiate good selling prices, lack of knowledge about the Brazilian e-waste regulation	(FERREIRA, GONÇALVES-DIAS, *et al.*, 2019)
	Consumer behaviour	Low consciousness of the population about proper disposal. The consumer needs to be encouraged of the benefits of proper disposal	(AUGUSTO, DEMAJOROVIC, *et al.*, 2018, DEMAJOROVIC, AUGUSTO, *et al.*, 2016)
		Population very often discards e-waste along with common recyclable waste in Brazil	(OLIVEIRA, José Diego De, FRANCISCO, *et al.*, 2020)
		Brazilian institutions and technical assistance stock their e-waste in the workplace or dispose of them in the municipal solid waste collection mostly due to the difficulty in elimination	(MOURA, GOHR PINHEIRO, *et al.*, 2017)
		Brazilian population tends to hold a positive intention towards e-waste recycling (mostly female, middle-aged individuals from lower-income groups, and residents of the South-east region), and researches indicated that only a minority adopts adequate recycling practices connected to e-waste	(ECHEGARAY, Fabian, HANSSTEIN, 2017)
		Consumers have experienced a shortened product lifespan over time, and this fails to fuel consumer dissatisfaction	(ECHEGARAY, F., 2016)
		Obsolescence: Subjective obsolescence is the main motive for rapid product replacement, far surpassing technical failure. The Brazilian consumers naturalize obsolescence by adjusting downwardly their product lifespan management behaviors	(ECHEGARAY, F., 2016)

3 METHODOLOGY

The adopted methodology was based on two main steps: (i) Proposal of a framework for WPCB value recovery in Brazil; (ii) Assessment of the proposed framework according to economic and environmental indicators when compared to the current scenario. **Figure 12** illustrates the main steps of this study.

Figure 12. Framework of the adopted methodology in this study



Section 3.1 describes the main methods used to identify the WPCB main clusters in Brazil and the assumed collection scenarios to be used in the assessment of the proposed WPCB value recovery framework, as explained in **Section 3.1**.

3.1 Proposal of a framework for WPCB value recovery in Brazil

This Section details the main steps of the proposal for the WPCB value recovery framework in Brazil. First, the e-waste/WPCB value recovery clusters were identified, followed by the determination of the collection scenarios to indicate the potential of WPCB urban mining in Brazil. No material losses from collection to recycling process were considered in this study, i.e., all volumes considered in the collection scenario were adopted as the total input for the proposed WPCB recycling units. The next section detailed the economic and environmental criteria adopted for assessing this proposed framework in comparison with the current scenario.

The WPCB advanced recycling logistics framework proposal in Brazil required the identification of potential poles or clusters of e-waste generation, which was estimated considering the average annual generation of e-waste per capita, 10.2 kg/inhabitant (FORTI, V, BALDÉ, *et al.*, 2020), and the population amount from the last Brazilian demographic census (IBGE - BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS, 2010). This e-waste per capita generation calculated by the Global E-waste Monitor 2020 (FORTI, V, BALDÉ, *et al.*, 2020) was based on empirical data from the apparent consumption method for calculating the EEE PoM (PoM = Domestic Production + Import – Export) and a sales-lifespan model. In this model, lifespan data for each product is subjected to the EEE PoM (using a Weibull function) to calculate the e-waste generated. For countries other than 28 EU member states (case of Brazil), statistical data on imports and exports were extracted from the UN Comtrade database between the years 1995 and 2018. The data on domestic production were retrieved from the United Nations Statistics Division (UNSD) database. More details of this method can be found in (FORTI, V, BALDÉ, *et al.*, 2020). Finally, the e-waste generation map was built with the support of ArcGIS software.

Despite the existence of other methods to estimate the e-waste generation, as those correlating the e-waste generated with the GDP per capita or the Purchasing Power Parity (PPP) of the population (HUISMAN, MAGALINI, *et al.*, 2008, KUSCH, HILLS, 2017), such methodologies demand previous availability of e-waste generation data to fit a regression equation that allows for further projections (ABBONDANZA, SOUZA, 2019). According to ABBONDANZA, SOUZA (2019), methods that apply mass balance are recommended by (UNEP, 2007) and rely on data such as the number of purchased appliances in each year, current stocks (equipment in use) in the studied year, and lifespan profiles of each type of appliance. The lifespan profiles can consider the discrete average lifespan value for each appliance or a lifespan distribution as adopted by the Market Supply method (WANG, HUISMAN, *et al.*, 2013). Although the limitations presented in the usage of the e-waste estimation model developed by FORTI, V, BALDÉ, *et al.* (2020) in the Brazilian case (as the regional socioeconomic disparities that are not considered when adopting a per capita e-waste generation factor), this method was selected for this thesis given the lack of more detailed data at the municipal level for estimating the e-waste production through other more assertive methodologies.

The estimated e-waste generation values per city were converted to WPCB generation in tonnes (t) per day in all Brazilian municipalities, especially for logistics purposes. A simple conversion was made, assuming, by the literature, that WPCB account for approximately 3% of e-waste mass (GHOSH, GHOSH, *et al.*, 2015, MISHRA, JHA, *et al.*, 2021). However, given that other variables might directly influence the e-waste generation, as the case of the gross domestic product (GDP) of a certain population, as demonstrated by KUMAR, HOLUSZKO, *et al.* (2017), the WPCB values obtained from the estimates of the per capita generation (FORTI, V, BALDÉ, *et al.*, 2020) were visually compared to the distribution of the highest municipal and state GDP values to indicate the most probable WPCB generation hotspots in the mapping of value recovery clusters.

The mapping of the e-waste reverse logistics agents (also referred to as recyclers, or those who work in the pretreatment and/or preprocessing stages) was developed with the support of the ArcGIS software and the consultation of preliminary results of the DATARE Project, developed by the Center of Mineral Technology (CETEM), a research institute in Brazil (CETEM, 2021). The list of 272 e-waste reverse logistics agents (CETEM, 2021) was filtered to consider the companies that work at any stage of WPCB management (collection, transport, storage, processing, disposal), verified through their websites information and contact via e-mail and phone calls. Regarding the processing stage, most companies work with segregation and some of them even with shredding for purposes of exportation. The largest companies (with a share capital equal to or higher than R$ 1.000.000,00, equivalent to US$ 186,198.90 in the first quarter of 2021) of this sample were selected. This size indicator was chosen for being a public datum available in the Brazilian legal person register (CNPJ, in Portuguese) database in the Brazilian Internal Revenue Service. The selected reverse logistics agents were mapped using their geographic coordinates in the georeferencing software ArcGIS.

Considering the potential WPCB generation per state and per municipality, besides the distribution of the main WPCB reverse logistics agents and the relevant GDP values, the clusters for WPCB value recovery were proposed and mapped.

The collection scenarios for each cluster were calculated based on three different scenarios for WPCB inputs: low, medium and high. The first scenario considered that only 1% of the generated WPCB could be collected and reached to value recovery processes through recycling, as already performed by some countries (e.g., India, Peru, etc). The second scenario assumed this recycling ratio at 10%, a range that is achieved by some emerging and developed countries, as in the case of Australia, China, Canada, etc. The third scenario is mainly performed by developed countries (e.g., most European countries), and, in this study, the considered range values started from 30%. These values were adopted in a way to achieve the collection scenarios of certain countries, as presented in **Table 20**.

Table 20. Proposal of ranges for collection scenarios based on e-waste collection and treatment rates of various countries

Possible scenarios	Country	E-waste collection and treatment rates
Low (1 - 9%)	India	1%
	Peru	1%
	Argentina	3%
	Chile	3%
	Mexico	3%
	South Africa	5%
	Russia	6%
	Kazakhstan	7%
Medium (10 – 29%)	Australia	11%
	Canada	14%
	United States	15%
	China	16%
	Turkey	18%
	Japan	22%
High (30 – 100%)	Spain	33%
	Italy	34%
	Portugal	42%
	Netherlands	46%
	Germany	52%
	Norway	72%

Source: (STEP INITIATIVE, 2017)

The lowest values in each range were adopted for each of the 3 scenarios, i.e., 1% for the low scenario, 10% for the medium, and 30% for the highest. The small, medium and large-size plants were considered from the study of KAYA (2019) based on the calculated WPCB inputs, as presented in **Table 21**.

Table 21. Main e-waste/WPCB recycling plants types and their capacities

Parameters	Capacity
Small size plant	0.2-0.3 t/h
Medium-size plant	0.3-1 t/h
Large size plant	1-1.5 t/h

Source: Adapted from Kaya (2019)

The values of WPCB processing capacity in each plant in **Table 21** were used to support the economic analysis of estimated costs and revenues for WPCB recycling in Brazil.

3.2 Assessment of the proposed framework

The assessment of the proposed WPCB recycling framework in Brazil considered several environmental, economic and socioeconomic criteria, as presented in **Table 22**. Two scenarios were defined to be further compared: the baseline and the alternative scenarios.

The baseline scenario was based on the current Brazilian context regarding WPCB flows. In this scenario, Brazil generates great amounts of WPCB, and 30% (optimistic) of this waste is collected by the Reverse Logistics System (RLS). The informal destinations were not considered in this study, i.e., all collected WPCB were assumed to be formally collected and directed to the reverse logistics agents (e.g., pickers cooperatives, metals and e-waste pre-processing companies, and other recycling agents, for instance, metals, plastic recyclers) in the country. Since there is no formal WPCB processing industry for precious metals recovery in Brazil, in the reference scenario, all WPCB collected were, finally, exported to refineries abroad.

Table 22. Adopted criteria to calculate the costs, revenues, emissions and energy of the baseline and alternative scenarios

Criteria		Value	Source
Economic	**Distance per litre (km/L)**	3.4	Estimated for semi-heavy trucks operating with diesel (BRAZILIAN MINISTRY OF THE ENVIRONMENT (MMA), 2013)
	Diesel price (R$/L)	2.33	BRAZILIAN MINISTRY OF MINES AND ENERGY (2020)
	Diesel price (USD/L)	0.43	Calculated (1 BRL=0,18 USD)
	Diesel price (USD/km)	0.14	Calculated (0.43 USD/L * 3.4 km/L)
	Bunker price (USD/t)	370	FOLHAPRESS (2020)
	Travelled sea distances (km/d)	464.29	Estimated from the route Salvador-Lisbon
	Demanded bunker (t/d)*	150	NOTTEBOOM, CARRIOU (2009)
	Bunker price (USD/km)	119.54	Calculated
	Processing costs (USD/t)*	900,00	YANG, SUN, et al. (2021)
	Processing revenues (USD/t)*	25192	
Environmental	**Diesel emission (kgCO2e./km)**	1.28	Carvalho (2011)
	Bunker emission (kgCO2e./MJ)	0.069-0.076 (assumed 0.07)	HSIEH, FELBY (2017)
	WPCB processing emissions (tCO2/t metal produced)	3.73	KAYA (2019)
	Diesel low calorific power (MJ/kg)	43	LIMA ([S.d.])
	Bunker low calorific power (MJ/kg)	39	HSIEH, FELBY (2017)
	Diesel density (kg/L)	0.837	LIMA ([S.d.])
	Energy from Diesel (MJ/L)	35.991	Calculated
	Energy from Diesel (MJ/km)	10.586	Calculated
	Energy from Bunker (MJ/d)	5,850,000	Calculated
	WPCB processing energy (MJ/t WPCB)	7763	YANG, SUN, et al. (2021)
Socioeconomic	**Average wage (R$/month)**	2308.00	IBGE (2019)
	Average wage (USD/year)	4985.28	Calculated

* Assumed for a containership (8,000 TEU at 21 knots)

The details of the reference scenario contemplated a survey of the exportation patterns related to e-waste in Brazil. Therefore, the COMTRADE database (UNITED NATIONS, [S.d.]) was consulted for each month of the year 2020. Considering that WPCB encompasses the fraction with the most valuable elements in e-waste, such as precious metals, the commodity code 7112 (Waste and scrap of precious metal or metal clad with precious metal; other waste and scrap containing precious metal or precious metal compounds, of a kind used principally for the recovery of the precious metal) was selected.

The comprehension of the potential exportation patterns was used as a parameter of the chosen assumptions for the reference scenario. As a simplification of the method, it was assumed that all collected WPCB was exported to a recycling facility in Belgium, considering the transport through ships operating with bunker oil.

The approximate carbon emissions, demanded energy and costs calculation for the reference scenario were performed based on the following steps:

(i) **Estimative of WPCB generation hotspots in Brazil:** the average annual generation of e-waste per capita, 10,2 kg/inhabitant (Forti et al., 2020) was considered, as well as the population amount from the last Brazilian demographic census (IBGE, 2010), and the conversion factor of 3%, corresponding to the average proportion of WPCB in e-waste (GHOSH, GHOSH, *et al.*, 2015, MISHRA, JHA, *et al.*, 2021). The numbers were converted to generation in kilograms (kg) per day in all Brazilian municipalities, especially for logistics purposes;

(ii) **Identification of the main Brazilian reverse logistics agents:** step already performed in the previous section from the list of e-waste reverse logistics agents of CETEM (2021), which was filtered to consider the companies that work at any stage of WPCB management. The largest companies (with a share capital equal to or higher than R$ 1.000.000,00, equivalent to US$ 186,198.90 in the first quarter of 2021) of this sample were selected and mapped using ArcGIS software;

(iii) **Identification of the main Brazilian ports:** The main ports were obtained from (LÓPEZ-BERMÚDEZ, FREIRE-SEOANE, *et al.*, 2019) and mapped using ArcGIS software;

(iv) **Calculation of the average distances along the main Brazilian roads from the WPCB hotspots to the main reverse logistics agents, and then, from these recyclers to the closest identified ports:** this step was performed with the support of Google maps engine search;

(v) **Calculation of the average sea distances from Brazil to Belgium:** this step was performed with the support of the Google maps engine search, considering the Antwerp Port (Belgium) as the final destination. The Antwerp Port was chosen because a relevant WPCB recycling industry, which will be used in part of this simulation, is based close to this port. Considering that a typical trip from Salvador (Brazilian city) to Lisbon (Portuguese city) can reach 14 days by ship and corresponds to approximately 6500 km, the other distances from the Brazilian ports to Belgium were estimated in days (using this approximated Salvador-Lisbon factor of 464,29 km/d);

(vi) **Estimate of the emissions and demanded energy related to the road transport and the sea transport:** the metric adopted is based on Global Warming Potential (GWP), in kg CO2e., of each stage, considering 1,28 kg CO2/km (CARVALHO, 2011) for Brazilian heavy vehicles operating with diesel. The spent energy for road transport was calculated assuming that a semi-heavy truck demanded 1L of diesel to move 3.4 km (BRAZILIAN MINISTRY OF THE ENVIRONMENT (MMA), 2013) and that the generated energy from diesel was 35.99 MJ/L, or 10.586 MJ/km (35.99 MJ/L / 3.4 km/L = 10.586 MJ/km). The emissions for ships operating with bunker oil were indicated in the literature as 69-76 gCO2e/MJ (HSIEH, FELBY, 2017), and, in this study, the value considered was 0.07 kgCO2e/MJ. For matters of simplification, it was assumed that a containership demands 150 t of bunker oil per day and that the lower calorific value of HFO (bunker oil) is approximately 39 MJ/kg (HSIEH, FELBY, 2017). Therefore, a containership demanded, in this study, 5,850,000 MJ/d. The duration of the trip from the Brazilian ports to Belgium, in a total of days, was estimated based on the regular maritime routes between both countries;

(vii) **Transportation costs estimates:** the economic costs for the baseline scenario were calculated in USD/year, using the criteria in **Table 22**. The price of the diesel was obtained from BRAZILIAN MINISTRY OF MINES AND

ENERGY (2020) and converted into 0.14 USD/km, considering that the road transport would be performed by semi-heavy trucks operating with diesel that run 3.4 km/L (BRAZILIAN MINISTRY OF THE ENVIRONMENT (MMA), 2013). In the case of sea transport, the costs of bunker oil were considered, calculated as 119.54 USD/km. These values per kilometre we multiplied by the corresponding calculated distances, resulting in the total transportation costs (road plus sea) for the baseline scenario.

(viii) **Revenues estimates with the sales of WPCB to foreign recycling companies:** The revenues from the sales of WPCB to foreign recycling companies can be estimated in a simplified way by considering the average value charged by the Brazilian companies that export WPCB of about 30 BRL/kg of WPCB (data obtained from the regular prices of some consulted formalized companies that collect and export WPCB in Brazil). This value was converted to USD/t of WPCB considering the exchange rate of 1BRL = 0.18 USD on August 19, 2021. The exported WPCB amounts were estimated as the same as those calculated for the alternative scenario in tonnes, generating an approximated value of the revenues obtained in the baseline scenario to be further compared to the alternative scenario.

The alternative scenario considered the implementation and operation of the WPCB processing units (one per cluster) for value recovery in Brazil. Therefore, the exportation of WPCB would be no longer necessary.

For the alternative scenario, the methodology was segmented in the following steps:

(i) **Selection of the best locations for the Brazilian WPCB recycling plants:** The indication of the more favourable sites for implementing advanced recycling units in each cluster was based on logistics, economic, environmental and social criteria, as described in **Table 23**. First, the municipality with the highest WPCB daily generation (WPCB hotspot) was selected for each cluster since the distance between these hotspots and the advanced recycling units to be determined is an important factor for efficient logistics planning for urban mining. Then, the analysis of the closest municipalities regarding the criteria in **Table 23** was performed in the identified clusters. The scoring point method for ranking the most favourable municipalities was based on the type of answer of each indicator. In the cases in which the indicators present the metric of YES/NO answers, the municipalities with NO as an answer were excluded from the map, and YES answers corresponded to the highest weights in that category. When the indicators presented the metrics based on numeric values, such data were scaled in ranges, in which the highest values in each scale were ranked with greater scores, and vice versa. The total sum of the weights of each indicator provided the order of the most favourable municipalities, considering the preference for the highest sum. The main indicators were organized and converted into shapefiles format, to be further processed in ArcGIS software, generating maps to help the visual analysis of best locations for implementing the advanced recycling plants of each cluster.

Table 23. Indicators to assess the most favourable sites for implementing e-waste/WPCB advanced recycling plants in Brazil

Criteria	Indicator	Year	Measuring unit	Source
Logistics	Municipal WPCB generation	2019	kg/d	Mishra et al. (2021); Forti et al. (2020); IBGE (2010)
Logistics	Distance to the main WPCB generation pole (municipality)	-	km	Georeferencing tools
Logistics	WPCB reverse logistics agents	2021	units	(CETEM, 2021)
Economic	Municipal GDP	2018	BRL (R$)	(IBGE, 2018)
Environmental	Municipality considered in the Sectoral Agreement for electronics RLS	2020	YES or NO	(BRAZIL, 2020)
Social	Municipal Human Development Index (MHDI)	2010	0 (less developed) to 1 (most developed)	(UNDP, 2010)

(ii) **Calculation of the average distances along the main Brazilian roads from the WPCB hotspots to the main reverse recyclers, and then, from these recyclers to the Brazilian WPCB recycling plants:** this phase was performed with the support of Google maps engine search;

(iii) **Estimative of the emissions and demanded energy related to the road transport to the WPCB recycling plants and their operations:** the metric adopted is based on GWP, in kg CO2 eq., of each stage, considering 1,28 kg CO2/km (CARVALHO, 2011) for Brazilian heavy vehicles operating with diesel. The spent energy for road transport was calculated assuming that a semi-heavy truck demanded 1L of diesel to move 3.4 km (BRAZILIAN MINISTRY OF THE ENVIRONMENT (MMA), 2013) and that the generated energy from diesel was 10.586 MJ/km (35.99 MJ/L / 3.4 km/L = 10.586 MJ/km). The average emissions of a typical WPCB recycling plant, considering the pyrometallurgical route, were obtained from the literature (KAYA, 2019);

(iv) **Costs and revenues estimative:** the costs for the alternative scenario were calculated in terms of transport and processing operations, and the revenues considered all gains derived from the potential of WPCB recycling. The transportation costs were based on the calculated road distances, and the processing costs were obtained from the estimated values suggested by the literature of between 100 and 900 USD/t of processed e-waste (YANG, SUN, *et al.*, 2021). The most conservative scenario was assumed for this simulation (900 USD/t). As for the revenues, the same authors indicated an average of 25192 USD/t of processed e-waste (YANG, SUN, *et al.*, 2021). These factors were multiplied by the approximate processed WPCB in each cluster, resulting in the final costs and revenues on an annual basis;

(v) **Potential generated jobs:** as previously performed by YANG, SUN, *et al.* (2021), the calculation of potential jobs generated by the revenues from WPCB processing in the country could be performed by considering the average wage in Brazil, obtained from (IBGE, 2019). This number was converted into an annual value in USD, considering the exchange rate of 1BRL = 0.18 USD on August 19, 2021. The total revenue was divided by the annual average wage, indicating a dimension of potential generated jobs by the WPCB value recovery activities in Brazil.

Finally, both reference and alternative scenarios were compared in terms of costs, revenues, emissions and energy, considering, therefore, a certain number of rounds per year to indicate the total emissions and demanded energy annually and the best option for the Brazilian EWMS. In the baseline scenario, a daily WPCB route was considered from the hotspot to the reverse logistics agents along the year, i.e., 365 rounds/year. From these agents to the ports, a weekly flow was assumed, or 52 rounds per year. These values were kept in the alternative scenario, changing only the destination from the reverse logistics agents to the proposed WPCB recycling units.

A similar methodology was adopted in previous studies, in which the best routes between e-waste hotspots and reverse logistics agents were identified in the Metropolitan Region of Rio de Janeiro, Brazil (OTTONI, DIAS, *et al.*, 2020), and in the economic analysis of the routes between the e-waste collection points of the proposed RLS and the reverse logistics agents in São Paulo, Brazil (AZEVEDO, ARAÚJO, *et al.*, 2019). The calculation of costs, revenues, carbon emissions and demanded energy in the Brazilian e-waste RLS routes were suggested as indicators for the circular economy in the electronics segment.

The overall assumptions of the referred scenarios were summarized in **Table 24**.

Table 24. General description and assumptions of the two scenarios adopted in this study

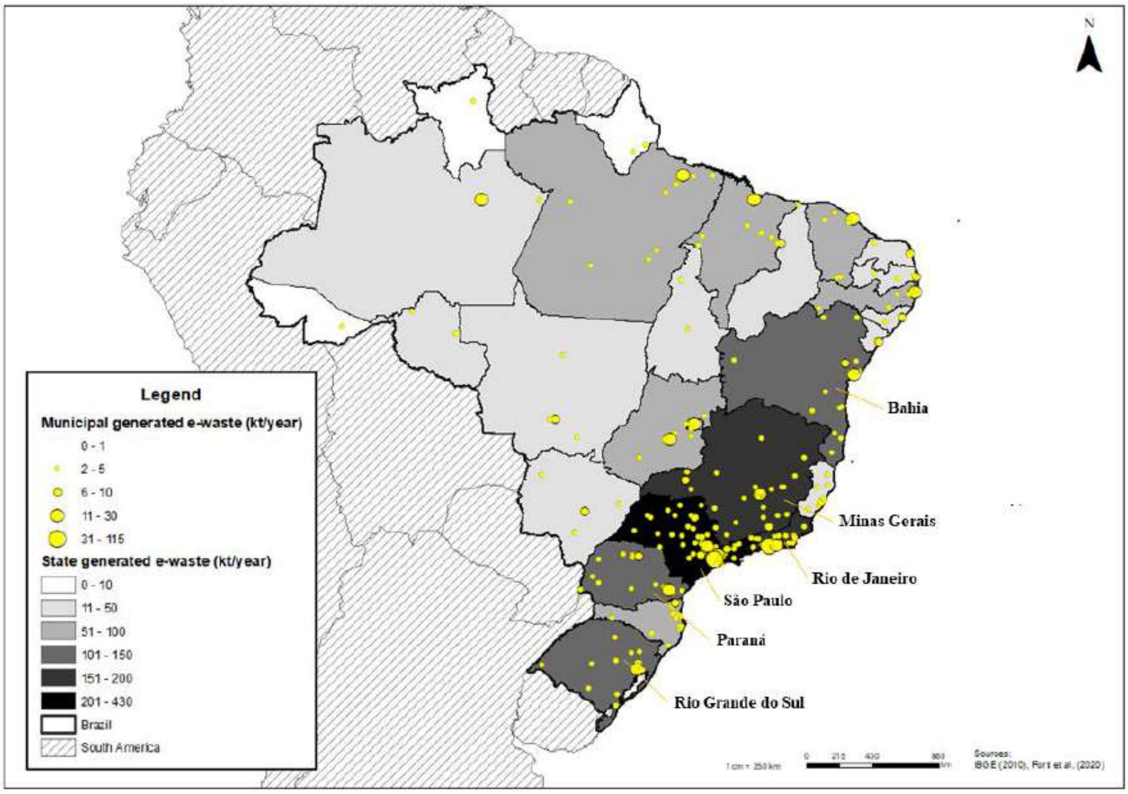
	Scenario 1 (Baseline)	**Scenario 2 (Alternative)**
General description	- Brazil in the current context regarding WPCB fluxes - 30% of the WPCB s generated were assumed to be formally collected and directed to reverse logistics agents in the country - This transportation of WPCB within the country was made by road, considering heavy vehicles operating with diesel for scaling factor - All collected WPCB were, finally, exported to an advanced recycling plant in Belgium, considering transportation by ships operating with bunker oil (Heavy Fuel Oil – HFO).	- Implementation and operation of the WPCB recycling plants in Brazil - Just one recycling plant per cluster - No WPCB exportation (i.e., Brazil keeps the WPCB value in the national territory) - 30% of the collected WPCB were assumed to be formally collected and directed to reverse logistics agents in the country - This transportation of WPCB within the country was made by road, considering heavy vehicles operating with diesel for scaling factor - All collected WPCB were, finally, sent from reverse logistics agents to the WPCB recycling plants by heavy vehicles operating with diesel

4 RESULTS AND DISCUSSION

4.1 Framework for WPCB value recovery in Brazil

Even with the initial infrastructure for e-waste collection at a national scale and the established goals in Decree 10,240/2020 until 2025, the e-waste generation in the country is estimated to be proportionally much higher than the present infrastructure can support. In this sense, **Figure 13** presents the estimated distribution of the e-waste generated in the country.

Figure 13. Municipal and state e-waste estimated generation in Brazil

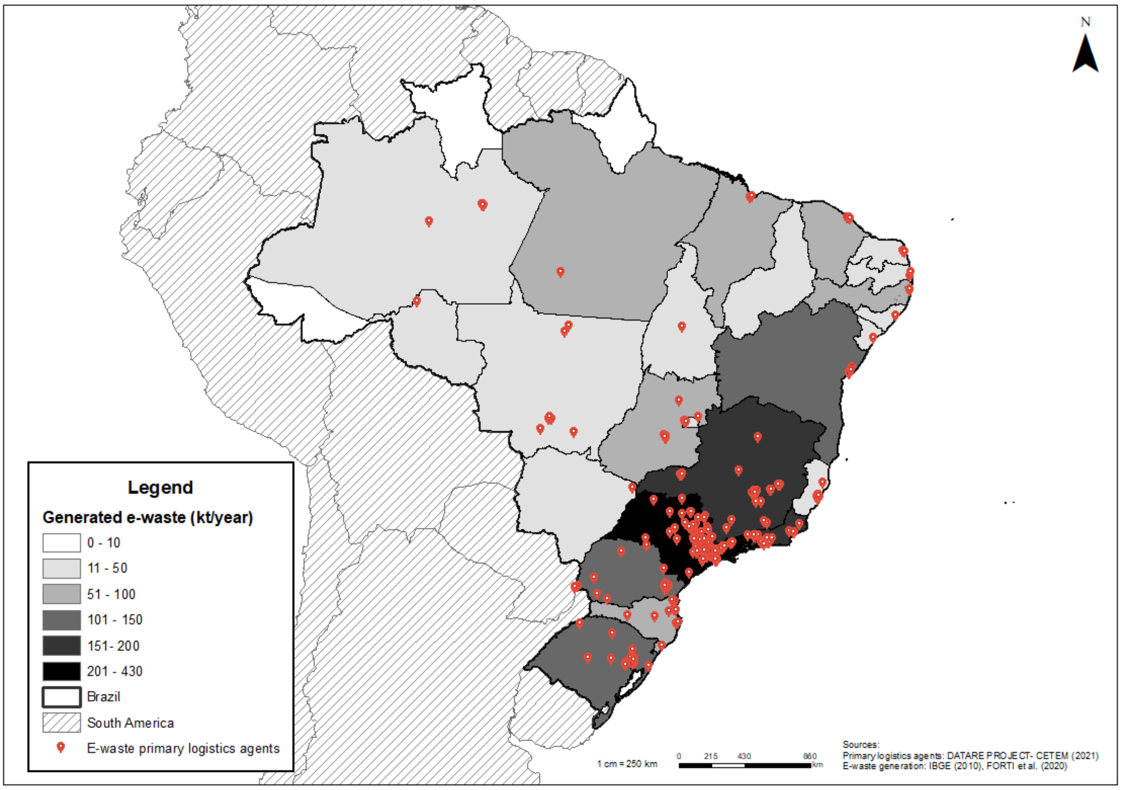


Source: The author, based on data from (FORTI, V, BALDÉ, *et al.*, 2020, IBGE, 2010)

As observed in **Figure 13**, most estimated e-waste generated in Brazil is concentrated on the coast side, especially in the Southeast portion of the country, with emphasis to São Paulo, Rio de Janeiro and Minas Gerais, followed by Bahia, Paraná and Rio Grande do Sul. Comparing such results with the distribution of the e-waste VDPs of ABREE and Green Eletron, in **Figure 6**, this same trend is observed: collection points concentrated on the coast and in the Southeast states. According to SOUZA (2019), more specialized operations within the e-waste take-back routes are concentrated in the Southeast and South regions of the country. ABREE's collectors are also more distributed in the innermost and central parts of the country (**Figure 6**). The estimated e-waste generation in Brazil calculated in this study was used to support the logistical proposal for advanced recycling in the country.

The current e-waste treatment infrastructure in Brazil is composed of numerous reverse logistics agents (popularly called "recyclers", even though most of them only perform pre-processing stages, and not recycling itself). The recent survey developed by DATARE PROJECT of the Center of Mineral Technology (CETEM) has identified 272 formal e-waste reverse logistics agents in Brazil (CETEM, 2021), performing diverse activities in the e-waste reverse supply chain (e.g., collection, transportation, storage, pre-processing, processing, exporting). **Figure 14** presents the geographical distribution of such e-waste reverse logistics companies compared to the main e-waste hotspots in the Brazilian states.

Figure 14. E-waste reverse logistics agents and estimated generation in Brazil



Sources: CETEM (2021)

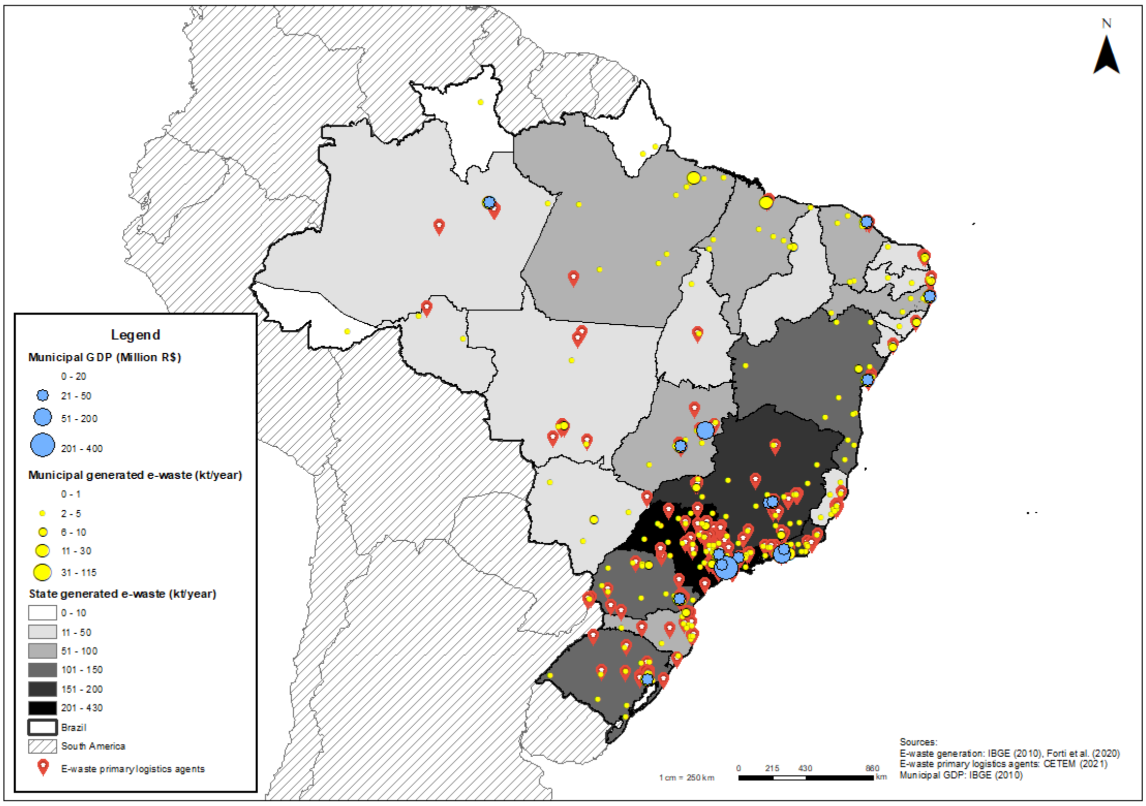
As illustrated by **Figure 14**, most e-waste recyclers are concentrated in the

Southeast-South axis and the coast side of the country, which corresponds to the distribution of the e-waste generation hotspots. LOPES DOS SANTOS (2020) analysed some of the stakeholders who play a central role in the recycling of e-waste in Brazil, located in the São Paulo Macrometropolis (the biggest e-waste generation cluster in the country), and found out that these companies only have the technology to perform the initial (collection and pre-treatment) and intermediate levels (pre-processing) of the e-waste recycling process. DIAS, MACHADO, *et al.* (2018) also identified that 89% of the Brazilian e-waste recycling companies only undertake the pretreatment phase in the recycling process (sorting and dismantling), at least 92% dismantle it manually and that more complex e-waste is still shipped abroad for foreign companies. According to AZEVEDO, DA SILVA ARAÚJO, *et al.* (2017), the installation of industries for the WPCB processing in Brazil has the potential to increase earnings since legal export costs, environmental taxes, and charges can be replaced by environmental taxes and charges in Brazil, and maritime freight costs would be eliminated. As presented in the e-waste recycling levels diagram of **Figure 5**, the e-waste recycling companies in Brazil perform until Level 2 (intermediate, with physical fragmentation processes). The absence of recyclers that have the technology to perform Level 3 (advanced recycling, with processes for valuable fractions recovery) is closely related to the irregularity of a minimal amount of e-waste collected, which is needed to offset the high machinery and processing costs (LOPES DOS SANTOS, 2020).

Figure 15 gathers the e-waste estimated generation in the municipalities and states, the distribution of the e-waste reverse logistics agents and the municipal GDP.

The map in **Figure 15** highlights the evidence of the potential main cluster of e-waste generation in the axis São Paulo - Rio de Janeiro - Minas Gerais, especially for concentrating most e-waste recyclers, highest GDP values and population. For the recycling infrastructure assessment, details regarding the reverse logistics agents that necessarily process WPCB were also considered, given that this study focused on proposing a logistical framework for advanced recycling of this e-waste fraction. **Section 4.2** will present the WPCB generation estimate, the GDP patterns and the identification of the reverse logistics agents that process WPCB to support the main potential WPCB recycling clusters for the country.

Figure 15. E-waste generation, reverse logistics agents and municipal GDP



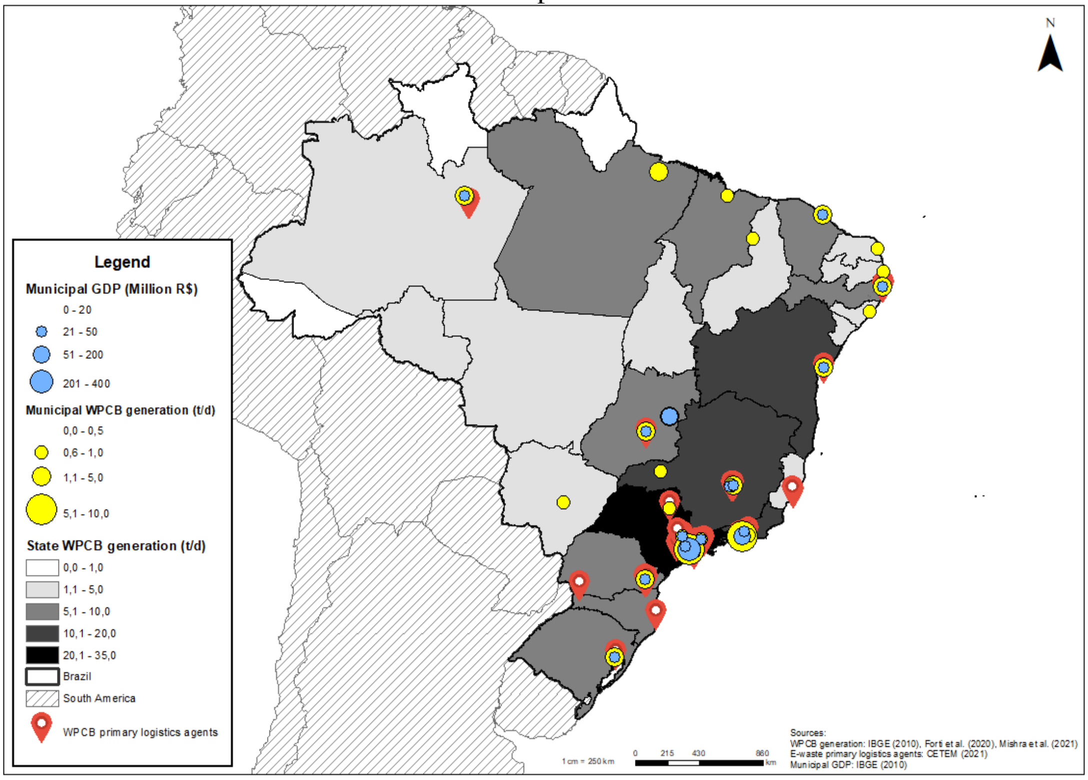
Sources: Data from CETEM (2021), FORTI, BALDÉ, *et al.* (2020), (IBGE, 2010)

The estimative of the WPCB generation values per day was calculated for each state and municipality, being compared to the municipal GDP and the distribution of the reverse logistics agents that process WPCB (**Figure 16**). This combination of information indicates the main potential WPCB hotspots (or possibly the most favourable WPCB recycling clusters) in Brazil. **Appendix B** presents the list of the considered reverse logistics agents for this study, selected from the list of the first phase of DATARE Project (CETEM, 2021).

As observed from **Figure 16**, various WPCB estimated municipal hotspots coincide with the highest GDP values, a trend that is also noted for the distribution of the WPCB reverse logistics agents, especially in the axis Southeast-South. Even though some WPCB generation hotspots could also be found in the Northeast region of the country, much fewer WPCB recyclers were identified, which demonstrates the opportunity for placing companies to supply the potentially increasing demand for the next years in this region.

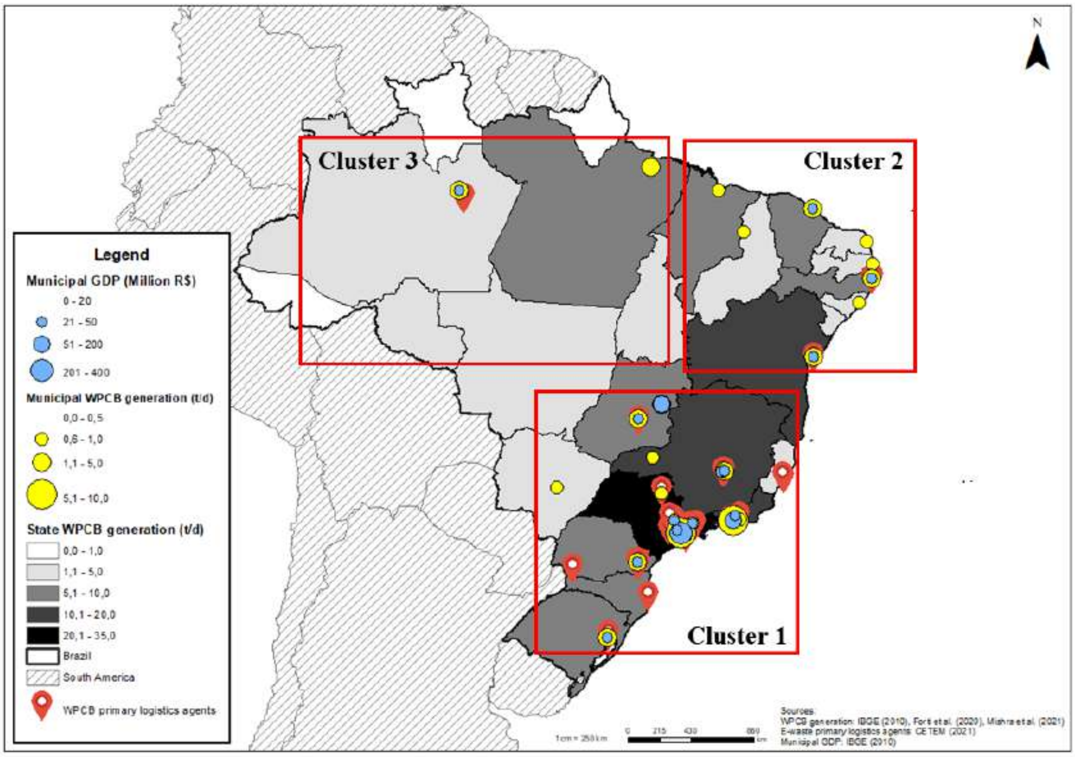
The map in **Figure 17** highlighted a visual distribution of potential clusters for WPCB advanced processing in the country.

Figure 16. WPCB generation, reverse logistics agents that process WPCB and municipal GDP



Sources: Data from CETEM (2021), FORTI, BALDÉ, *et al.* (2020), IBGE (2010)

Figure 17. Potential WPCB value recovery clusters in Brazil



According to **Figure 17**, three main WPCB value recovery clusters could be identified as potential regions to place one or more processing units to perform WPCB advanced recycling as an alternative for reducing e-waste exportation and concentrating e-waste value in Brazil. Cluster 1 gathers the axis Southern-South regions, which are potentially the greatest e-waste generators, and, therefore, might consider the biggest processing infrastructure. Cluster 2 is located in the Northeast portion of the country and may need a smaller infrastructure when compared to Cluster 1, especially for generating less e-waste and concentrating fewer reverse logistics agents. Cluster 3 comprises the North and part of the Midwest region of Brazil. Even though considering the states with fewer e-waste estimated generation, this cluster is important for supplying the demand related to the industrial, commercial and agricultural pole in the Amazon, the Free Economic Zone of Manaus (ZFM, in Portuguese), which has one of the most modern technological poles for a significant production line in several industrial areas, including electronics (BRAZIL, 2015). For defining the WPCB collection scenarios for value recovery, details on the WPCB generation and the identified reverse logistics agents for each proposed cluster were presented in **Table 25**.

Table 25. WPCB estimated generation and number of main reverse logistics agents along with the proposed WPCB value recovery clusters for Brazil

Cluster	States	Brazilian Region	WPCB generation (t per day)	WPCB reverse logistics agents (units)
1	Espírito Santo	Southeast	3.37	2
	Minas Gerais	Southeast	17.75	2
	Rio de Janeiro	Southeast	14.47	6
	São Paulo	Southeast	38.50	31
	Paraná	South	9.59	6
	Rio Grande do Sul	South	9.54	1
	Santa Catarina	South	6.01	1
	Distrito Federal	Midwest	2.53	0
	Goiás	Midwest	5.88	1
	Mato Grosso do Sul	Midwest	2.33	0
	TOTAL		**109.97 t/d = 4.58 t/h**	**50**
2	Alagoas	Northeast	2.80	0
	Bahia	Northeast	12.47	1
	Ceará	Northeast	7.66	0
	Maranhão	Northeast	5.93	0
	Paraíba	Northeast	3.37	0
	Pernambuco	Northeast	8.01	3
	Piauí	Northeast	2.74	0

	Rio Grande do Norte	Northeast	2.94	0
	Sergipe	Northeast	1.93	0
	TOTAL		**47.85 t/d = 1.99 t/h**	**4**
3	Acre	North	0.74	0
	Amapá	North	0.71	0
	Amazonas	North	3.47	3
	Pará	North	7.21	0
	Rondônia	North	1.49	0
	Roraima	North	0.51	0
	Tocantins	North	1.32	0
	Mato Grosso	Midwest	2.92	0
	TOTAL		**18.37 t/d = 0.76 t/h**	**3**
Total			**176.19 t/d = 64 kt/y**	**57**

As described in **Table 25**, the WPCB generation values were estimated also for tonnes per hour (t/h), especially because this metric is used for projecting recycling plants. In these cases, an uninterrupted production is considered, that is, 24h a day. In total, the country has the potential to generate approximately 64 kt/y of WPCB.

Cluster 1 has the estimated potential to achieve about 110 t/d of WPCB or to consider 4.6 t/h of WPCB as input for recycling processes. The Cluster 2 might achieve almost 48 t/d (or about 2 t/h), and Cluster 3, 18 t/d (or about 0.75 t/h). However, given the time spent in collection and transport, besides the deficiency in the collection system in the country, this full capacity must not be adopted for projecting purposes, especially for avoiding overestimated projections. Therefore, three collection scenarios (low, medium and high) were assumed for this proposal, as presented in **Table 26**.

Table 26. Estimated WPCB collection scenarios in each proposed cluster

Cluster	Potential capacity		Collection scenarios (t/h)		
	t/d	**t/h**	**Low (1%)**	**Medium (10%)**	**High (30%)**
1	109.97	4.58	0.0458	0.458	1.374 ~ 1.4
2	47.85	1.99	0.0199	0.199 ~ 0.2	0.597 ~ 0.6
3	18.37	0.76	0.0076	0.076	0.228 ~ 0.2
Total	**176.19**	**7.33**	**0.0733**	**0.733**	**2.199 ~ 2.2**

Out of this project scope
Small-size plant (0.2 - 0.3 t/h)
Medium-size plant (0.3 - 1 t/h)
Large-size plant (1 - 1.5 t/h)

All estimated quantities in the low collection scenario were out of this project scope mainly because of lacking information about e-waste mechanical recycling plants details for processing capacities lower than 0.2 t/h in the literature. In the medium collection scenario, Cluster 3 also showed an estimated WPCB generation capacity lower than 0.2 t/h, and, therefore, this scenario was also excluded from this project scope. The high collection scenario was chosen to be further assessed in this study, especially for indicating the potentials for value recovery from e-waste if well performed in the country, assuming ambitious goals for a transition to a more circular economy in the next years.

4.2 Assessment of the proposed framework

The assessment of the proposed framework for WPCB value recovery in Brazil was divided into three subsections for detailing the current scenario for WPCB flows from formal chains considering exportation as a final destination (baseline scenario), the alternative scenario, based on the implementation of WPCB recycling unit in the three proposed clusters, and the comparative analysis between both scenarios. The logistics of the baseline scenario was assessed according to transportation costs, emissions and demanded energy. The most favourable municipalities for siting a WPCB recycling unit were determined for the alternative scenario, besides the approximated calculation of potential revenues obtained from WPCB recycling, costs, emissions and energy from the logistics and processing operations.

4.2.1 Baseline scenario

Table 27 presents the exportation trade values and net weight related to “Waste and scrap of precious metal or metal clad with precious metal; other waste and scrap containing precious metal compounds, of a kind use principally for the recovery of precious metal”, as indicated by the commodity code 7112, obtained from the United Nations Comtrade Database (UNITED NATIONS, [n.d.]) for 2020. Even though code 7112 was used in this study to indicate the possible dimension of WPCB exportation from Brazil, this category also might include other sources of waste containing precious metals, like jewellery, mining residues, among others.

Table 27. Waste containing precious metals exportation trade values and net weight from Brazil in 2020

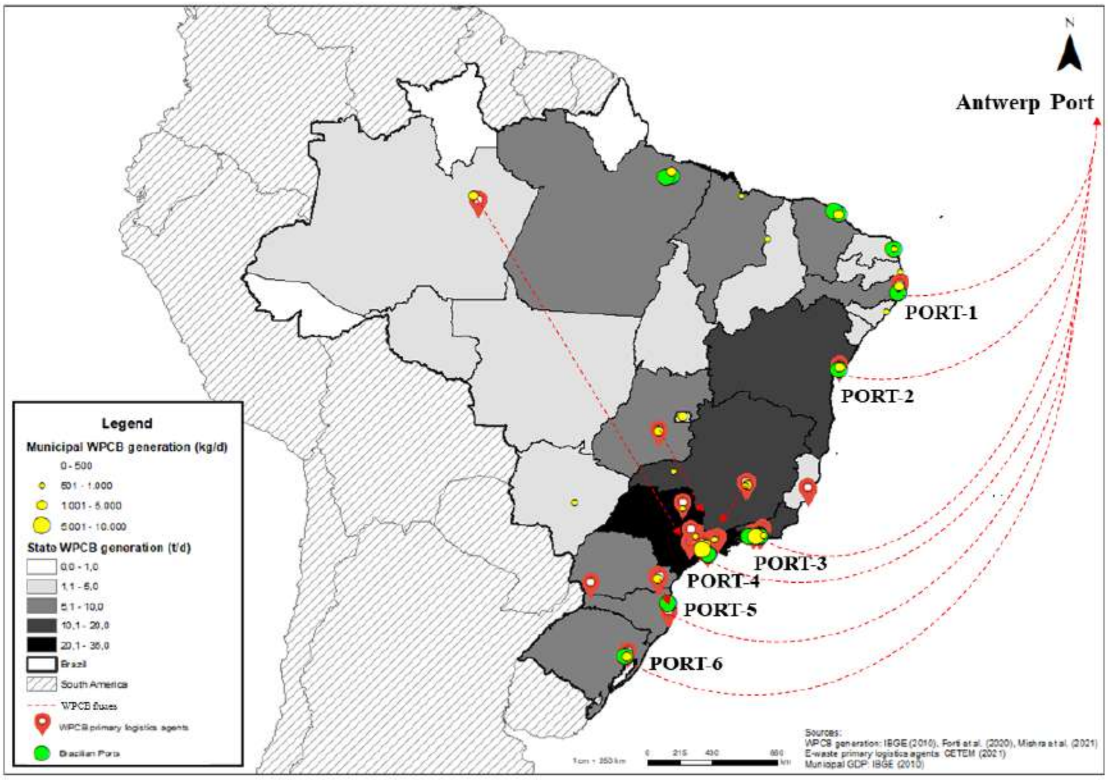
Month	Origin	Destination	Commodity Code	Trade Value (US$)	Netweight (kg)
January 2020	Brazil	Belgium	7112	$10,871,215	326,159
	Brazil	Germany	7112	$1,334,924	298,248
	Brazil	Japan	7112	$529,445	42,486
February 2020	Brazil	Belgium	7112	$15,181,749	142,589
	Brazil	Germany	7112	$1,062,294	274,05
	Brazil	Japan	7112	$1,119,963	44,943
March 2020	Brazil	Belgium	7112	$1,182,861	127,453
	Brazil	Germany	7112	$1,164,967	294,373
	Brazil	Japan	7112	$763,493	24,248
April 2020	Brazil	Belgium	7112	$16,182,046	342,234
	Brazil	Germany	7112	$1,572,675	327,264
	Brazil	Japan	7112	$767,264	23,854
May 2020	Brazil	Belgium	7112	$5,534,063	185,135
	Brazil	Germany	7112	$1,287,819	318,87
	Brazil	Japan	7112	$591,848	29,619
June 2020	Brazil	Belgium	7112	$6,205,680	184,833
	Brazil	Germany	7112	$839,568	171,177
	Brazil	Japan	7112	$1,512,051	150,718
July 2020	Brazil	Belgium	7112	$9,200,217	342,312
	Brazil	Germany	7112	$1,460,655	333,432
	Brazil	Japan	7112	$1,503,247	88,644
August 2020	Brazil	Belgium	7112	$5,785,799	438,509
	Brazil	Germany	7112	$1,917,046	229,014
	Brazil	Japan	7112	$465,864	83,088
September 2020	Brazil	Belgium	7112	$3,592,753	116,831
	Brazil	Germany	7112	$1,003,079	237,272
	Brazil	Japan	7112	$349,954	42,124
October 2020	Brazil	Belgium	7112	$6,271,134	269,051
	Brazil	Germany	7112	$1,523,333	302,673
	Brazil	Japan	7112	$197,270	41,259
November 2020	Brazil	Germany	7112	$715,597	153,978
	Brazil	Japan	7112	$2,406,394	147,743
	Brazil	Belgium	7112	$12,062,396	322,933
December 2020	Brazil	Canada	7112	$56,570	2
	Brazil	France	7112	$924	3
	Brazil	Germany	7112	$1,072,488	303,822
	Brazil	Japan	7112	$213,895	28,671
	Brazil	Belgium	7112	$10,120,728	52,058
TOTAL				**$127,623,268**	**6841672**

Source: (UNITED NATIONS, [S.d.])

As observed in **Table 27**, Germany, Belgium and Japan were the most preferred destinations for wastes containing precious metals in 2020, totalizing 3,244,173 kg, 2,850,097 kg and 747,397 kg in a year, respectively. This result can be directly related to the location of three of the biggest precious metals refining facilities in the world: Aurubis, in Germany, Umicore, in Belgium, and DOWA, in Japan. Trade value for exportation includes, generally, the transaction value of the goods and the value of services performed to deliver goods to the border of the exporting country (UN TRADE STATISTICS, 2010).

However, considering that Umicore integrated smelter-refinery has the biggest e-waste recycling capacity worldly (KAYA, 2019), this plant was selected for simulating the WPCB exportation trades from Brazil, as illustrated in the map of **Figure 18**. Since Umicore main plant is located in Antwerp, the Antwerp Port was adopted as the final destination of the Brazilian WPCB flows.

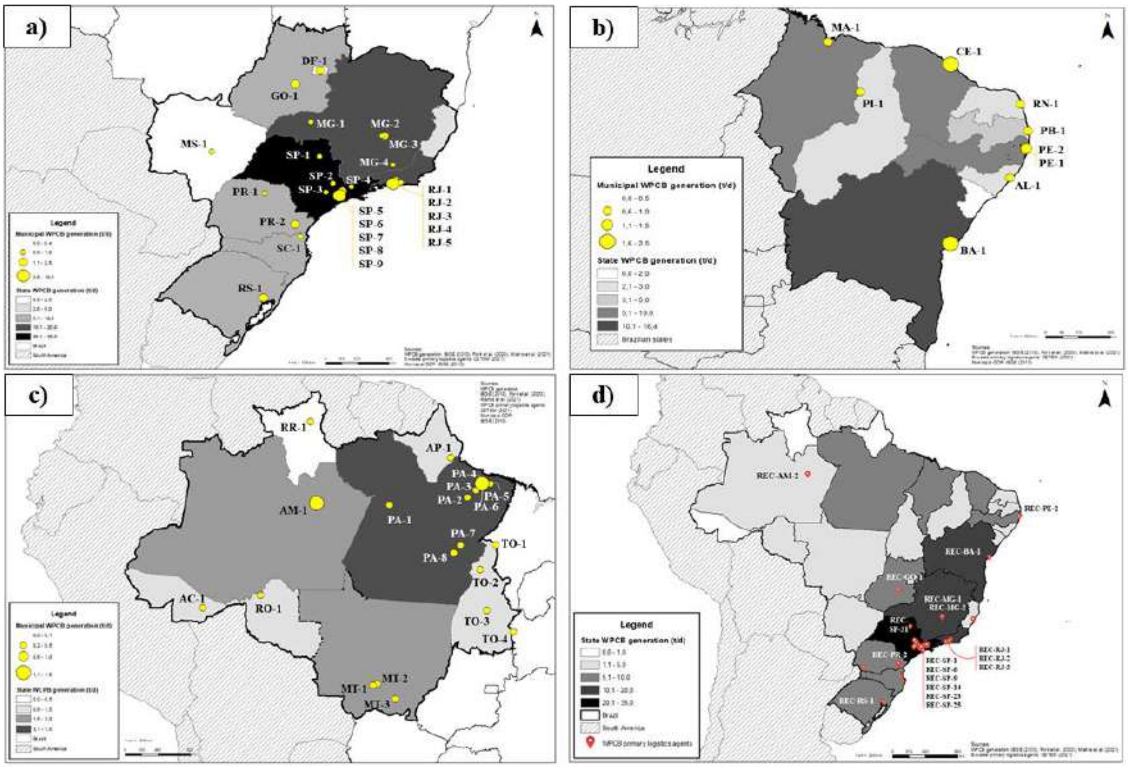
Figure 18. WPCB flows from reverse logistics agents to ports (reference scenario)



Sources: Data from CETEM (2021), FORTI, BALDÉ, *et al.* (2020), IBGE (2010)

As presented in **Figure 18**, most of the considered ports are located in the Southeast-south axis, mainly because these regions concentrate on WPCB generation. The Northeast portion of the country was also contemplated in this simulation, especially the states with more potential to generate WPCB and with the presence of reverse logistics agents that are typically exporters. The ports in the North region were not considered for the potentially lower WPCB volumes (as estimated in **Table 25**) and the absence of WPCB reverse logistics agents that are specialized in exportation. The Amazonas state was the exception in this geographical region, given the higher amounts of e-waste potentially generated and for hosting two industries specialized in WPCB export: Umicore and Lorene. In this particular case, it was assumed that the generated and preprocessed WPCB in this hotspot was transported to the main Brazilian port (Port 4), even though some evidence indicates that Lorene export this fraction to an e-waste refining industry in Canada (IMBELLONI, 2012). **Figure 19** presented the main WPCB hotspots and reverse logistics agents considered in the reference scenario for each Cluster and their codes to be used in the simulation of routes.

Figure 19. Codes of the WPCB hotspots and reverse logistics agents in the reference scenario: a) WPCB hotspots in Cluster 1; b) WPCB hotspots in Cluster 2; c) WPCB hotspots in Cluster 3; d) Reverse logistics agents



The assumed flows for the reference scenario were based on the routes from hotspots (**Figure 19a, b, c**) to reverse logistics agents (**Figure 19d**), and from them to the selected ports (**Figure 18**). **Table 28** presented the considered routes for the simulation of the WPCB flows in the reference scenario, their distances, potential emissions and demanded energy.

Table 28. Calculation of potential emissions and demanded energy in the WPCB flows of the reference scenario

Hotspot-Reverse logistics agents	Distances (km)	Emissions (tCO2e./round)	Energy (MJ)	Reverse logistics agents -Ports	Distances (km)	Emissions (tCO2e./round)	Energy (MJ)	BR Ports-Antwerp (Belgium)	Distances (km)	Emissions (tCO2e./round)	Energy (MJ)
[CE-1] – [REC-PE-2]	760	0.97	8045	[REC-PE-2] – [PORT-1]	40	0.05	423	[PORT-1] - [ANTWERP]	8000	7056	100,800,000.00
[RN-1] – [REC-PE-2]	290	0.37	3070								
[PB-1] – [REC-PE-2]	120	0.15	1270								
[PE-1] – [REC-PE-2]	15	0.02	159								
[PE-2] – [REC-PE-2]	10	0.01	106								
[AL-1] – [REC-PE-2]	330	0.42	3493								
[BA-1] – [REC-BA-1]	10	0.01	106	[REC-BA-1] – [PORT-2]	10	0.01	106	[PORT-2] - [ANTWERP]	8200	7232.4	103,320,000.00
[MA-1] – [REC-BA-1]	1590	2.04	16831								
[PI-1] – [REC-BA-1]	1150	1.47	12173								
[MG-4] – [REC-RJ-1]	110	0.14	1164	[REC-RJ-1] - [PORT-3]	60	0.08	635	[PORT-3] - [ANTWERP]	10000	8820	126,000,000.00
[RJ-3] – [REC-RJ-1]	25	0.03	265								
[RJ-4] – [REC-RJ-1]	40	0.05	423								
[RJ-5] – [REC-RJ-1]	50	0.06	529								
[RJ-2] – [REC-RJ-2]	30	0.04	318	[REC-RJ-2] - [PORT-3]	10	0.01	106				
[RJ-1] – [REC-RJ-3]	25	0.03	265	[REC-RJ-3] - [PORT-3]	10	0.01	106				
[RR-1] – [REC-AM-2]	750	0.96	7939	[REC-AM-2] - [PORT-4]	4000	5.12	42342	[PORT-4] - [ANTWERP]	10500	9261	132,300,000.00
[AC-1] – [REC-AM-2]	1400	1.79	14820								
[RO-1] – [REC-AM-2]	900	1.15	9527								
[AM-1] – [REC-AM-2]	10	0.01	106								
[PA-1] – [REC-AM-2]	2110	2.70	22336								
[PA-2] – [REC-AM-2]	2850	3.65	30169								
[PA-3] – [REC-AM-2]	2950	3.78	31227								
[AP-1] – [REC-AM-2]	-	-	-								
[PA-4] – [REC-GO-1]	2000	2.56	21171	[REC-GO-1] - [PORT 4]	1000	1.28	10586				
[PA-5] – [REC-GO-1]	2000	2.56	21171								
[PA-6] – [REC-GO-1]	2000	2.56	21171								
[PA-7] – [REC-GO-1]	1500	1.92	15878								
[PA-8] – [REC-GO-1]	1500	1.92	15878								
[AP-1] – [REC-GO-1]	-	-	-								
[TO-1] – [REC-GO-1]	1500	1.92	15878								

[TO-2] – [REC-GO-1]	1160	1.48	12279								
[TO-3] – [REC-GO-1]	850	1.09	8998								
[TO-4] – [REC-GO-1]	850	1.09	8998								
[MT-1] – [REC-GO-1]	950	1.22	10056								
[MT-2] – [REC-GO-1]	920	1.18	9739								
[MT-3] – [REC-GO-1]	750	0.96	7939								
[GO-1] – [REC-GO-1]	13	0.02	138								
[DF-1] – [REC-GO-1]	190	0.24	2011								
[MS-1] – [REC-SP-1]	738	0.94	7812	[REC-SP-1] - [PORT-4]	250	0.32	2646				
[SP-1] – [REC-SP-31]	10	0.01	106	[REC-SP-31] - [PORT-4]	450	0.58	4764				
[MG-1] – [REC-SP-31]	230	0.29	2435								
[MG-2] – [REC-MG-2]	8	0.01	85	[REC-MG-2] - [PORT-4]	700	0.90	7410				
[MG-3] – [REC-MG-1]	1	0.00	11	[REC-MG-1] - [PORT-4]	750	0.96	7939				
[SP-2] – [REC-SP-6]	25	0.03	265	[REC-SP-6] - [PORT-4]	200	0.26	2117				
[SP-3] – [REC-SP-9]	5	0.01	53	[REC-SP-9] - [PORT-4]	200	0.26	2117				
[SP-4] – [REC-SP-25]	20	0.03	212	[REC-SP-25] - [PORT-4]	180	0.23	1905				
[SP-5] – [REC-SP-23]	10	0.01	106	[REC-SP-23] - [PORT-4]	130	0.17	1376				
[SP-6] – [REC-SP-14]	5	0.01	53	[REC-SP-14] - [PORT-4]	100	0.13	1059				
[SP-7] – [REC-SP-14]	20	0.03	212								
[SP-8] – [REC-SP-14]	40	0.05	423								
[SP-9] – [REC-SP-14]	40	0.05	423								
[PR-1] – [REC-PR-2]	290	0.37	3070								
[PR-2] – [REC-PR-2]	15	0.02	159	[REC-PR-2] - [PORT-5]	220	0.28	2329	[PORT-5] - [ANTWERP]	10750	9481.5	135,450,000.00
[SC-1] – [REC-PR-2]	130	0.17	1376								
[RS-1] – [REC-RS-1]	20	0.03	212	[REC-RS-1] - [PORT-6]	10	0.01	106	[PORT-6] - [ANTWERP]	11100	9790.2	139,860,000.00
TOTAL	**33315**	**42.64**	**352659**	**TOTAL**	**8320**	**10.65**	**88072**	**TOTAL**	**58550**	**51641.10**	**737,730,000**

As observed in the calculated data in **Table 28**, the emissions related to maritime transport from the Brazilian ports to Antwerp correspond to the highest emissions of the reference scenario. This fact becomes even more relevant when considering the evidence from the COMTRADE database (UNITED NATIONS, [S.d.]) of monthly e-waste exportations from Brazil mainly to European countries, as described in **Table 27**. This same disparity was observed for the demanded energy. While road transport was equivalent to about 440,000 MJ, sea transport demands approximately 1600 times more energy.

Between the road transport, the routes from hotspots to the reverse logistics agents were four times more impactful in terms of demanded energy and CO2e. emissions than the routes from the reverse logistics agents to the ports. This fact could be attributed to the lower distances between these recyclers and the ports as a logistical strategy to cheapen the transport of WPCB for these industries. The higher distances from hotspots to the recyclers are a reflection of the continental proportions of the country (XAVIER, OTTONI, *et al.*, 2021) and the dispersed e-waste generation. Thus, the total estimated emissions reached about 51.7 ktCO2e./round and approximately 738.2 TJ/round of demanded energy for the reference scenario. These values were converted to annual quantities in **Section 4.2.3 (Comparative analysis)**.

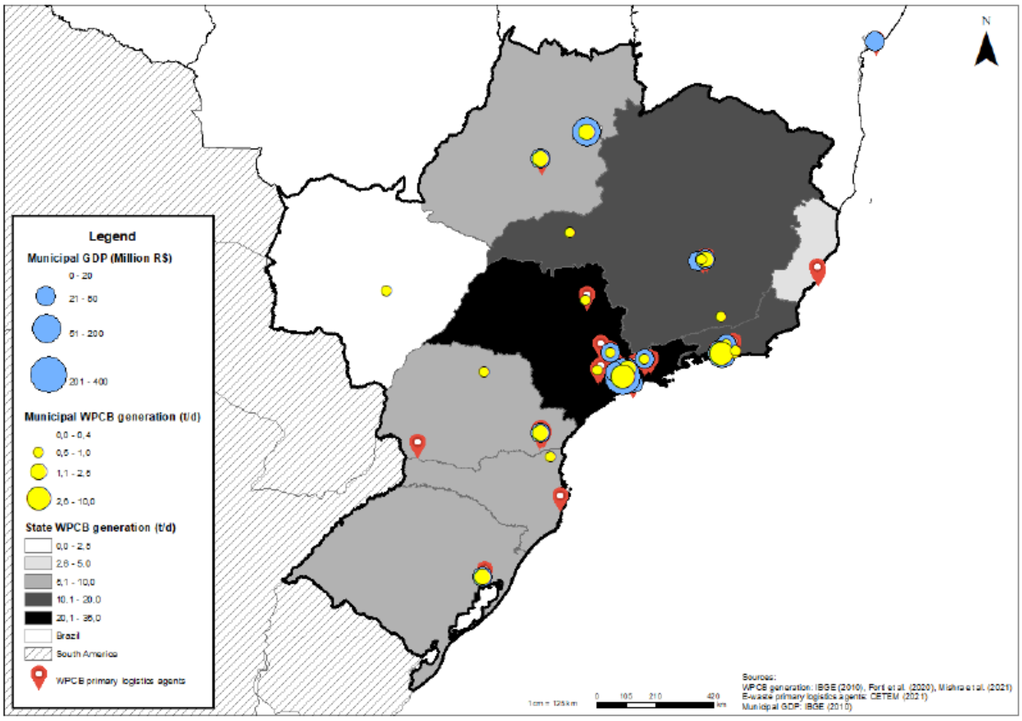
4.2.2 Alternative scenario

This section was divided into the assessment of the three proposed WPCB value recovery clusters, considering the facilities' siting analysis of each WPCB recycling unit (WRU), the calculation of the distances, costs, emissions and demanded energy between the hotspots, the reverse logistics agents and the WRU, and the revenues obtained from the WPCB value recovery.

4.2.2.1 Cluster 1

Cluster 1 potentially concentrates the biggest WPCB portion of Brazil, especially in São Paulo state, as indicated in black in **Figure 20**.

Figure 20. Configuration of Cluster 1 in terms of WPCB generation, reverse logistics agents and GDP



Sources: Data from CETEM (2021), FORTI, BALDÉ, *et al.* (2020), IBGE (2010)

The reverse logistics agents and the highest GDP values are also placed in São Paulo, which configures the greatest WPCB pole of the country, followed by its neighbouring states, Rio de Janeiro and Minas Gerais, in darker grey colour in **Figure 20**.

This first spatial analysis indicated the most probable best places for siting the proposed WRU in this cluster. **Table 29** presents the adopted criteria for verifying the most favourable municipalities for implementing such plants, considering that São Paulo city is the municipality with the highest WPCB generation. Therefore, the closest municipalities to São Paulo were assessed.

As presented in **Table 29**, the most indicated cities for siting a recycling unit, according to the selected criteria, would be São Paulo, Guarulhos and Campinas, mostly because of their WPCB generation patterns, higher GDP values and number of reverse logistics agents. The distance to the main hotspot of Cluster 1 (São Paulo city) was also considered, especially for logistics purposes. In this case, Guarulhos and Jundiaí stood out. For MHDI, Santos and Jundiaí had the highest scores. All eight best cities were considered in the list of the official Reverse Logistics System, and, thus, their scores did not count to the final scoring. Therefore, São Paulo city was the best choice for implementing a WRU in Cluster 1.

Table 29. Cluster 1 facility's siting analysis for WPCB recycling unit

Municipality	WPCB (kg/d)	Score	GDP (million R$)	Score	MHDI	Score	Dist.Hotspot (km)	Score	RLS	Score	Reverse logistics agents	Score	Total
São Paulo	9434.4	8	714683.00	8	0.805	4	0	7	Yes	0	7	7	34
Guarulhos	1024.5	7	61326.00	6	0.763	1	21	6	Yes	0	3	3	23
Campinas	905.5	6	61397.00	7	0.805	4	94	3	Yes	0	3	3	23
São José dos Campos	528.1	5	39698.00	4	0.807	5	94	3	Yes	0	1	1	18
Ribeirão Preto	506.9	4	34328.00	2	0.800	3	315	1	Yes	0	1	1	11
Sorocaba	491.8	3	35015.00	3	0.798	2	105	2	Yes	0	2	2	12
Santos	351.6	2	22477.00	1	0.840	7	81	4	Yes	0	1	1	15
Jundiaí	310.3	1	43633.00	5	0.822	6	60	5	Yes	0	1	1	18

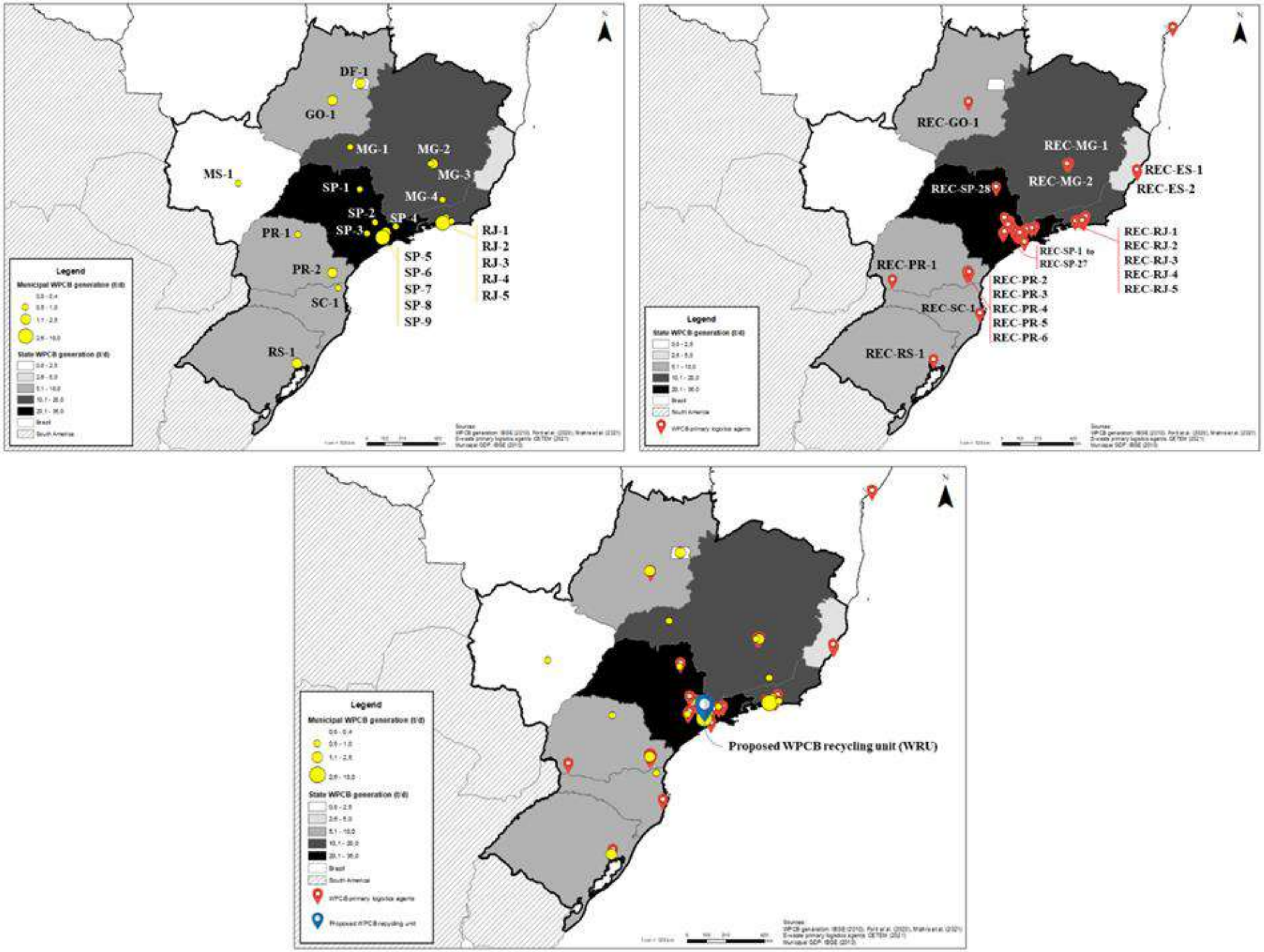
After defining the best location for the WRU of Cluster 1, the routes between WPCB generation and reverse logistics agents, and from them to WRU were established and the distances were calculated. The main codes of the hotspots and the recyclers were illustrated in the map of **Figure 21**.

All codes presented in **Figure 21** were used in **Table 30**, which also displays the distances, emissions and energy of each route in Cluster 1.

Considering that the reverse logistics agents are mostly concentrated in São Paulo state (SP), the further the hotspot is from SP the highest are the emissions and demanded energy (and, hence, the logistics costs, which will be detailed in **Section 4.2.3**).

The same logic is applied to the proximity from reverse logistics agents to the WRU. As shown in **Table 30**, the routes that most contribute to total emissions and demanded energy were those from the recyclers to the recycling unit in Cluster 1, representing approximately 2.5 times more emissions and needed energy than the route from hotspots to recyclers. The highest distances were related to the routes from both Goiás (GO) and Rio Grande do Sul (RS) to the WRU, in SP.

Figure 21. Details of Cluster 1: a) WPCB hotspots; b) Reverse logistics agents; c) WRU siting



Sources: Data from CETEM (2021), FORTI, BALDÉ, *et al.* (2020), IBGE (2010)

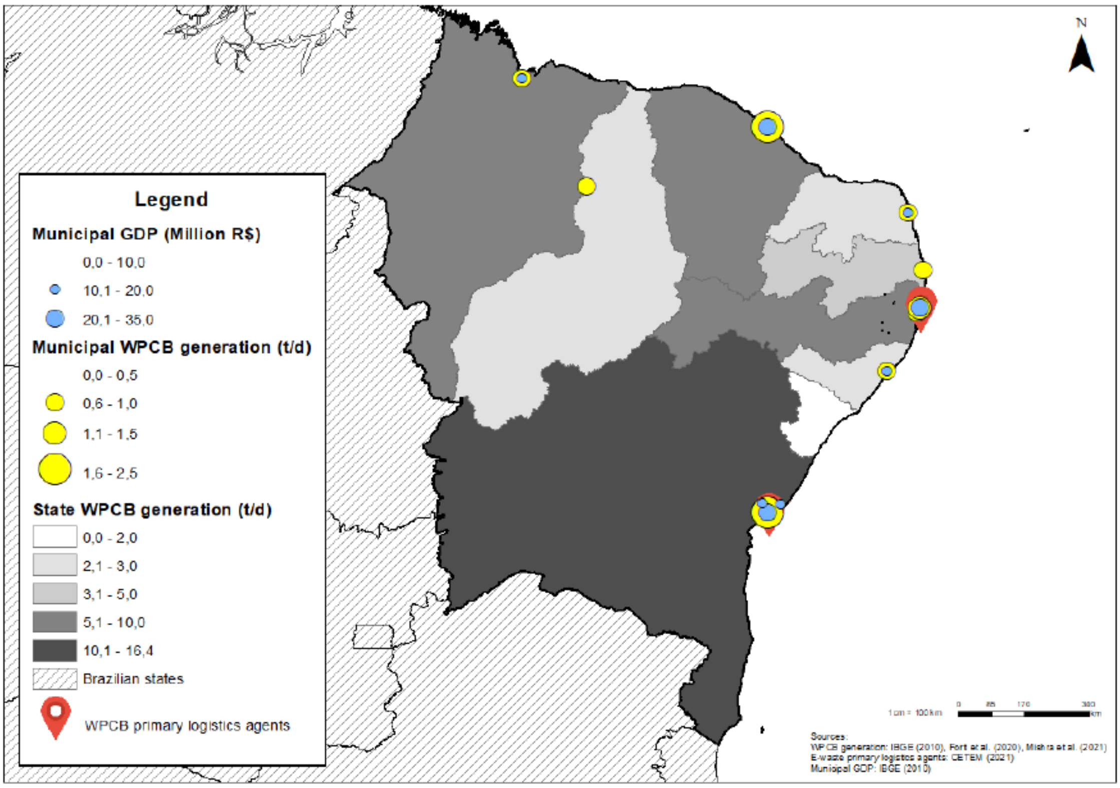
Table 30. Distances, emissions and energy for Cluster 1 in the alternative scenario

Hotspot-Reverse logistics agents	Distances (km)	Emissions (tCO2e./round)	Energy (MJ)	Reverse logistics agents-WPCP Recycling Unit	Distances (km)	Emissions (tCO2e.)	Energy (MJ)
[MS-1] – [REC-SP-1]	738	0.945	7812	[REC-SP-1] – [WRU1]	120	0.154	1270
[GO-1] – [REC-GO-1]	13	0.017	138	[REC-GO-1] – [WRU1]	900	1.152	9527
[DF-1] – [REC-GO-1]	190	0.243	2011				
[SP-1] – [REC-SP-31]	10	0.013	106	[REC-SP-31] – [WRU1]	300	0.384	3176
[MG-1] – [REC-SP-31]	230	0.294	2435				
[MG-2] – [REC-MG-2]	8	0.010	85	[REC-MG-2] – [WRU1]	500	0.640	5293
[MG-3] – [REC-MG-1]	1	0.001	11	[REC-MG-1] – [WRU1]	510	0.653	5399
[MG-4] – [REC-RJ-1]	110	0.141	1164	[REC-RJ-1] – [WRU1]	400	0.512	4234
[RJ-3] – [REC-RJ-1]	25	0.032	265				
[RJ-4] – [REC-RJ-1]	40	0.051	423				
[RJ-5] – [REC-RJ-1]	50	0.064	529				
[RJ-2] – [REC-RJ-2]	30	0.038	318	[REC-RJ-2] – [WRU1]	380	0.486	4023
[RJ-1] – [REC-RJ-3]	25	0.032	265	[REC-RJ-3] – [WRU1]	400	0.512	4234
[SP-2] – [REC-SP-6]	25	0.032	265	[REC-SP-6] – [WRU1]	80	0.102	847
[SP-3] – [REC-SP-9]	5	0.006	53	[REC-SP-9] – [WRU1]	90	0.115	953
[SP-4] – [REC-SP-25]	20	0.026	212	[REC-SP-25] – [WRU1]	90	0.115	953
[SP-5] – [REC-SP-23]	10	0.013	106	[REC-SP-23] – [WRU1]	40	0.051	423
[SP-6] – [REC-SP-14]	5	0.006	53	[REC-SP-14] – [WRU1]	10	0.013	106
[SP-7] – [REC-SP-14]	20	0.026	212				
[SP-8] – [REC-SP-14]	40	0.051	423				
[SP-9] – [REC-SP-14]	40	0.051	423				
[PR-1] – [REC-PR-2]	290	0.371	3070	[REC-PR-2] – [WRU1]	400	0.512	4234
[PR-2] – [REC-PR-2]	15	0.019	159				
[SC-1] – [REC-PR-2]	130	0.166	1376				
[RS-1] – [REC-RS-1]	20	0.026	212	[REC-RS-1] – [WRU1]	1000	1.280	10586
TOTAL	**2090**	**2.68**	**22124**	**TOTAL**	**5220**	**6.68**	**55257**

4.2.2.2 Cluster 2

Figure 22 presents the configuration of Cluster 2 considering the potential WPCB hotspots, the reverse logistics agents' location and the municipal GDP.

Figure 22. Configuration of Cluster 2 in terms of WPCB generation, reverse logistics agents and GDP



Sources: Data from CETEM (2021), FORTI, BALDÉ, *et al.* (2020), IBGE (2010)

In Cluster 2, as shown in **Figure 22**, two main hotspots were identified: Salvador (Bahia, BA) and Recife (Pernambuco, PE) municipalities. Considering only the WPCB generation as a criterion, Salvador stands out over Recife, and, therefore, can be considered for the next step of the facility's siting analysis of the most favourable spot for implementing a WPCB recycling unit along with the closest cities, as presented in **Table 31**.

However, when taking into account other criteria, such as MHDI and the number of identified reverse logistics agents, Recife got the highest score over Salvador, as shown in **Table 32**. Even so, given that BA tends to generate more WPCB than PE, Salvador was chosen as the first option as the best option for WPCB recycling in Cluster 2, and Recife was considered the second alternative.

Table 31. Cluster 2 facility's siting analysis for WPCB recycling plant

Municipality	WPCB (kg/d)	Score	GDP (million R$)	Score	MHDI	Score	Dist.Hotspot (km)	Score	RLS	Score	Reverse logistics agents	Score	Total
Salvador	2243.15	8	63526.00	8	0.759	8	0	8	Yes	0	1	1	33
Feira de Santana	466.66	7	14683.00	6	0.712	5	116	3	Yes	0	0	0	21
Vitória da Conquista	257.26	6	7036.00	5	0.678	2	519	2	Yes	0	0	0	15
Camaçari	203.70	5	23823.00	7	0.694	4	52	4	Yes	0	0	0	20
Lauro de Freitas	137.03	4	6450.00	4	0.754	7	31	6	Yes	0	0	0	21
Barreiras	115.21	3	4744.00	2	0.721	6	873	1	Yes	0	0	0	12
Simões Filho	98.97	2	5813.00	3	0.675	1	29	7	Yes	0	0	0	13
Candeias	69.72	1	4358.00	1	0.691	3	51	5	Yes	0	0	0	10

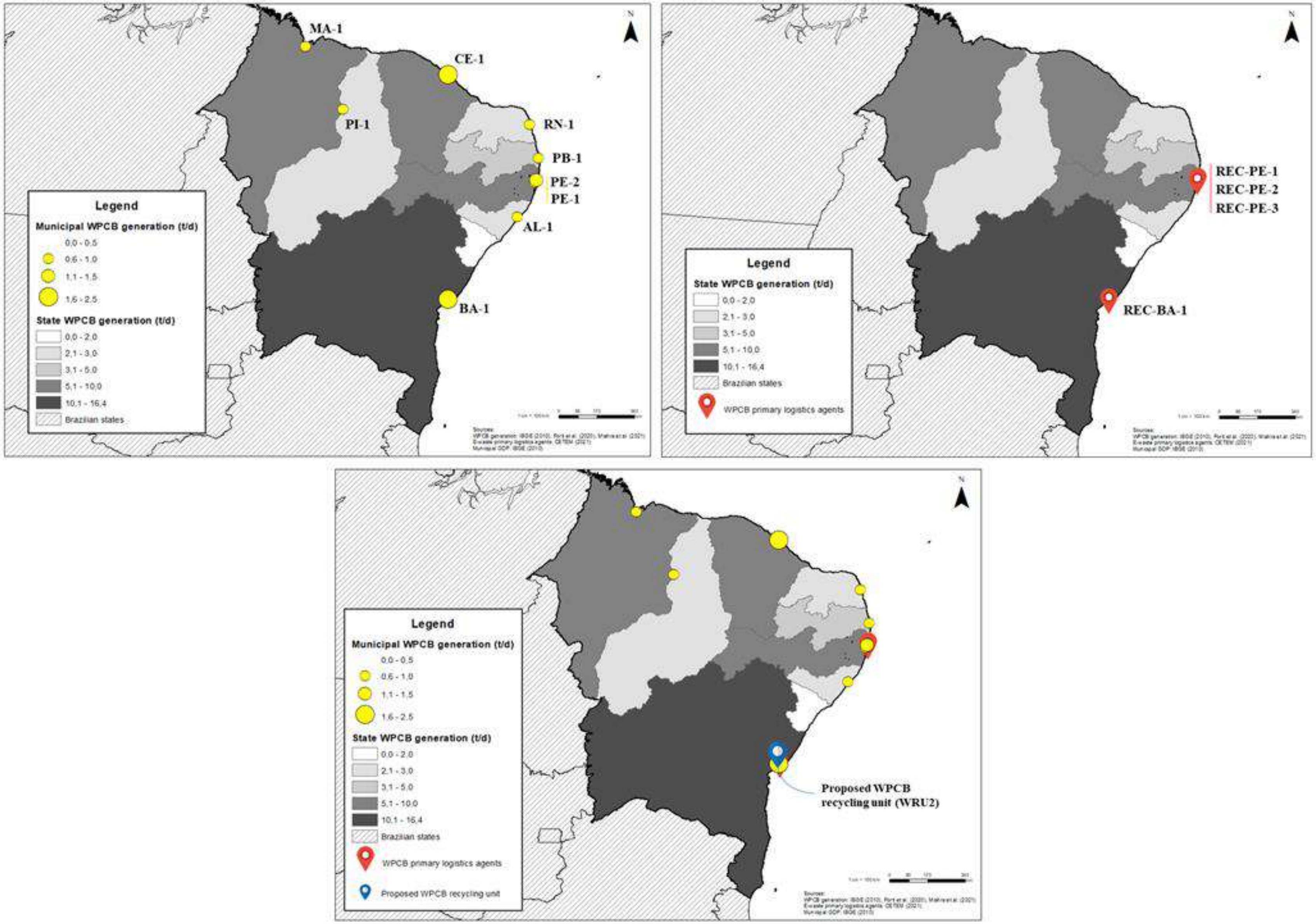
Table 32. Cluster 2 facility's siting analysis for WPCB recycling plant considering Salvador and Recife

Municipality	State	WPCB (kg/d)	Score	GDP (million R$)	Score	MHDI	Score	Dist.Hotspot (km)	Score	RLS	Score	Reverse logistics agents	Score	Total
Salvador	BA	2243.15	2	63526.00	2	0.759	1	0	0	Yes	0	1	1	6
Recife	PE	1289.14	1	51859.62	1	0.772	2	0	0	Yes	0	3	3	7

The routes between WPCB generation and reverse logistics agents, and from them to WRU were established and the distances were calculated for Cluster 2. Also, the main codes of the hotspots and the recyclers were illustrated in **Figure 23**. All codes presented in **Figure 23** were used in **Table 33**, which also displays the distances, emissions and energy of each route in Cluster 2.

Considering that the reverse logistics agents are mostly concentrated in Pernambuco and Bahia (**Figure 23b**), when the hotspots are further from these states, the emissions and demanded energy (and, consequently, the costs, which will be detailed in **Section 4.2.3**). derived from the reverse logistics are also higher. As presented in **Table 33**, the routes that most contribute to total emissions and demanded energy were those from the hotspots to the reverse logistics agents in Cluster 2, representing five times more than the routes from the reverse logistics agents to the WRU. The highest distances were related to the routes from both Maranhão (MA) and Piauí (PI) to the reverse logistics agent in BA, which means that these routes tend to generate more emissions, demand more energy and potentially represent higher costs per round.

Figure 23. Details of Cluster 2: a) WPCB hotspots; b) Reverse logistics agents; c) WRU siting



Sources: Data from CETEM (2021), FORTI, BALDÉ, *et al.* (2020), IBGE (2010)

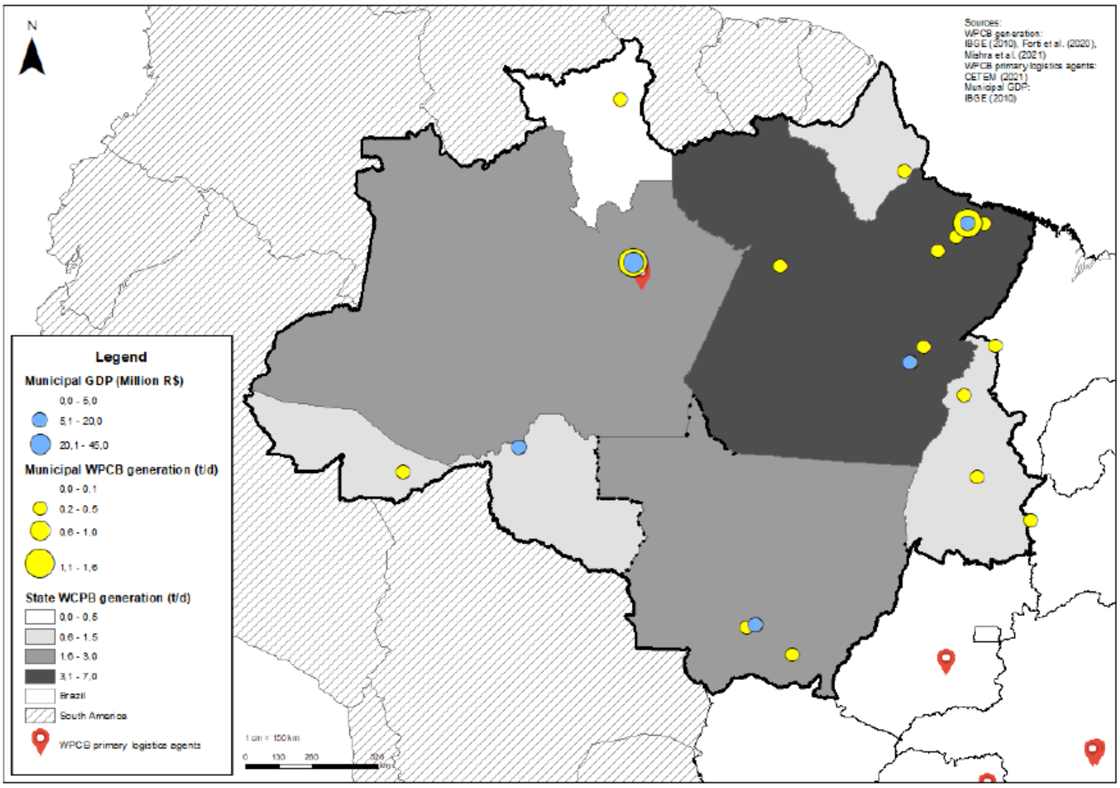
Table 33. Distances, emissions and energy for Cluster 2 in the alternative scenario

Hotspot-Reverse logistics agents	Distances (km)	Emissions (tCO2e./round)	Energy (MJ)	Reverse logistics agents - WPCP Recycling Unit	Distances (km)	Emissions (tCO2e./round)	Energy (MJ)
[BA-1] – [REC-BA-1]	10	0.013	106	[REC-BA-1] – [WRU2]	10	0.013	106
[MA-1] – [REC-BA-1]	1590	2.035	16831				
[PI-1] – [REC-BA-1]	1150	1.472	12173				
[CE-1] – [REC-PE-2]	760	0.973	8045	[REC-PE-2] – [WRU2]	800	1.024	8468
[RN-1] – [REC-PE-2]	290	0.371	3070				
[PB-1] – [REC-PE-2]	120	0.154	1270				
[PE-1] – [REC-PE-2]	15	0.019	159				
[PE-2] – [REC-PE-2]	10	0.013	106				
[AL-1] – [REC-PE-2]	330	0.422	3493				
TOTAL	**4265**	**5.46**	**45148**	**TOTAL**	**810**	**1.04**	**8574**

4.2.2.3 Cluster 3

The configuration of Cluster 3 in terms of potential WPCB hotspots, the reverse logistics agents' location and the municipal GDP were illustrated in **Figure 24**.

Figure 24. Configuration of Cluster 3 in terms of WPCB generation, reverse logistics agents and GDP



Sources: Data from CETEM (2021), FORTI, BALDÉ, *et al.* (2020), IBGE (2010)

The only municipality with reverse logistics agents was Manaus, especially because of the Free Economic Zone of Manaus, which comprises the industrial, commercial and agricultural pole in the Amazon. This industrial zone has one of the most modern technological poles for several industrial areas, including electronics (BRAZIL, 2015), and, therefore, has a great potential to implement a WRU, especially because of the existing reverse logistics agents that already preprocess WPCB, such as Umicore and Lorene. Currently, these companies involved in preprocessing e-waste, particularly WPCB, in Manaus, export this fraction to an e-waste refining industry in Canada (IMBELLONI, 2012) or even transport part of it to be processed in São Paulo and further exported to refineries abroad.

As stated by AZEVEDO, L.P., ARAÚJO, *et al.* (2019) and confirmed by the geographical analysis, most of the transportation in the Amazon region is done using the rivers. Therefore, the road distances from the municipalities to the main hotspot (Manaus, in this case) were not considered, as presented in **Table 34**.

Besides, only five municipalities were included in the WRU siting analysis (**Table 34**) given that the other cities closest to Manaus not only had very potentially low WPCB generation and GDP values but also did not have WPCB reverse logistics agents and were not considered in the national RLS list.

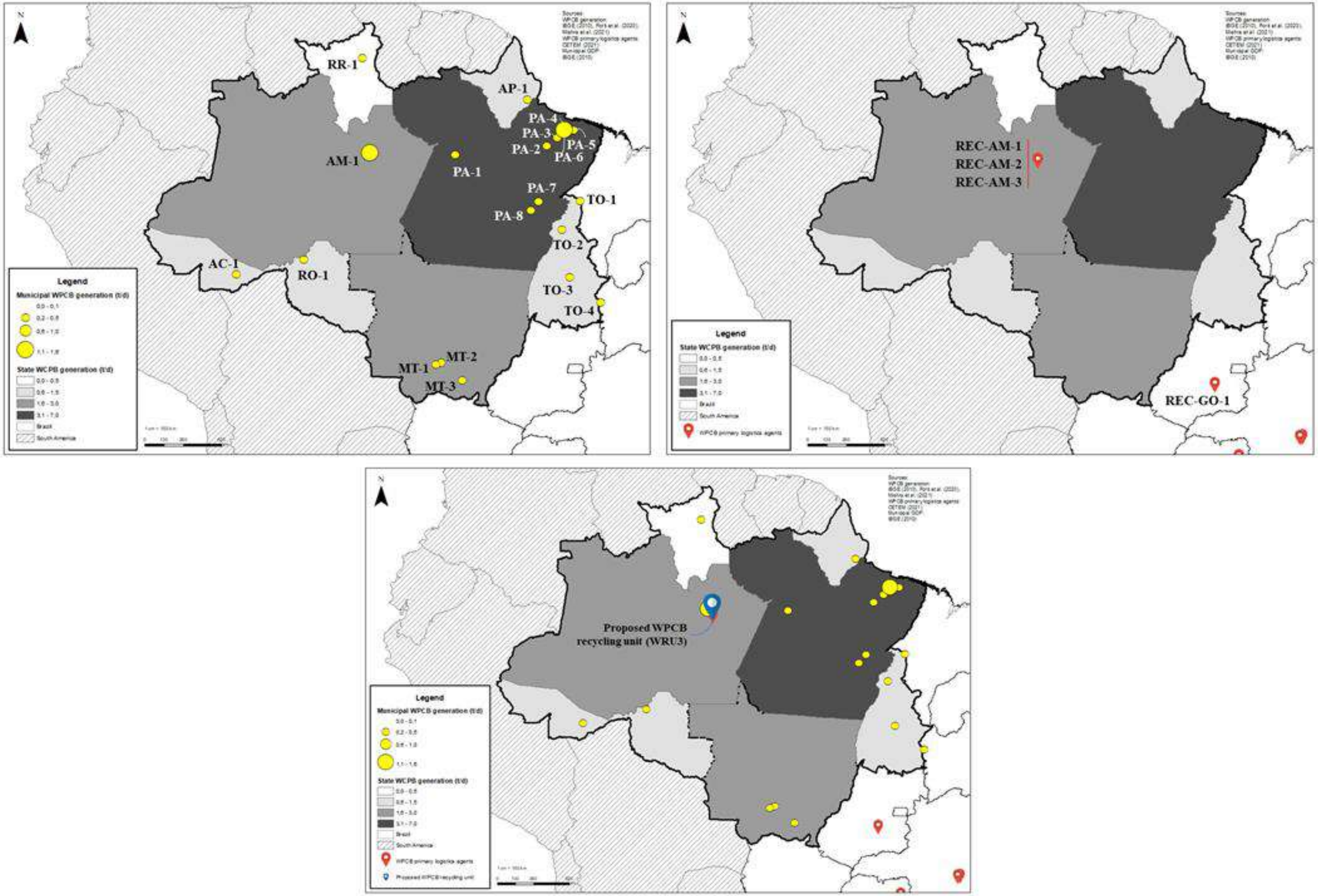
The routes and distances between WPCB generation and reverse logistics agents, and from them to WRU were calculated for Cluster 3, and the main codes of the hotspots and the recyclers were illustrated in **Figure 25**. Besides Umicore and Lorene, the third reverse logistics agent considered was Geodis, a transporting company that, even though does not perform any kind of preprocessing stages, might contribute to WPCB transportation to other recyclers in Brazil or even abroad (**Figure 25b**). These codes were used in **Table 35**, which also presents the distances, emissions and energy of each route in Cluster 3.

As shown in **Table 35**, this cluster contributes significantly to emissions and demanded energy for reverse logistics, especially because of the large distances between the considered routes from the hotspots to the reverse logistics agents. These routes represented almost 30 times more emissions and demanded energy than those from the reverse logistics agents to the WRU. The highest distances were related to the routes from Pará (PA) to the reverse logistics agents in Amazonas (AM). Even though these two states are neighbours, the highways are long to deviate from the abundant rivers in this region, which justifies the significant calculated distances.

Table 34. Cluster 3 facility's siting analysis for WPCB recycling plant

Municipality	WPCB (kg/d)	Score	GDP (million R$)	Score	MHDI	Score	Dist.Hotspot (km)	Score	RLS	Score	Reverse logistics agents	Score	Total
Manaus	1510.73	5	78192.00	5	0.737	5	0	5	Yes	0	3	3	23
Parintins	85.54	4	1119.00	1	0.658	4	-	0	Yes	0	0	0	9
Itacoatiara	72.80	3	1881.00	3	0.644	3	-	0	Yes	0	0	0	9
Manacapuru	71.38	2	1428.00	2	0.614	2	-	0	Yes	0	0	0	6
Coari	63.69	1	2016.00	4	0.586	1	-	0	Yes	0	0	0	6

Figure 25. Details of Cluster 3: a) WPCB hotspots; b) Reverse logistics agents; c) WRU siting



Sources: Data from CETEM (2021), FORTI, BALDÉ, *et al.* (2020), IBGE (2010)

Table 35. Distances, emissions and energy for Cluster 3 in the alternative scenario

Hotspot-Reverse logistics agent	Distances (km)	Emissions (tCO2e./round)	Energy (MJ)	Reverse logistics agent-WPCP Recycling Unit	Distances (km)	Emissions (tCO2e./round)	Energy (MJ)
[RR-1] – [REC-AM-2]	750	0.960	7939	[REC-AM-2] – [WRP3]	10	0.013	106
[AC-1] – [REC-AM-2]	1400	1.792	14820				
[RO-1] – [REC-AM-2]	900	1.152	9527				
[AM-1] – [REC-AM-2]	10	0.013	106				
[PA-1] – [REC-AM-2]	2110	2.701	22336				
[PA-2] – [REC-AM-2]	2850	3.648	30169				
[PA-3] – [REC-AM-2]	2950	3.776	31227				
[AP-1] – [REC-AM-2]	-	-	-				
[PA-4] – [REC-GO-1]	2000	2.560	21171	[REC-GO-1] – [WRP1]	900	1.152	9527
[PA-5] – [REC-GO-1]	2000	2.560	21171				
[PA-6] – [REC-GO-1]	2000	2.560	21171				
[PA-7] – [REC-GO-1]	1500	1.920	15878				
[PA-8] – [REC-GO-1]	1500	1.920	15878				
[AP-1] – [REC-GO-1]	-	-	-				
[TO-1] – [REC-GO-1]	1500	1.920	15878				
[TO-2] – [REC-GO-1]	1160	1.485	12279				
[TO-3] – [REC-GO-1]	850	1.088	8998				
[TO-4] – [REC-GO-1]	850	1.088	8998				
[MT-1] – [REC-GO-1]	950	1.216	10056				
[MT-2] – [REC-GO-1]	920	1.178	9739				
[MT-3] – [REC-GO-1]	750	0.960	7939				
TOTAL	**26950**	**34.50**	**285282**	**TOTAL**	**910**	**1.16**	**9633**

Table 36 presents the summary of results obtained in the alternative scenario for calculated distances, emissions and energy per transportation round in the three considered clusters.

Table 36. Comparison of estimated distances, emissions and energy per round in each Cluster (alternative scenario)

Cluster	Reverse Logistics		
	Distances (km/round)	**Emissions (tCO2e./round)**	**Energy (GJ/round)**
1	7310	9	77
2	5075	6	54
3	27860	36	295
Total	**40245**	**52**	**426**

As demonstrated by **Table 36**, Cluster 3 was responsible for the highest distances and derived emissions, demanded energy and related transportation costs in comparison to the other two Clusters. Most of this difference is a result of the difficulty of road transportation in this area. Thus, possibly other transportation modes can be considered for the WPCB reverse logistics fluxes in this Cluster, as inland waterways, given that since the Amazon region has several rivers that can be used for transport.

4.2.3 Comparative analysis

Section 4.2.1 presented the calculated numbers for the baseline scenario considering distances, emissions and energy per round. In this section, the estimates for potential costs with transportation considering fuel expenses (0.143 USD/km) and average distances for both road and maritime routes were obtained, based on the economic criteria defined in **Section 3.1** (**Table 22**). All results regarding environmental and economic analysis in the baseline scenario were compiled in **Table 37**.

As shown in **Table 37**, the rounds in a year varied from the type of flow. From hotspots to reverse logistics agents, a daily route was assumed during the year. From the reverse logistics agents to the ports, the adopted frequency was once a week, considering 52 weeks in a year. Finally, the periodicity of exportations from the Brazilian ports to the chosen port in Antwerp was assumed as once in a month, especially given the brief analysis of potential exportation frequency from COMTRADE Database in **Table 27**, which indicated a possible monthly trade of waste containing precious metals from

Brazil to other countries.

Table 37 highlights that the baseline scenario (considering WPCB exportation) can reach about 86 million USD of costs, 636 ktCO2e. and 9 PJ of demanded energy in a year. Most of these values were related to the exportation route, with the highest logistics costs, emissions values and demanded energy when compared to the other routes. This fact can be explained not only by the longer distances in this route, which influence the final numbers but also, in the case of costs, the higher prices of bunker oil in comparison to diesel used for road transportation (see **Table 22**, in **Section 3.1**). Even though the frequency of rounds per year is lower than in the other routes, sea transport demonstrated a higher negative impact in this scenario, according to the analyzed criteria.

The revenues from the sales of WPCB to foreign recycling companies were estimated considering the average market price paid for WPCB by the exportation companies as 5300 USD/t and total exported WPCB amount of 19,272 t/year (the same value calculated in **Table 26** for the alternative scenario, as a simplification assumption of the simulation). The multiplication of these values resulted in a final estimated revenue of 102 million USD/year that is obtained in the exportation scenario.

In the alternative scenario, the environmental and economic analyses were segmented into two main parts: the reverse logistics (transportation from hotspots to the recycling units) and the processing stages (activities performed in the recycling units), as indicated by **Table 38**. The routes from hotspots to reverse logistics agents were those that most contributed to costs, emissions and demanded energy in reverse logistics when compared to the route from the recyclers to WRU, given the higher distances travelled and the number of rounds in a year. Regarding the processing stages, WRU 1 was the recycling plant that most influenced the final results of costs, emissions and demanded energy, but also was responsible for the higher obtained revenues with WPCB value recovery, especially because of the bigger amounts of processed WPCB than the other clusters.

Table 37. Costs, emissions, energy and revenues estimated for the baseline scenario on an annual basis

Routes	Distances (km/round)	Costs (USD/round)	Rounds /year	Costs (million USD/year)	Emissions (tCO2e./round)	Rounds /year	Emissions (ktCO2e./year)	Energy (MJ/round)	Rounds /year	Energy (TJ/year)
Hotspot-Reverse logistics agents	33315	4,213.37	365	1.54	42.64	365	15.56	352,659	365	128.72
Reverse logistics agents-Ports	8320	1,052.24	52	0.054	10.65	52	0.55	88,072	52	4.58
BR Ports-Antwerp (Belgium)	58550	6,998,979.18	12	83.99	51641.10	12	619.69	737,730,000	12	8,852.76
TOTAL	**100185**	**7,004,244.78**		**85.6**	**51694.39**		**635.81**	**738,170,731**		**8,986.06**
Exportation	**WPCB market price (USD/t)**	**WPCB assumed exported amounts (t/year)**		**Revenues (million USD/year)**						
	5300	**19272**		**102.1**						

Table 38. Distances, costs, emissions and energy estimated for the alternative scenario (reverse logistics + processing) on an annual basis

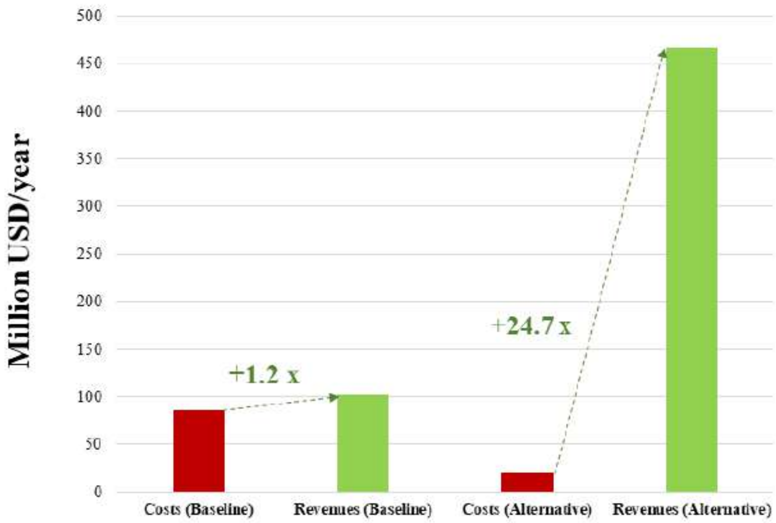
Reverse Logistics Routes	Distances (km/round)	Costs (USD/round)	Rounds /year	Costs (million USD/year)		Emissions (tCO2e./round)	Rounds /year	Emissions (ktCO2e./year)	Energy (MJ/round)	Rounds /year	Energy (TJ/year)
Hotspot - Reverse logistics agents	33305	4,212.10	365	1.54		42.63	365	15.56	352,553	365	128.68
Reverse logistics agents - WPCB Recycling Units	6940	877.71	52	0.046		8.88	52	0.46	73,464	52	3.82
TOTAL	**40245**	**5090**		**1.58**		**52**		**16**	**426,017**		**132.5**
Processing	**Processing costs (USD/t)***	**Processing revenues (USD/t)***	**Processed WPCB (t/year)**	**Costs (million USD/year)**	**Revenues (million USD/year)**	**Emissions (tCO2/t metal produced)****	**Processed WPCB (t/year)**	**Emissions (ktCO2e./year)**	**Energy (MJ/t WPCB)***	**Processed WPCB (t/year)**	**Energy (TJ/year)**
WRU 1			12264	11.04	308.95		12264	45.74		12264	95.21
WRU 2	900	25192	5256	4.73	132.41	3.73	5256	19.60	7763	5256	40.80
WRU 3			1752	1,58	44.14		1752	6.53		1752	13.60
TOTAL			**19272**	**17.35**	**485.50**		**19272**	**71.9**		**19272**	**149.6**
TOTAL (Reverse Logistcs + Processing)				**466.57**				**87.9**			**282.1**

*(YANG, SUN, *et al.*, 2021), **(KAYA, 2019)

Comparing reverse logistics and processing stages of the alternative scenario, the costs and emissions of the former were lower than the latter and the demanded energy was practically the same, which demonstrates that processing can be more impactful than transporting, but the positive economic aspects (as the potential revenues) can outweigh the negative ones and serve to mitigate those impacts. Therefore, even though the processing costs were almost 11 times higher than the reverse logistics costs in the alternative scenario, the revenues obtained from WPCB value recovery can cover this difference and represent positive contributions when compared to the exportation context. According to **Table 38**, the alternative scenario with its three clusters might reach 466 million USD of final positive balance in a year for Brazil, which is a significant benefit.

The comparison of the baseline and alternative scenarios considering the total costs and revenues from WPCB exportation (baseline) and WPCB recycling (alternative) was illustrated in **Figure 26**.

Figure 26. Comparison of the baseline and alternative scenarios considering the total costs and revenues



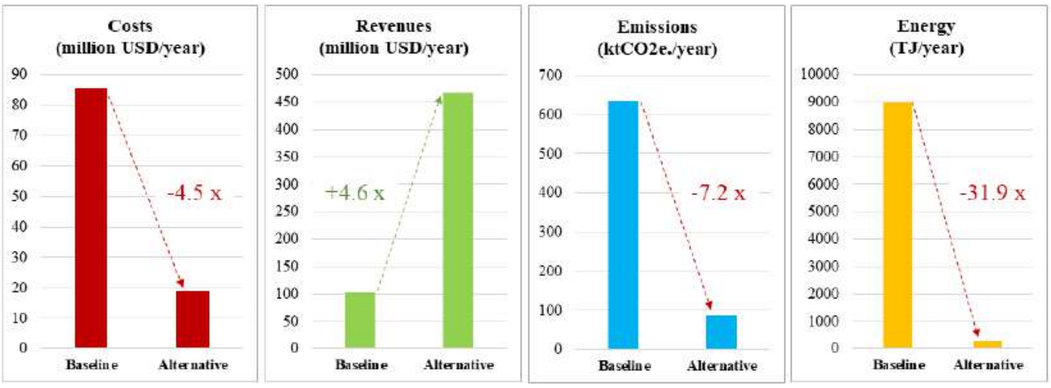
Criteria	Million USD/year
Costs (Baseline) (Cb)	85.60
Costs (Alternative) (Ca)	18.93
Revenues (Baseline) (Rb)	102.14
Revenues (Alternative) (Ra)	466.57
Ra/Ca	24.7
Rb/Cb	5.5

As indicated in **Figure 26**, the revenues obtained from WPCB exportation can be

1.2 times higher than the costs in this same scenario, while the revenues from the WPCB recycling might be 24.7 times greater than its costs. This final revenue value might represent more jobs for the country. In a simplified analysis considering the average wage of a Brazilian inhabitant of 4985,28 USD/year (equivalent to R$ 2308,00 per month converted to annual values in dollars at the average exchange rate of 1 BRL=0.18 USD), as shown in **Table 22** of **Section 3.2**, these revenues obtained from WPCB value recovery in Brazil have the potential to generate approximately 93590 jobs, which represents a positive impact in the economy of the country.

All results regarding the comparison of economic and environmental criteria between the baseline and the alternative scenarios were compiled in **Figure 27**.

Figure 27. Compilation of the economic and environmental results of the baseline and alternative scenarios and their comparison



Scenarios' Comparison	Costs (million USD/year)	B/A	Revenues (million USD/year)	A/B	Emissions (ktCO2e./year)	B/A	Energy (TJ/year)	B/A
Baseline (B)	85.60	4.5	102.14	4.6	635.81	7.2	8,986.06	31.9
Alternative (A)	18.93		466.57		87.91		282.11	

As illustrated in **Figure 27**, the revenues obtained in the alternative scenario were almost five times higher than the estimated revenues in the baseline scenario. This result indicates the economic potential of performing WPCB value recovery through recycling directly in Brazil since selling these components for recyclers abroad depreciates the added value of WPCB for Brazil. As shown in **Figure 26**, the potential revenues with recycling surpass almost 25 times the recycling costs.

Besides the economic gains, as the alternative scenario costs were about five times lower than the total costs of the baseline scenario (**Figure 27**), some environmental benefits could also be highlighted in this WPCB recovery context. The implementation of this framework with three WRU could reduce the emissions 7.2 times when compared to the exportation activities currently in operation, and the demanded energy has the potential to be more than 30 times smaller than the baseline scenario, even considering the WPCB recycling stages. These results can be explained by the most impactful potential of the exportation by maritime route, with the highest logistics costs, emissions values and demanded energy when compared to the other routes. Even though the frequency of rounds per year was assumed as lower than in the other routes, the exportation comprehended not only longer distances, which influence the final emission and demanded energy numbers, but also the higher prices of bunker oil in comparison to diesel used for road transportation (**Table 22**). Also, the scenario with recycling units has the potential to increase the control over pollution mainly because the facilities have to be equipped with filters and pollution control mechanisms required by Law to operate in the country.

In the numbers of **Table 37** and **Table 38**, a scenario without losses was considered. The sensibility analysis can provide the variations of the costs, revenues, emissions and energy according to the WPCB losses from collection until the recycling itself. Thus, this assessment contributes to understanding the effects of different scenarios of material losses into the input volumes of WPCB in the recycling units. **Table 39** presents the sensibility analysis of WPCB recycling considering various scenarios of material losses from collection until recycling.

Table 39. Sensibility analysis of WPCB recycling considering various scenarios losses from collection until recycling

Collected WPCB (t/year)	Losses for recycling	WPCB to be recycled (t/year)	Processing costs (million USD/year)	Total costs (million USD/year)	Processing revenues (million USD/year)	Total revenues (million USD/year)	Processing emissions (ktCO2e./ year)	Total emissions (ktCO2e./ year)	Processing energy (TJ/year)	Total energy (TJ/year)
19272	0%	19272	17.34	**18.92**	485.50	**466.58**	71.9	**87.9**	149.6	**282.1**
19272	20%	15418	13.88	**15.46**	388.40	**372.94**	57.5	**73.5**	119.7	**252.2**
19272	50%	9636	8.67	**10.25**	242.75	**232.50**	35.9	**51.9**	74.8	**207.3**
19272	80%	3854	3.47	**5.05**	97.10	**92.05**	14.4	**30.4**	29.9	**162.4**

In **Table 39**, the total costs, revenues, emissions and energy considered the sum of logistics values (the same as those presented in **Table 38**) and processing numbers (which were modified according to the different values of losses, varying from 0% to 80%). It was assumed that 100% losses would make the recycling unfeasible, and, therefore, this scenario was not considered in the analysis.

The economic results in the sensibility analysis indicate that the costs of the alternative scenario vary from about 5 million USD/year (scenario with high losses) until 19 million USD/year (scenario with low losses). The revenues, ranging from 92 million (scenario with high losses) USD/year to 466 million USD/year (scenario with low losses), have the potential to far surpass the logistics and processing costs of WPCB recycling in Brazil, reinforcing the economic positive impact of WPCB recycling in the country when compared to exportation.

Regarding the environmental impacts of such variations in WPCB material losses, **Table 39** showed that the total emissions and demanded energy reduce with the increase of material losses. However, the impacts in the logistics phase increase proportionally with the higher material losses and generate negative effects in the economic feasibility of the alternative scenario. Besides, the material losses of WPCB might imply the reduction of value recovery and its destination to less preferable options, as landfilling or even illegal recycling processes or disposal of in dumpsites, which can cause negative environmental impacts.

Therefore, the adoption of a framework that considers the e-waste reverse logistics to direct the collected WPCB to value recovery operations through recycling inside the country could generate positive impacts not only economically but also under environmental (reducing total emissions and energy) and social perspectives (creating jobs) than exporting this material to refineries abroad.

In terms of carbon mitigation, these avoided GHG emissions were not substantial to contribute to the Brazilian NDC of the Paris Agreement (achieving a limit of 1.76 GtCO2e by 2025, according to Observatório do Clima (2020)) for mitigating climate change effects. However, the proposed alternative scenario might represent an important measure for reducing the carbon footprint of the electronics industry and a trend for future strategic planning.

Nevertheless, the success of such a strategy of WPCB value recovery in Brazil must count on an effective reverse logistics system (RLS), considering high collection rates (in this study, 30% was the assumed value for the e-waste collection scenario). Even though Brazil is in its first year of the e-waste RLS, the sum of the annual goals for e-waste collection (1%, 3%, 6%, 12%, 17%, not cumulative and based on 2018 PoM values) presented in the Decree 10,240:2020 (BRAZIL, 2020), which implements the e-waste RLS in the country, will reach 39% by the end of 2025. Thus, this suggested collection rate of at least 30% is possible to be achieved within the next years in Brazil for being already demanded by Law. The identification of optimal routes for reverse logistics might help reduce costs with the collection, transport and storage, besides increasing e-waste collected, which is of crucial importance for guaranteeing the real potential of recycling (KAYA, 2020a). Investing in the improvement of the RLS for guaranteeing the minimum volumes for recycling is an important measure to be taken for the adequate accomplishment of e-waste urban mining in Brazil.

Some other recommendations would include the implementation of cargo consolidation points to concentrate the e-waste/WPCB volumes in more distant routes, such as those in Clusters 2 and 3, to make the transport service cheaper and guarantee minimum processing volumes.

Besides, the investment in traceability systems for e-waste/WPCB reverse logistics represent a solution for reducing informality in this industrial sector. The lack of an e-waste official database (XAVIER, OTTONI, *et al.*, 2021) and integrated traceability systems is a weakness of the current e-waste management in Brazil, which means that the investment in such technologies might guarantee not only the increase in the e-waste collected amounts to be further recovered or recycled but also in the reduction of the e-waste volumes sent to the informal chains and its consequent environmental impacts. In addition, the investment in adequate and continuous training for formal and informal agents that already perform the collection, pretreatment or preprocessing of these materials can reduce informality, increase the number of reverse logistics agents in the RLS and avoid contamination. Indeed, according to SOUZA (2019), the existence of a large number of waste pickers’ cooperatives is a reality in Brazil, and, therefore, proper training should be stimulated. Therefore, strategic planning for increasing the collection goals, selecting the most favourable cargo consolidation and intermediate dismantling stations along with the country, and developing traceability systems should gradually increase the e-waste/WPCB collected amounts.

Also, the environmental education campaigns, permanent programs and other incentive mechanisms for encouraging the consumers' participation in the RLS should be considered as a priority. The regular disclosure (on websites, reports, social media, etc.) of RLS numbers of reliable collected, treated and recycled e-waste volumes is an example of transparency and encouraging measures to the consumers to contribute to the reverse supply chain.

The implementation of severe punitive legal mechanisms is important to inhibit informality all along with the electronics sector in the country, from product stage until treatment and disposal, and for guaranteeing safe and environmentally sound management. The use of primitive techniques, as generally performed in informal chains, exposes individuals to the dangers of the e-waste contaminants (OTTONI, DIAS, *et al.*, 2020, SOUZA, Ricardo Gabbay, 2019), and the role played by the regulators is fundamental to control and solve such reality.

Also, investing in e-waste/WPCB recycling technologies and internal processes that demand less energy, considering that energy generation is one of the highest contributors for increasing the carbon footprint of a process from a lifecycle perspective. Therefore, even though recycling may create carbon savings because it usually takes less energy to produce recycled materials than raw materials (UK PARLIAMENTARY OFFICE OF SCIENCE AND TECHNOLOGY, 2011), the internal recycling processes also must be continuously improved regarding material and energy efficiency to reduce costs and climate impacts. The same efficiency criteria should be applied for the treatment systems for emissions, effluents and production wastes, to avoid the threats of the environmental impacts, related costs for remediation in case of accidents and to promote more circular and sustainable patterns for the electronics sector through the recycling and precious metals recovery from e-waste/WPCB. In this aspect, hydrometallurgical processes generally demand less energy, emissions and related costs than pyrometallurgy (VALERO NAVAZO, VILLALBA MÉNDEZ, *et al.*, 2014, YANG, SUN, *et al.*, 2021), which could be considered when planning the recycling routes in each WRU.

Finally, under a legal perspective, the main existing legal framework should be revised, considering detailed special taxation for recyclers to encourage the recycling chain, and more detailed definitions of the e-waste hazardousness within management stages at a federal level, if possible. This fact is due to the different definitions of e-waste as a hazardous material along with the Brazilian states, which represents an obstacle to efficient reverse logistics in the country. Also, the regulations should consider more rational criteria for approving the reverse logistics agents in the RLS. The current adopted rules are severely restrictive on accepting only recyclers that have international certifications, which represents high costs for small recycling organizations. Therefore, only the largest intermediate recycling companies can afford such parameters, and these small recyclers generally end up going bankrupt or entering the informal market for lack of opportunities in the official RLS. Thus, fairer criteria within the environmental conformities should be considered to expand the formal reverse supply chain in the country, besides financial support to expand e-waste recycling in its different levels in the country. The development of monitoring systems for inhibiting non-conformities in the e-waste/WPCB recycling and informal activities along the stages of the electronics sector is, also, of great importance for increasing circularity and sustainable patterns in Brazil.

Therefore, the adoption of the e-waste/WPCB recycling units in the country is favourable for the current context in Brazil, but it should be developed simultaneously with other procedures, such as strategic and efficient logistics with traceable systems at a federal level and revision of legal mechanisms for turning the electronics reverse chain environmentally safer, socially fairer and economically feasible.

5 CONCLUSION

The present study demonstrated that Brazil has a great potential for urban mining from e-waste, particularly from WPCB, which concentrates the most valuable metal fractions. Also, the promotion of e-waste urban mining is a strategic measure to increase circularity and sustainability in all its three aspects: economic, environmental and social.

The literature review performed in this study showed the status of the Brazilian EWMS as an emerging country and explained that closing the loop within the e-waste management sector in Brazil has faced a relevant advance after the implementation of the RLS at a national scale. However, there is still a long way for Brazil to reach higher levels of circularity through the increased resources recovery from e-waste. Even though e-waste urban mining in Brazil is still incipient in the current context, the country has developed infrastructure for remanufacturing processes (also considered as a reuse approach), but urban mining itself (which considers secondary resources exploitation) is mostly performed at laboratory scale in Brazil, especially for the most valuable metal fractions. The e-waste from formal chains that contain precious metals is, therefore, exported to be processed and refined abroad, which represents a loss of material value and higher energy expenditure, considering the international dimension of logistics.

In this aspect, a reverse logistics framework was proposed for WPCB fractions generated in Brazil, which can reach about 64 kt/year, as estimated in this study. Considering an analysis with an assumed collection and recycling rate of 30%, and the comparison of the current flows of WPCB collection, preprocessing and exportation

(Baseline scenario) and the proposed framework with the collection, preprocessing and recycling in the country (Alternative scenario), this thesis demonstrated positive economic, environmental and social results for WPCB value recovery in Brazil rather than exporting it.

The main findings showed that the implementation of complete recycling (third-level treatment) of WPCB in the country could reduce the reverse logistics costs by up to almost 67 million USD/year (4.5 times less than the exportation context), which might represent, in a simplified analysis, about 93590 jobs for the country. Besides, the revenues were calculated as 4.6 higher with recycling in Brazil than exporting WPCB overseas, demonstrating the economic potential of the recycling market in Brazil. Also, around up to 550 ktCO2e. and 8.7 PJ of emissions and demanded energy can be avoided (7.2 and 31.9 times less than in the baseline scenario, respectively). Therefore, the proposed framework that includes WPCB processing in Brazil instead of exporting this fraction to refineries abroad has proved to be a more sustainable alternative for the country if the RLS proves to be efficient, the informality in the sector is reduced through legal mechanisms and the government incentives are adequately implemented to encourage the recycling market. Other actions to increase the efficiency of the RLS and value recovery in Brazil would be investing in traceability systems, applying labelling into electronics devices to facilitate the recycling, formalization, and training of recycling agents, as in the case of cooperatives and associations of waste pickers, among others.

Thus, the future efficient energetic perspectives for e-waste urban mining in Brazil might consider investments in e-waste recycling units to perform processing and refining operations to avoid long-distance transportation (such as those demanded in exportation) and, hence, higher energy expenditure and related GHG emissions. By doing so, the country retains the material value, which influences positively the national economy, generating jobs and reducing the material supply dependence from other countries. Finally, such recycling units might contribute to closing the loop within the electronics industry, especially for recovering secondary resources to be reinserted in new productive cycles, increasing the circularity levels of this sector in Brazil.

Besides, value recovery measures for the next years might include the prepare for reuse approach, as already discussed in the international scientific community, as in the case of the European Union. These strategies for reuse (sharing, repairing, remanufacturing, refurbishing, etc) are taken as priorities in the Circular Economy principles and waste hierarchy frameworks when compared to recycling and energy recovery, for instance.

The lack of an official Brazilian e-waste database limited the calculation of a more realistic estimative of the e-waste generation and flows in the country, especially considering the values for WPCB generation and collection rates. In this regard, assumptions from the literature were considered in this study, which can reduce the accuracy of final values and the proximity to the real context. The chosen method for estimating e-waste production in the country did not consider the regional socioeconomic disparities when adopting a per capita e-waste generation factor nor the probabilistic lifespan of electronic products. Also, this economic analysis did not consider infrastructure costs for implementing the WRU, only the transporting and processing costs. The estimate of the infrastructure costs of such recycling units would demand a more detailed project considering the specifications of the metallurgical routes, which is out of the scope of this thesis. Besides, estimating these values from the existing companies worldwide was a challenge, especially due to the scarce available information since these costs involve strategic data for such companies.

Therefore, future studies could address the development of other methodologies for estimating e-waste generation and main fluxes in Brazil, taking into account its socioeconomic particularities along with the Brazilian regions and the lifespan methods for electronic devices. Future research can also evaluate the circularity and sustainability potentials of the e-waste urban mining in Brazil through selected indicators, pointing out solutions for more circular patterns in this industry and more detailed studies for technical-economic assessment for WPCB recycling routes in Brazil.

This thesis innovated by presenting the simulation of the current Brazilian WPCB scenario considering exportation values, contrasting them with a proposed framework for WPCB value recovery in the country, and indicating through quantitative and qualitative analysis the economic, environmental and social benefits for Brazil in investing in WPCB recycling. By doing so, the present study has addressed, to the best of our knowledge, an identified gap in the literature of quantifying the real benefits under the sustainability perspective of performing complete e-waste recycling in the country, as exemplified by the WPCB case. Previous studies have discussed the qualitative aspects of implementing such industries so far or even calculated the benefits of reverse logistics routes to preprocessing, not processing and refining itself. Therefore, this study has shown some possibilities for Brazil to develop more circular and sustainable patterns for the future years regarding the electronics industry and might serve as an inspiration for next research in other developing countries.

REFERENCES

ABALANSA, S., MAHRAD, B. El, ICELY, J., *et al.* "Electronic waste, an environmental problem exported to developing countries: The good, the bad and the ugly", **Sustainability (Switzerland)**, v. 13, n. 9, p. 1–24, 2021. DOI: 10.3390/su13095302.

ABBONDANZA, M. N. M., SOUZA, R. G. "Estimating the generation of household e-waste in municipalities using primary data from surveys: A case study of Sao Jose dos Campos, Brazil", **Waste Management**, v. 85, p. 374–384, 2019. DOI: 10.1016/j.wasman.2018.12.040.

ABDI. "Logística Reversa de Equipamentos Eletroeletrônicos Análise de Viabilidade Técnica e Econômica", **Agência Brasileira de Desenvolvimento Industrial - ABDI**, p. 177, 2013.

ABREE. **ABREE COMEMORA 10 ANOS DE ATUAÇÃO (ABREE CELEBRATES 10 YEARS OF OPERATION)**. 2021. Available at: http://abree.org.br/noticias/53/abree-comemora-10-anos-de-atuacao. Accessed in: 14 Jul. 2021.

AFONSO, J. C. "Waste electrical and electronic equipment: The Anthropocene knocks on our door", **Revista Virtual de Quimica**, v. 10, n. 6, p. 1849–1897, 2018. DOI: 10.21577/1984-6835.20180121.

ALVES, R., FERREIRA, K. L. A., LIMA, R. da S., *et al.* "An Action Research Study for Elaborating and Implementing an Electronic Waste Collection Program in Brazil", **Systemic Practice and Action Research**, v. 34, n. 1, p. 91–108, 2021. DOI: 10.1007/s11213-019-09509-5.

ARAUJO, D. R. R., DE OLIVEIRA, J. D., SELVA, V. F., *et al.* "Generation of domestic waste electrical and electronic equipment on Fernando de Noronha Island: qualitative and quantitative aspects", **Environmental Science and Pollution Research**, v. 24, n. 24, p. 19703–19713, 2017. DOI: 10.1007/s11356-017-9648-3.

ARAUJO, R. A. De, OTTONI, M., XAVIER, L. H. "ANALYSIS OF E-WASTE VOLUNTARY DELIVERY POINTS (VDP) LOCATION IN THE CITY OF RIO DE JANEIRO , BRAZIL", n. November, 2020.

ARAUJO, R. A. de, XAVIER, L. H. "Banco de dados e estudo geoespacial de organizações do segmento de resíduos eletroeletrônicos no Brasil.", **Série Jornada de iniciação Científica**, p. 199–203, 2019. Available at: https://www.cetem.gov.br/jornadas/jornada-de-iniciacao-cientifica/itemlist/category/108-2019?start=10.

ARAUJO, M. G. "Modelo de avaliação do ciclo de vida para a gestão de resíduos de equipamentos eletroeletrônicos no Brasil", p. 217, 2013.

ARAÚJO, M. G., MAGRINI, A., MAHLER, C. F., *et al.* "A model for estimation of potential generation of waste electrical and electronic equipment in Brazil", **Waste Management**, v. 32, n. 2, p. 335–342, 2012. DOI: 10.1016/j.wasman.2011.09.020.

ARAUJO, M. V. F., OLIVEIRA, U. R., MARINS, F. A. S., *et al.* "Cost assessment and benefits of using RFID in reverse logistics of waste electrical & Electronic equipment (WEEE)", **Procedia Computer Science**, v. 55, n. Itqm, p. 688–697, 2015. DOI: 10.1016/j.procs.2015.07.075.

ARAUJO, R., CUGULA, J., APOLONIO, L., *et al.* "SPATIAL DISTRIBUTION ANALYSIS OF E- WASTE VOLUNTARY DELIVERY POINTS (VDP) BY GREEN ELETRON MANAGER IN SÃO PAULO CITY (SP , BRAZIL)", n. November, 2020.

ARDI, R. "Waste Electrical and Electronic Equipment (Weee) Management Systems in the Developed and the Developing Countries: a Comparative Structural Structural Study", p. 205, 2016. Available at: https://duepublico.uni-duisburg-

essen.de/servlets/DerivateServlet/Derivate-42445/Ardi_Diss.pdf.
AUGUSTO, E. E. F., DEMAJOROVIC, J., MELGAREJO-MORENO, J. "The impact of cooperation on the implementation of the 'descarte on' weee reverse logistics pilot project in Brazil", **WIT Transactions on the Built Environment**, v. 179, p. 269–280, 2018. DOI: 10.2495/UG180251.
AWASTHI, A. K., LI, J. "Management of electrical and electronic waste: A comparative evaluation of China and India", **Renewable and Sustainable Energy Reviews**, v. 76, n. December 2015, p. 434–447, 2017. DOI: 10.1016/j.rser.2017.02.067.
AWASTHI, A. K., LI, J. "Sustainable Bioprospecting of Electronic Waste", **Trends in Biotechnology**, v. 37, n. 7, p. 677–680, 2019. DOI: 10.1016/j.tibtech.2019.03.004.
AWASTHI, A. K., ZENG, X. **Recycling printed circuit boards**. [S.l.], Elsevier Ltd, 2019. Available at: http://dx.doi.org/10.1016/B978-0-08-102158-3.00011-2.
AZEVEDO, L. P., ARAÚJO, F. G. S., LAGARINHOS, C. A. F., *et al.* "E-waste management and sustainability: a case study in Brazil", **Environmental Science and Pollution Research**, v. 24, n. 32, p. 25221–25232, 2017. DOI: 10.1007/s11356-017-0099-7.
AZEVEDO, L. P., ARAÚJO, F. G. S., LAGARINHOS, C. A. F., *et al.* "Resource recovery from e-waste for environmental sustainability: A case study in brazil", **Electronic Waste Management and Treatment Technology**, p. 175–200, 2019. DOI: 10.1016/B978-0-12-816190-6.00008-X.
BAKHIYI, B., GRAVEL, S., CEBALLOS, D., *et al.* "Has the question of e-waste opened a Pandora's box? An overview of unpredictable issues and challenges", **Environment International**, v. 110, n. November 2017, p. 173–192, 2018. DOI: 10.1016/j.envint.2017.10.021.
BOULDING, K. E. "The Economics of the Coming Spaceship Earth", **Environmental Quality in A Growing Economy: Essays from the Sixth RFF Forum - New York, RFF Press**, p. 3–14, 1966. DOI: 10.4324/9781315064147. Available at: https://www.laceiba.org.mx/wp-content/uploads/2017/08/Boulding-1996-The-economics-of-the-coming-spaceship-earth.pdf.
BRAZIL. **Brazilian Policy on Solid Waste**. 2010a. Available at: https://www.wiego.org/sites/default/files/resources/files/Pereira-Brazilian-Waste-Policy.pdf. Accessed in: 20 Jun. 2021.
BRAZIL. **Decree No 10,240, of 12 february 2020. Regulates law No 12,305/2010 and complements the decree No 9,177/2017**. 2020. Available at: https://www.legisweb.com.br/legislacao/?id=389786. Accessed in: 20 Jun. 2021.
BRAZIL. **Decree No 7,404, of 23 December 2010. Regulates Law No 12,305/2010 on the National Policy on Solid Waste Management**. 2010b. Available at: http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/decreto/d7404.htm. Accessed in: 20 Jun. 2021.
BRAZIL. **History - Free Economic Zone of Manaus**. 2015. Available at: https://www.gov.br/suframa/pt-br/zfm/o-que-e-o-projeto-zfm. Accessed in: 17 Jul. 2021.
BRAZIL. **Programa 2050 Mudança do Clima (2050 Program - Climate Change)**. . [S.l: s.n.], 2016. Available at: https://www.gov.br/agricultura/pt-br/acesso-a-informacao/acoes-e-programas/ppa/plano-plurianual-ppa-2016-2019-1/relatorio_avaliacao_programa_2050-mudanca_do_clima.pdf.
BRAZILIAN MINISTRY OF MINES AND ENERGY. **Esclarecimentos a respeito do preço do diesel (Clarifications regarding diesel price)**. 2020. Available at: https://www.gov.br/anp/pt-br/canais_atendimento/imprensa/noticias-comunicados/esclarecimentos-a-respeito-do-preco-do-diesel. Accessed in: 19 ago. 2021.
BRAZILIAN MINISTRY OF THE ENVIRONMENT (MMA). **Inventário Nacional de**

Emissões Atmosféricas por Veículos Automotores Rodoviários 2013 (Brazilian Inventory of Atmospheric Emissions by Road Motor Vehicles 2013). . [S.l: s.n.], 2013. Available at: https://antigo.mma.gov.br/images/arquivo/80060/Inventario_de_Emissoes_por_Veiculos_Rodoviarios_2013.pdf.
BRAZILIAN MINISTRY OF THE ENVIRONMENT (MMA). **Sectoral agreement for the implementation of the reverse logistics system for household electrical and electronic products and their components**. 2019. Available at: https://sinir.gov.br/images/sinir/Acordos_Setoriais/Eletroeletrônicos/Acordo_Setorial_-_Eletroeletrônicos__sem_anexos.pdf. Accessed in: 20 Jun. 2021.
CAETANO, M. O., DE LEON, L. G., PADILHA, D. W., *et al.* "Risk analysis in the operation of waste electrical and electronic equipment recycling plants", **Gestao e Producao**, v. 26, n. 2, p. 1–12, 2019. DOI: 10.1590/0104-530X3018-19. .
CAIADO, N., GUARNIERI, P., XAVIER, L. H., *et al.* "A characterization of the Brazilian market of reverse logistic credits (RLC) and an analogy with the existing carbon credit market", **Resources, Conservation and Recycling**, v. 118, p. 47–59, 2017. DOI: 10.1016/j.resconrec.2016.11.021.
CAMPOLINA, J. M., SIGRIST, C. S. L., PAIVA, J. M. F., *et al.* "A study on the environmental aspects of WEEE plastic recycling in a Brazilian company", **International Journal of Life Cycle Assessment**, v. 22, n. 12, p. 1957–1968, 2017. DOI: 10.1007/s11367-017-1282-2.
CANAL MARQUES, A., CABRERA, J. M., DE FRAGA MALFATTI, C. "Printed circuit boards: A review on the perspective of sustainability", **Journal of Environmental Management**, v. 131, p. 298–306, 2013. DOI: 10.1016/j.jenvman.2013.10.003.
CARVALHO, C. H. R. de. "Emissões relativas de poluentes do transporte urbano", **Boletim Regional, Urbano e Ambiental IPEA**, n. 5, p. 123–139, 2011. Available at: http://repositorio.ipea.gov.br/bitstream/11058/5574/1/BRU_n05_emissões.pdf.
CAYUMIL, R., KHANNA, R., RAJARAO, R., *et al.* "Environmental Impact of Processing Electronic Waste – Key Issues and Challenges", **E-Waste in Transition - From Pollution to Resource**, 2016. DOI: 10.5772/64139. .
CEMPRE. "Pesquisa Ciclosoft 2018", p. 1–23, 2018. Available at: https://cempre.org.br/wp-content/uploads/2020/08/Pesquisa-Ciclosoft-2018.pdf.
CETEM – CENTER FOR MINERAL TECHNOLOGY. **Recicladores (Recyclers)**. 2021. Available at: https://www.cetem.gov.br/reminare/recicladores. Accessed in: 10 Feb. 2021.
CHEN, M., OGUNSEITAN, O. A., WANG, J., *et al.* "Evolution of electronic waste toxicity: Trends in innovation and regulation", **Environment International**, v. 89–90, p. 147–154, 2016. DOI: 10.1016/j.envint.2016.01.022.
CLIMATE TRANSPARENCY. **The Climate Transparency Report - Brazil, Country Profile 2020**. . [S.l: s.n.], 2020. Available at: https://www.climate-transparency.org/media/brazil-country-profile-2020.
CORREIA, A. J. C., NETO, G. C. O., SILVA, P. C. "Comparative analysis of regulatory instruments in reverse logistics for electrical and electronic wastes", **7th International ACM Conference on Management of Computational and CollEctive Intelligence in Digital EcoSystems, MEDES 2015**, p. 207–213, 2015. DOI: 10.1145/2857218.2857266.
COSSU, R., WILLIAMS, I. D. "Urban mining: Concepts, terminology, challenges", **Waste Management**, v. 45, p. 1–3, 2015. DOI: 10.1016/j.wasman.2015.09.040. .
CUGULA, J., APOLONIO, L., ARAUJO, R., *et al.* "E-WASTE HOTSPOTS AND BEST ROUTES ANALYSIS FOR REVERSE LOGISTICS IN THE CITY OF SÃO PAULO , BRAZIL", n. November, p. 1–5, 2020. .

CUI, J., FORSSBERG, E. "Mechanical recycling of waste electric and electronic equipment: A review", **Journal of Hazardous Materials**, v. 99, n. 3, p. 243–263, 2003. DOI: 10.1016/S0304-3894(03)00061-X. .
DA SILVA, J. R. A., AUGUSTO, J., BEZANA, T., *et al.* "Rematronic: Project to recovery precious metals from electronic waste", **7th International ACM Conference on Management of Computational and CollEctive Intelligence in Digital EcoSystems, MEDES 2015**, n. June 2016, p. 221–227, 2015. DOI: 10.1145/2857218.2857268.
DARBY, L., OBARA, L. "Household recycling behaviour and attitudes towards the disposal of small electrical and electronic equipment", **Resources, Conservation and Recycling**, v. 44, n. 1, p. 17–35, 2005. DOI: 10.1016/j.resconrec.2004.09.002.
DE ALBUQUERQUE, C. A., MELLO, C. H. P., GOMES, J. H. de F., *et al.* "E-waste in the world today: An overview of problems and a proposal for improvement in Brazil", **Environmental Quality Management**, v. 29, n. 3, p. 63–72, 2020. DOI: 10.1002/tqem.21682.
DEMAJOROVIC, J., AUGUSTO, E. E. F., DE SOUZA, M. T. S. "Reverse logistics of E-waste in developing countries: Challenges and prospects for the Brazilian model", **Ambiente e Sociedade**, v. 19, n. 2, p. 117–136, 2016. DOI: 10.1590/1809-4422ASOC141545V1922016.
DIAS, P., DE OLIVEIRA, E., VEIT, H. "Lead hazard evaluation for cathode ray tube monitors in Brazil", **Brazilian Journal of Chemical Engineering**, v. 35, n. 1, p. 43–49, 2018. DOI: 10.1590/0104-6632.20180351s20160367.
DIAS, P., MACHADO, A., HUDA, N., *et al.* "Waste electric and electronic equipment (WEEE) management: A study on the Brazilian recycling routes", **Journal of Cleaner Production**, v. 174, p. 7–16, 2018. DOI: 10.1016/j.jclepro.2017.10.219.
DIESTE, M., VIAGI, A. F., PANIZZOLO, R., *et al.* "Reverse logistics models for the collection of Waste Electrical and Electronic Equipment: The Brazilian case", **2018 International Conference on Production and Operations Management Society, POMS 2018**, n. March 2019, p. 1–8, 2019. DOI: 10.1109/POMS.2018.8629480.
ECHEGARAY, F. "Consumers' reactions to product obsolescence in emerging markets: the case of Brazil", **Journal of Cleaner Production**, v. 134, p. 191–203, 2016. DOI: 10.1016/j.jclepro.2015.08.119.
ECHEGARAY, Fabian, HANSSTEIN, F. V. "Assessing the intention-behavior gap in electronic waste recycling: the case of Brazil", **Journal of Cleaner Production**, v. 142, p. 180–190, 2017. DOI: 10.1016/j.jclepro.2016.05.064. Available at: http://dx.doi.org/10.1016/j.jclepro.2016.05.064.
EHRENFELD, J. R. "Would industrial ecology exist without sustainability in the background?", **Journal of Industrial Ecology**, v. 11, n. 1, p. 73–84, 2007. DOI: 10.1162/jiec.2007.1177.
ELLEN MACARTHUR FOUNDATION. **TOWARDS THE CIRCULAR ECONOMY: Economic and business rationale for an accelerated transition**. . [S.l: s.n.], 2013. Available at: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf.
ERKMAN, S. "Industrial ecology: An historical view", **Journal of Cleaner Production**, v. 5, n. 1–2, p. 1–10, 1997. DOI: 10.1016/s0959-6526(97)00003-6.
EUROPEAN ENVIRONMENTAL BUREAU. **A timeline for the EU 's transition to a circular economy**. . [S.l: s.n.], 2018. Available at: https://www.businessart.at/download/EEB-ZeroWasteEU_ Waste-timeline.pdf.
EUROPEAN UNION. "DIRECTIVE 2012/19/EU OF THE EUROPEAN

PARLIAMENT AND OF THE COUNCIL of 4 July 2012 on waste electrical and electronic equipment (WEEE)", 2012. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0019&from=EN.
EUROPEAN UNION. **Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS)**. [S.d.]. Available at: https://ec.europa.eu/environment/topics/waste-and-recycling/rohs-directive_en. Accessed in: 30 Jun. 2021.
FERNANDES DO NASCIMENTO, H. F., XAVIER, L. H. "Urban Mining and Circular Economy: E-Waste Management in Rio De Janeiro City, Brazil", **Fourth Symposium on Urban Mining and Circular Economy** , n. February, 2018.
FERREIRA, V. F. M., GONÇALVES-DIAS, S. L. F., VALLIN, I. de C. "Inclusion of waste pickers in the reverse logistics of Waste Electrical and Electronic Equipment (WEEE) – the case study of Projeto Eco Eletro", **Desenvolvimento e Meio Ambiente**, v. 51, p. 263–281, 2019. DOI: 10.5380/dma.v51i0.59970.
FIORE, S., IBANESCU, D., TEODOSIU, C., *et al.* "Improving waste electric and electronic equipment management at full-scale by using material flow analysis and life cycle assessment", **Science of the Total Environment**, v. 659, p. 928–939, 2019. DOI: 10.1016/j.scitotenv.2018.12.417.
FOLHAPRESS. **Óleo combustível fica mais caro que diesel e afeta cabotagem (Fuel oil is more expensive than diesel and affects coastal shipping)**. 2020. Available at: https://www.folhape.com.br/economia/oleo-combustivel-fica-mais-caro-que-diesel-e-afeta-cabotagem/164175/. Accessed in: 20 Aug. 2021.
FORTI, V, BALDÉ, C. P., KUEHR, R., *et al.* **The Global E-waste Monitor 2020: Quantities, Flows, and the Circular Economy Potential**. [S.l: s.n.], 2020.
FORTI, Vanessa, BALDÉ, C. P., KUEHR, R. **E-waste Statistics: Guidelines on Classifications, Reporting and Indicators**. Second ed. Bonn, Germany., United Nations University, ViE – SCYCLE, 2018.
FREEDMAN, B. **Environmental Science: A Canadian Perspective**. [S.l.], Dalhousie Libraries Digital Editions, 1998. Available at: https://ecampusontario.pressbooks.pub/environmentalscience/.
FROSCH, R. A., GALLOPOULOS, N. E. "Strategies for Manufacturing the impact of industry on the environment", **Scientific American**, n. September, p. 144–153, 1989. .
GALLOPÍN, G. **A systems approach to sustainability and sustainable development**. Santiago, ECLAC/ Government of the Netherlands Project NET/00/063 "Sustainability Assessment in Latin America and the Caribbean", 2003.
GEISSDOERFER, M., SAVAGET, P., BOCKEN, N. M. P., *et al.* "The Circular Economy – A new sustainability paradigm?", **Journal of Cleaner Production**, v. 143, p. 757–768, 2017. DOI: 10.1016/j.jclepro.2016.12.048.
GHIMIRE, H., ARIYA, P. A. "E-Wastes: Bridging the Knowledge Gaps in Global Production Budgets, Composition, Recycling and Sustainability Implications", **Sustainable Chemistry**, v. 1, n. 2, p. 154–182, 2020. DOI: 10.3390/suschem1020012.
GHISOLFI, V., DINIZ CHAVES, G. de L., RIBEIRO SIMAN, R., *et al.* "System dynamics applied to closed loop supply chains of desktops and laptops in Brazil: A perspective for social inclusion of waste pickers", **Waste Management**, v. 60, p. 14–31, 2017. DOI: 10.1016/j.wasman.2016.12.018.
GHOSH, B., GHOSH, M. K., PARHI, P., *et al.* "Waste Printed Circuit Boards recycling: An extensive assessment of current status", **Journal of Cleaner Production**, v. 94, p. 5–19, 2015. DOI: 10.1016/j.jclepro.2015.02.024.
GOLDBERG, T. "What about the Circularity of Hazardous Materials?", **Journal of Industrial Ecology**, v. 21, n. 3, p. 491–493, 2017. DOI: 10.1111/jiec.12585.

GOUVEIA, N., BUZZO, M. L., GROSSI, M. G. D. L., *et al.* "Occupational exposure to mercury in recycling cooperatives from the metropolitan region of são paulo, Brazil", **Ciencia e Saude Coletiva**, v. 24, n. 4, p. 1517–1526, 2019. DOI: 10.1590/1413-81232018244.01332017.

GREEN ELETRON. **Meet Green Eletron collectors**. 2019. Available at: https://www.greeneletron.org.br/blog/conheca-os-coletores-da-green-eletron/. Accessed in: 7 maio 2020.

GREEN ELETRON. **O que podemos descartar nos coletores da Green Eletron? (What can we discard in Green Eletron collectors?)**. 2020. Available at: https://greeneletron.org.br/blog/o-que-podemos-descartar-nos-coletores-da-green-eletron/. Accessed in: 14 Jul. 2021.

GREGORY, J., MAGALINI, F., KUEHR, R., *et al.* "Solving the E-Waste Problem (StEP) White Paper: E-waste Take-Back System Design and Policy Approaches", v. 3576, n. January, p. 24, 2009. Available at: http://www.step-initiative.org/files/step/_documents/StEP_TF1_WPTakeBackSystems.pdf.

GUARNIERI, P., E SILVA, L. C., LEVINO, N. A. "Analysis of electronic waste reverse logistics decisions using Strategic Options Development Analysis methodology: A Brazilian case", **Journal of Cleaner Production**, v. 133, p. 1105–1117, 2016. DOI: 10.1016/j.jclepro.2016.06.025.

GUO, X., QIN, H., TIAN, Q., *et al.* "Recovery of metals from waste printed circuit boards by selective leaching combined with cyclone electrowinning process", **Journal of Hazardous Materials**, v. 384, n. September 2019, p. 121355, 2020. DOI: 10.1016/j.jhazmat.2019.121355.

HADI, P., XU, M., LIN, C. S. K., *et al.* "Waste printed circuit board recycling techniques and product utilization", **Journal of Hazardous Materials**, v. 283, p. 234–243, 2015. DOI: 10.1016/j.jhazmat.2014.09.032.

HAGELUKEN C. "Improving metal returns and eco-efficiency in electronics recycling", **Proceedings of the 2006 IEEE conference**, n. May, p. 218–223, 2006. Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Improving+metal+returns+and+eco-efficiency+in+electronics+recycling+-#0.

HAO, J., WANG, Y., WU, Y., *et al.* "Metal recovery from waste printed circuit boards: A review for current status and perspectives", **Resources, Conservation and Recycling**, v. 157, n. July 2019, p. 104787, 2020. DOI: 10.1016/j.resconrec.2020.104787.

HSIEH, C.-W. C., FELBY, C. "Biofuels for the marine shipping sector: An overview and analysis of sector infrastructure, fuel technologies and regulations", p. 86, 2017. Available at: https://www.ieabioenergy.com/wp-content/uploads/2018/02/Marine-biofuel-report-final-Oct-2017.pdf.

HUISMAN, J., MAGALINI, F., KUEHR, R., *et al.* **Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE) - Final report**. **Commissioned by the European Commission, Contract No: 07010401/2006/442493/ETU/G4**. [S.l: s.n.], 2008. Available at: http://ec.europa.eu/environment/waste/weee/pdf/final_rep_unu.pdf.

HUISMAN, J., STEVELS, A., BALDÉ, K., *et al.* **The e-waste development cycle - part i, introduction and country status**. [S.l.], Elsevier Ltd, 2019. Available at: http://dx.doi.org/10.1016/B978-0-08-102158-3.00002-1.

IBGE. **Trabalho e rendimento (Work and income)**. 2019. Available at: https://educa.ibge.gov.br/criancas/brasil/nosso-povo/19626-trabalho-e-rendimento.html. Accessed in: 20 Aug. 2021.

IBGE - BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS. **Census 2010**. 2010. Available at: https://censo2010.ibge.gov.br/materiais/guia-do-

censo/operacao-censitaria.html. Accessed in: 10 Feb. 2021.
IBGE – BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS. **Gross Domestic Product - GDP**. 2018. Available at: https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9088-produto-interno-bruto-dos-municipios.html?=&t=resultados. Accessed in: 24 Jul. 2021.
ILANKOON, I. M. S. K., GHORBANI, Y., CHONG, M. N., *et al.* "E-waste in the international context – A review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery", **Waste Management**, v. 82, p. 258–275, 2018. DOI: 10.1016/j.wasman.2018.10.018.
IMBELLONI, R. **Em Manaus, empresa compra lixo eletrônico para reciclar (In Manaus, the company buys electronic waste to recycle)**. 2012. Available at: http://www.portalamazonia.com.br/editoria/meio-ambiente/em-manaus-empresa-compra-lixo-eletronico-para-reciclar/. Accessed in: 27 Aug. 2021.
KALMYKOVA, Y., SADAGOPAN, M., ROSADO, L. "Circular economy - From review of theories and practices to development of implementation tools", **Resources, Conservation and Recycling**, v. 135, n. November 2017, p. 190–201, 2018. DOI: 10.1016/j.resconrec.2017.10.034.
KAMBEROVIĆ, Ž., RANITOVIĆ, M., KORAĆ, M., *et al.* "Pyro-Refining of Mechanically Treated Waste Printed Circuit Boards in a DC Arc-Furnace", **Journal of Sustainable Metallurgy**, v. 4, n. 2, p. 251–259, 2018. DOI: 10.1007/s40831-018-0167-3.
KAYA, M. **Current WEEE recycling solutions**. [S.l.], Elsevier Ltd, 2018. Available at: http://dx.doi.org/10.1016/B978-0-08-102057-9.00003-2.
KAYA, M. **Industrial-Scale E-Waste / WPCB Recycling**. [S.l: s.n.], 2019.
KAYA, M. "Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes", **Waste Management**, v. 57, p. 64–90, 2016. DOI: 10.1016/j.wasman.2016.08.004.
KAYA, M. **Waste Printed Circuit Board (WPCB) Recovery Technology: Disassembly and Desoldering Approach**. [S.l.], Elsevier Ltd., 2020a. Available at: http://dx.doi.org/10.1016/B978-0-12-803581-8.11246-9.
KAYA, M. **Waste Printed Circuit Board (WPCB) Recycling: Conventional and Emerging Technology Approach**. [S.l.], Elsevier Ltd., 2020b. Available at: http://dx.doi.org/10.1016/B978-0-12-803581-8.11296-2.
KHALIQ, A., RHAMDHANI, M. A., BROOKS, G., *et al.* "Metal extraction processes for electronic waste and existing industrial routes: A review and Australian perspective", **Resources**, v. 3, n. 1, p. 152–179, 2014. DOI: 10.3390/resources3010152. .
KIDDEE, P., NAIDU, R., WONG, M. H. "Electronic waste management approaches: An overview", **Waste Management**, v. 33, n. 5, p. 1237–1250, 2013. DOI: 10.1016/j.wasman.2013.01.006.
KIRCHHERR, J., REIKE, D., HEKKERT, M. "Conceptualizing the circular economy: An analysis of 114 definitions", **Resources, Conservation and Recycling**, v. 127, n. September, p. 221–232, 2017. DOI: 10.1016/j.resconrec.2017.09.005.
KORHONEN, J. "Two paths to industrial ecology: Applying the product-based and geographical approaches", **Journal of Environmental Planning and Management**, v. 45, n. 1, p. 39–57, 2002. DOI: 10.1080/09640560120100187.
KORHONEN, Jouni, HONKASALO, A., SEPPÄLÄ, J. "Circular Economy: The Concept and its Limitations", **Ecological Economics**, v. 143, p. 37–46, 2018. DOI: 10.1016/j.ecolecon.2017.06.041.
KUMAR, A., HOLUSZKO, M. E., JANKE, T. "Characterization of the non-metal fraction of the processed waste printed circuit boards", **Waste Management**, v. 75, p.

94–102, 2018. DOI: 10.1016/j.wasman.2018.02.010.
KUMAR, A., HOLUSZKO, M., ESPINOSA, D. C. R. "E-waste: An overview on generation, collection, legislation and recycling practices", **Resources, Conservation and Recycling**, v. 122, p. 32–42, 2017. DOI: 10.1016/j.resconrec.2017.01.018.
KUSCH, S., HILLS, C. D. "The link between e-waste and GDP-New insights from data from the pan-European region", **Resources**, v. 6, n. 2, 2017. DOI: 10.3390/resources6020015.
LEPAWSKY, J. "Legal geographies of e-waste legislation in Canada and the US: Jurisdiction, responsibility and the taboo of production", **Geoforum**, v. 43, n. 6, p. 1194–1206, 2012. DOI: 10.1016/j.geoforum.2012.03.006.
LEPAWSKY, J. **Reassembling Rubbish**. [S.l: s.n.], 2018.
LI, J., ZENG, X. "Recycling printed circuit boards", **Waste Electrical and Electronic Equipment (WEEE) Handbook**, p. 287–311, 2012. DOI: 10.1533/9780857096333.3.287.
LIMA, A. **Poder Calorífico (Calorific power)**. [S.d.]. Available at: https://www.antoniolima.web.br.com/arquivos/podercalorifico.htm. Accessed in: 20 ago. 2021.
LIMA, A. B., ROCHA, T., PIMENTEL, M., *et al.* "The Brazilian government efforts to support electronic recycling facilities to comply with environmental sound practices", **2016 Electronics Goes Green 2016+, EGG 2016**, p. 1–8, 2017. DOI: 10.1109/EGG.2016.7829837.
LOPES DOS SANTOS, K. "The recycling of e-waste in the Industrialised Global South: the case of Sao Paulo Macrometropolis", **International Journal of Urban Sustainable Development**, v. 00, n. 00, p. 1–14, 2020. DOI: 10.1080/19463138.2020.1790373.
LÓPEZ-BERMÚDEZ, B., FREIRE-SEOANE, M. J., GONZÁLEZ-LAXE, F. "Efficiency and productivity of container terminals in Brazilian ports (2008–2017)", **Utilities Policy**, v. 56, n. November 2018, p. 82–91, 2019. DOI: 10.1016/j.jup.2018.11.006.
LU, Y., XU, Z. "Precious metals recovery from waste printed circuit boards: A review for current status and perspective", **Resources, Conservation and Recycling**, v. 113, n. 2016, p. 28–39, 2016. DOI: 10.1016/j.resconrec.2016.05.007.
LUNDGREN, K. **The global impact of e-waste: Addressing the challenge**. [S.l: s.n.], 2012.
MARRA, A., CESARO, A., BELGIORNO, V. "Separation efficiency of valuable and critical metals in WEEE mechanical treatments", **Journal of Cleaner Production**, v. 186, p. 490–498, 2018. DOI: 10.1016/j.jclepro.2018.03.112.
MGG - MÜLLER-GUTTENBRUNN GROUP. **Non-Ferrous Scrap**. [S.d.]. Available at: https://mgg-recycling.com/recycling-services/non-ferrous-scrap/. Accessed in: 20 Jun. 2021.
MILLAR, N., MCLAUGHLIN, E., BÖRGER, T. "The Circular Economy: Swings and Roundabouts?", **Ecological Economics**, v. 158, n. April 2018, p. 11–19, 2019. DOI: 10.1016/j.ecolecon.2018.12.012.
MISHRA, G., JHA, R., RAO, M. D., *et al.* "Recovery of silver from waste printed circuit boards (WPCBs) through hydrometallurgical route: A review", **Environmental Challenges**, v. 4, n. March, p. 100073, 2021. DOI: 10.1016/j.envc.2021.100073.
MOURA, J. M. B. M., GOHR PINHEIRO, I., LISCHESKI, D., *et al.* "Relation of Brazilian institutional users and technical assistances with electronics and their waste: What has changed?", **Resources, Conservation and Recycling**, v. 127, n. September, p. 68–75, 2017. DOI: 10.1016/j.resconrec.2017.08.022.
NETO, G. C. O., CORREIA, A. J. C., SCHROEDER, A. M. "Economic and

environmental assessment of recycling and reuse of electronic waste: Multiple case studies in Brazil and Switzerland", **Resources, Conservation and Recycling**, v. 127, n. April, p. 42–55, 2017. DOI: 10.1016/j.resconrec.2017.08.011. Available at: https://doi.org/10.1016/j.resconrec.2017.08.011.

NETO, J. F. O., SILVA, M. M., SANTOS, S. M. "A Mini-Review of E-Waste Management in Brazil: Perspectives and Challenges", **Clean - Soil, Air, Water**, v. 47, n. 9, p. 1–10, 2019. DOI: 10.1002/clen.201900152.

NING, C., LIN, C. S. K., HUI, D. C. W., *et al.* "Waste Printed Circuit Board (PCB) Recycling Techniques", **Topics in Current Chemistry**, v. 375, n. 2, 2017. DOI: 10.1007/s41061-017-0118-7.

OBSERVATÓRIO DO CLIMA. **NDC and the carbon trick maneuver: how Brazil reduced the ambition of its goals under the Paris Agreement**. . [S.l: s.n.], 2020. Available at: https://www.oc.eco.br/wp-content/uploads/2020/12/NDC-analysis-EN.pdf.

OLIVEIRA, C. R., BERNARDES, A. M., GERBASE, A. E. "Collection and recycling of electronic scrap: A worldwide overview and comparison with the Brazilian situation", **Waste Management**, v. 32, n. 8, p. 1592–1610, 2012. DOI: 10.1016/j.wasman.2012.04.003.

OLIVEIRA, J. D. De, FRANCISCO, J., NETO, D. O., *et al.* "E-waste mistakenly disposed of as recyclable waste : A case study from Brazil This article has been accepted for publication and undergone full peer review but has not been through the copyediting , typesetting , pagination and proofreading process , whic", **Clean - Soil, Air, Water**, v. 48, n. (11), p. 2000115, 2020. DOI: 10.1002/clen.202000115.

OTTONI, M., DIAS, P., XAVIER, L. H. "A circular approach to the e-waste valorization through urban mining in Rio de Janeiro, Brazil", **Journal of Cleaner Production**, v. 261, p. 120990, 2020. DOI: 10.1016/j.jclepro.2020.120990.

PAES, C. E., BERNARDO, M., DA SILVA LIMA, R., *et al.* "Management of Waste Electrical and Electronic Equipment in Brazilian Public Education Institutions: Implementation Through Action Research on a University Campus", **Systemic Practice and Action Research**, v. 30, n. 4, p. 377–393, 2017. DOI: 10.1007/s11213-016-9399-y.

PANIZZON, T., REICHERT, G. A., SCHNEIDER, V. E. "Avaliação da geração de resíduos de equipamentos eletroeletrônicos (REEEs) em uma universidade particular", **Engenharia Sanitaria e Ambiental**, v. 22, n. 4, p. 625–635, 2017. DOI: 10.1590/S1413-41522017142636.

PEDRO, F., GIGLIO, E., CONTRERAS, L. V., *et al.* "Constructed governance as solution to conflicts in e-waste recycling networks", **Sustainability (Switzerland)**, v. 13, n. 4, p. 1–22, 2021. DOI: 10.3390/su13041701.

PETRIDIS, N. E., PETRIDIS, K., STIAKAKIS, E. "Global e-waste trade network analysis", **Resources, Conservation and Recycling**, v. 158, n. March, p. 104742, 2020. DOI: 10.1016/j.resconrec.2020.104742.

POLZER, V. R., PISANI, M. A. J., PERSSON, K. M. "The importance of extended producer responsibility and the national policy of solid waste in Brazil", **International Journal of Environment and Waste Management**, v. 18, n. 2, p. 101–119, 2016. DOI: 10.1504/IJEWM.2016.080398.

REIKE, D., VERMEULEN, W. J. V., WITJES, S. "The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options", **Resources, Conservation and Recycling**, v. 135, n. November 2017, p. 246–264, 2018. DOI: 10.1016/j.resconrec.2017.08.027.

ROCHA, T. B., PENTEADO, C. S. G. "Life cycle assessment of a small WEEE reverse logistics system: Case study in the Campinas Area, Brazil", **Journal of Cleaner**

Production, v. 314, n. June, p. 128092, 2021. DOI: 10.1016/j.jclepro.2021.128092.
RODRIGUES, A. C., GUNTHER, W. M. R., BOSCOV, M. E. G. "Estimativa da geração de resíduos de equipamentos elétricos e eletrônicos de origem domiciliar: Proposição de método e aplicação ao município de São Paulo, São Paulo, Brasil", **Engenharia Sanitaria e Ambiental**, v. 20, n. 3, p. 437–447, 2015. DOI: 10.1590/S1413-41522015020000133701.
SARIATLI, F. "Linear Economy Versus Circular Economy: A Comparative and Analyzer Study for Optimization of Economy for Sustainability", **Visegrad Journal on Bioeconomy and Sustainable Development**, v. 6, n. 1, p. 31–34, 2017. DOI: 10.1515/vjbsd-2017-0005.
SCHLUEP, M., FORUM, W. R., KUEHR, R., *et al.* "Recycling - from e-waste to resources", n. July, 2009.
SCHROEDER, A. M., DE OLIVEIRA NETO, G. C., DE SOUSA, W. C., *et al.* "Recycle and reuse process of E-Waste (Printed Circuit Boards) in Brazil: A Case Study", **7th International ACM Conference on Management of Computational and CollEctive Intelligence in Digital EcoSystems, MEDES 2015**, p. 214–220, 2015. DOI: 10.1145/2857218.2857267.
SEHNEM, S., VAZQUEZ-BRUST, D., PEREIRA, S. C. F., *et al.* "Circular economy: benefits, impacts and overlapping", **Supply Chain Management**, v. 24, n. 6, p. 784–804, 2019. DOI: 10.1108/SCM-06-2018-0213.
SEPÚLVEDA, A., SCHLUEP, M., RENAUD, F. G., *et al.* "A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from China and India", **Environmental Impact Assessment Review**, v. 30, n. 1, p. 28–41, 2010. DOI: 10.1016/j.eiar.2009.04.001.
SHAIKH, S., THOMAS, K., ZUHAIR, S. "An exploratory study of e-waste creation and disposal: Upstream considerations", **Resources, Conservation and Recycling**, v. 155, n. August 2019, p. 104662, 2020. DOI: 10.1016/j.resconrec.2019.104662.
SILVA, M. F., DUTRA, A. J. B., MANSUR, M. B. "Enrichment of copper, lead, and tin by mechanical dry processing of obsolete printed circuit board residues", **Materials Research**, v. 22, n. 5, p. 0–6, 2019. DOI: 10.1590/1980-5373-MR-2019-0341.
SILVAS, F. P. C., JIMÉNEZ CORREA, M. M., CALDAS, M. P. K., *et al.* "Printed circuit board recycling: Physical processing and copper extraction by selective leaching", **Waste Management**, v. 46, p. 503–510, 2015. DOI: 10.1016/j.wasman.2015.08.030.
SOUZA, R. G., ROSENHEAD, J., SALHOFER, S. P., *et al.* "Definition of sustainability impact categories based on stakeholder perspectives", **Journal of Cleaner Production**, v. 105, p. 41–51, 2015. DOI: 10.1016/j.jclepro.2014.09.051.
SOUZA, R.G., CLÍMACO, J. C. N., SANT'ANNA, A. P., *et al.* "Sustainability assessment and prioritisation of e-waste management options in Brazil", **Waste Management**, v. 57, p. 46–56, 2016. DOI: 10.1016/j.wasman.2016.01.034.
SOUZA, R.G. **E-waste situation and current practices in Brazil**. [S.l.], INC, 2019. In: Handbook of Electronic Waste Management, Butterworth-Heinemann, 2020. Pages 377-396. Available at: http://dx.doi.org/10.1016/B978-0-12-817030-4.00009-7.
STEP INITIATIVE. **E-waste World Map**. 2017. Available at: https://globalewaste.org/map/. Accessed in: 18 Jul. 2021.
STEP INITIATIVE. **StEP Organisation**. [S.d.]. Available at: https://www.step-initiative.org/. Accessed in: 1 Jul. 2021.
STEP INITIATIVE. "What is e-waste?", 2014. Available at: https://www.step-initiative.org/e-waste-challenge.html.
UK PARLIAMENTARY OFFICE OF SCIENCE AND TECHNOLOGY. **Carbon**

Footprint of Electricity Generation. . [S.l: s.n.], 2011. Available at: https://www.parliament.uk/globalassets/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf.
UN TRADE STATISTICS. **Trade valuation**. 2010. Available at: https://unstats.un.org/unsd/tradekb/Knowledgebase/Trade-valuation. Accessed in: 27 Jul. 2021.
UNDP - UNITED NATIONS DEVELOPMENT PROGRAM. **Municipal Human Development Index 2010**. 2010. Available at: https://www.br.undp.org/content/brazil/pt/home/idh0/rankings/idhm-municipios-2010.html. Accessed in: 24 Jul. 2021.
UNEP. **BASEL CONVENTION ON THE CONTROL OF TRANSBOUNDARY MOVEMENTS OF HAZARDOUS WASTES AND THEIR DISPOSAL**. . [S.l: s.n.], 2010. Available at: https://legal.un.org/avl/pdf/ha/bcctmhwd/bcctmhwd_e.pdf.
UNEP. **E-waste Volume I: Inventory Assessment Manual**. **United Nations Environment Programme**. [S.l: s.n.], 2007. Available at: www.unep.org.
UNEP - UN ENVIRONMENT PROGRAMME. "Basel Convention - E-waste Overview", [S.d.]. Available at: http://www.basel.int/Implementation/Ewaste/Overview/tabid/4063/Default.aspx#:~:text=E-waste is categorized as,according to the Basel Convention.
UNEP - UN ENVIRONMENT PROGRAMME. **E-WASTE - Volume II: E-waste Management Manual**. . [S.l: s.n.], 2007. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/9801/EWasteManual_Vol2.pdf?sequence=3&isAllowed=y.
UNITED NATIONS. **UN Comtrade Database**. [S.d.]. Available at: https://comtrade.un.org/data/. Accessed in: 27 Jul. 2021.
UPADHYAY, A., LAING, T., KUMAR, V., *et al.* "Exploring barriers and drivers to the implementation of circular economy practices in the mining industry", **Resources Policy**, v. 72, n. February 2020, p. 102037, 2021. DOI: 10.1016/j.resourpol.2021.102037.
VALENTE, D. B., GUABIROBA, R. C. da S., CONEJERO, M. A., *et al.* "Economic analysis of waste electrical and electronic equipment management: a study involving recycling cooperatives in Brazil", **Environment, Development and Sustainability**, n. 0123456789, 2021. DOI: 10.1007/s10668-021-01403-2.
VALERO NAVAZO, J. M., VILLALBA MÉNDEZ, G., TALENS PEIRÓ, L. "Material flow analysis and energy requirements of mobile phone material recovery processes", **International Journal of Life Cycle Assessment**, v. 19, n. 3, p. 567–579, 2014. DOI: 10.1007/s11367-013-0653-6.
VERMEŞAN, H., TIUC, A. E., PURCAR, M. "Advanced recovery techniques for waste materials from IT and telecommunication equipment printed circuit boards", **Sustainability (Switzerland)**, v. 12, n. 1, p. 1–23, 2020. DOI: 10.3390/SU12010074.
VIEIRA, B. de O., GUARNIERI, P., E SILVA, L. C., *et al.* "Prioritizing barriers to be solved to the implementation of reverse logistics of e-waste in Brazil under a multicriteria decision aid approach", **Sustainability (Switzerland)**, v. 12, n. 10, 2020. DOI: 10.3390/su12104337.
VIJAYAVENKATARAMAN, S., INIYAN, S., GOIC, R. "A review of climate change, mitigation and adaptation", **Renewable and Sustainable Energy Reviews**, v. 16, n. 1, p. 878–897, 2012. DOI: 10.1016/j.rser.2011.09.009.
WALKER, A. M., VERMEULEN, W. J. V., SIMBOLI, A., *et al.* "Sustainability assessment in circular inter-firm networks: An integrated framework of industrial ecology and circular supply chain management approaches", **Journal of Cleaner Production**, v. 286, p. 125457, 2021. DOI: 10.1016/j.jclepro.2020.125457.

WANG, F., HUISMAN, J., MESKERS, C. E. M., *et al.* "The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies", **Waste Management**, v. 32, n. 11, p. 2134–2146, 2012. DOI: 10.1016/j.wasman.2012.03.029.
WANG, F., HUISMAN, J., STEVELS, A., *et al.* "Enhancing e-waste estimates: Improving data quality by multivariate Input-Output Analysis", **Waste Management**, v. 33, n. 11, p. 2397–2407, 2013. DOI: 10.1016/j.wasman.2013.07.005.
WANG, H., ZHANG, S., LI, B., *et al.* "Recovery of waste printed circuit boards through pyrometallurgical processing: A review", **Resources, Conservation and Recycling**, v. 126, n. July, p. 209–218, 2017. DOI: 10.1016/j.resconrec.2017.08.001.
WEIL, E. D., LEVCHIK, S. "A Review of Current Flame Retardant Systems for Epoxy Resins", **Journal of Fire Sciences**, v. 22, n. 1, p. 25–40, 2004. DOI: 10.1177/0734904104038107.
WHITE, R. M., "Preface". **The Greening ofIndustrial Ecosystems**, Washington, D.C., National Academy Press, 1994. p. i–iv. DOI: https://doi.org/10.17226/2129.
XAVIER, L. H., GIESE, E. C., RIBEIRO-DUTHIE, A. C., *et al.* "Sustainability and the circular economy: A theoretical approach focused on e-waste urban mining", **Resources Policy**, n. August, p. 101467, 2019. DOI: 10.1016/j.resourpol.2019.101467.
XAVIER, L. H., LINS, F. A. F. "MINERAÇÃO URBANA DE RESÍDUOS ELETROELETRÔNICOS: Uma nova fronteira a explorar no Brasil", **Brasil Mineral**, v. 1, n. 379, p. 22–26, 2018.
XAVIER, L. H., OTTONI, M., ARAUJO, R. A., *et al.* **Manual de destinação de resíduos eletroeletrônicos. Orientações à sociedade sobre como dispor adequadamente os resíduos eletroeletrônicos no estado do Rio de Janeiro**. . Rio de Janeiro, RJ, Brazil, [s.n.], 2020. Available at: https://cetem.gov.br/livros/item/download/2921_2dfa6ad012b449b11c0d09c38f4afe27.
XAVIER, L. H., OTTONI, M., LEPAWSKY, J. "Circular economy and e-waste management in the Americas: Brazilian and Canadian frameworks", **Journal of Cleaner Production**, v. 297, p. 126570, 2021. DOI: 10.1016/j.jclepro.2021.126570.
YANG, W. D., SUN, Q., NI, H. G. "Cost-benefit analysis of metal recovery from e-waste: Implications for international policy", **Waste Management**, v. 123, p. 42–47, 2021. DOI: 10.1016/j.wasman.2021.01.023.
YLÄ-MELLA, J., POIKELA, K., LEHTINEN, U., *et al.* "Overview of the WEEE Directive and Its Implementation in the Nordic Countries: National Realisations and Best Practices", **Journal of Waste Management**, v. 2014, n. June 2000, p. 1–18, 2014. DOI: 10.1155/2014/457372.
YOUSEF, S., TATARIANTS, M., TICHONOVAS, M., *et al.* "Recycling of bare waste printed circuit boards as received using an organic solvent technique at a low temperature", **Journal of Cleaner Production**, v. 187, p. 780–788, 2018. DOI: 10.1016/j.jclepro.2018.03.227.
YU, L., HE, W., LI, G., *et al.* "The development of WEEE management and effects of the fund policy for subsidizing WEEE treating in China", **Waste Management**, v. 34, n. 9, p. 1705–1714, 2014. DOI: 10.1016/j.wasman.2014.05.012.
ZENG, X., LI, J. "Measuring the recyclability of e-waste: An innovative method and its implications", **Journal of Cleaner Production**, v. 131, p. 156–162, 2016. DOI: 10.1016/j.jclepro.2016.05.055.
ZENG, X., WANG, F., LI, J., *et al.* "A simplified method to evaluate the recycling potential of e-waste", **Journal of Cleaner Production**, v. 168, p. 1518–1524, 2017. DOI: 10.1016/j.jclepro.2017.06.232.
ZENG, X., YANG, C., CHIANG, J. F., *et al.* "Innovating e-waste management: From

macroscopic to microscopic scales", **Science of the Total Environment**, v. 575, p. 1–5, 2017. DOI: 10.1016/j.scitotenv.2016.09.078.
ZIS, T. P. V., PSARAFTIS, H. N., TILLIG, F., *et al.* "Decarbonizing maritime transport: A Ro-Pax case study", **Research in Transportation Business and Management**, v. 37, n. March, 2020. DOI: 10.1016/j.rtbm.2020.100565. .

APPENDICES

Appendix A. Most recent and relevant studies regarding e-waste management in Brazil

YEAR	AUTHOR	MACROTHEME	THEME	OBJECTIVE	FINDINGS	GAPS/LIMITATIONS
2021	Pedro et al. (2021)	EWMS	Governance and decision-making	Analysis of constructed governance as a solution to conflicts in e-waste recycling networks	Constructed governance could be a competent way to bring actors together to decide about collective rules and obtain a high volume of recycled material, compared with the actual numbers	Most e-waste management models are based on control, hierarchical governance, and the prohibition of commercial actions, which seems not to be successful
	Abalansa et al. (2021)	Social	E-waste transboundary movements	Comparison of the e-waste common drivers in six countries among the top 10 e-waste dumping sites in the world (including Brazil)	- Developed countries are not assuming full responsibility for their environmental problems, opting for exporting their e-waste rather than treating it nationally - The e-waste export to developing countries is driven by the need for novel sources of materials and constant technological advancement - Waste management facilities should be installed closer to where the waste is generated - There is an economic hierarchy among e-waste workers which provides the basis for managing e-waste activities in the informal sector	-The lack of data from Brazil and Mexico can probably be attributed to the limitations of searching for data only in English and not the languages of these two countries
	Xavier et al. (2021)	EWMS	Models for e-waste RLS	Analysis of e-waste generation patterns, fluxes and the regulatory frameworks in Brazil and Canada	Both countries lack harmonized regulation and have low control of the e-waste illegal trade and traceability	Absence of consistent data related to e-waste management for MERCOSUR countries
	Valente et al. (2021)	EWMS	Economic analysis	Economic analysis of e-waste management in recycling cooperatives in Brazil	- E-waste inclusion is economically attractive when recycling cooperative receives support from scrap dealers and the government - The distance between cooperatives and the recycling industry is generally long - Large generators and recycling industries do not establish agreements directly with cooperatives (because these cooperatives do not offer large volumes)	- Lack of studies that estimate e-waste generation at the municipal level mainly in developing countries - The participation of public authorities is necessary for the promotion and support of recycling cooperatives

	Alves et al. (2021)	Social	Consumer behaviour	Action Research (AR) to create and implement an e-waste collection program in Brazil	- The AR method proved to be highly efficient in dealing with e-waste reverse logistics - Consumers showed interest in participating and contributing to the proposed e-waste management program - The program ultimately collected 1710 kg of e-waste - Public awareness has led to a significant increase in the amount of collected waste	- Lack of infrastructure and hesitance of the public for implementing e-waste reverse logistics
	Rocha & Penteado (2021)	EWMS	Environmental analysis	Life cycle assessment of a small WEEE reverse logistics system in Campinas Area (CA), Brazil	- the benefits of reverse logistics outweigh its impacts due to the saving of metals and mineral resources recovered from recycling printed circuit boards, and to the reduction of the potential environmental impact in human toxicity categories - The material flow analysis showed that 85% of the e-waste materials (by mass) are effectively recovered, indicating a loss of 15% of all input material - the reverse logistics of all small WEEE generated in the case study (52,206 tonnes) has the potential to avoid about 149,000 tonnes of CO2 eq. and 2000 TJ of fossil resources	- Few studies on WEEE management, specifically on reverse logistics systems in Brazil
2020	Albuquerque et al. (2020)	EWMS	Models for e-waste RLS	Analysis of the e-waste production and treatment in Brazil and China	- More than 90% of e-waste volume in Brazil has an inadequate destination, due to financial factors and the lack of a robust environmental education policy - Most e-waste in Brazil is separated, exported or landfilled	- Brazil lacks a system that covers all stages of the e-waste treatment/processing - Lack of financial support for waste collectors - Lack of effective standards for collection systems - Lack of cooperation among waste stakeholders - Informal recycling of e-waste
	Vieira et al. (2020)	EWMS	Models for e-waste RLS	Identification of the main barriers to fully implementing the e-waste reverse logistics in Brazil according to the perceptions of the involved stakeholders	- Internal barriers with an organizational nature or related to infrastructure management are the main obstacles to the implementation of e-waste reverse logistics - Consumers consider the managerial barriers as a priority	- Not all Brazilian states were covered in the research - Non-identification of which type of EEE bought by consumers in second-hand

	Oliveira et al. (2020)	Social	Social inclusion	Characterization of e-waste sent to recyclable waste picker cooperatives in a Brazilian city	- E-waste volume in cooperatives tends to decrease, due to probable loss of family purchasing power, or the removal of e-waste by street waste pickers before the municipal selective collection - Framework for monitoring and analyzing e-waste flows that can be applied and replicated in other situations and contexts	- Population very often discards e-waste along with common recyclable waste - Cooperative members unsafely dismantle e-waste for resale - Short period of monitoring the e-waste flow in the cooperatives
	Santos (2020)	Technology	E-waste recycling	Analysis of the organisation of formal recyclers in São Paulo Macrometropolis (SPMM)	- The analysed companies only have the technology to perform the initial and intermediate levels of the e-waste recycling process - Most e-waste is sold to recyclers abroad that have the most advanced recycling technology	- Low/irregular flow of collected e-waste - Lack of technologies to enable the final stages of recycling in Brazil
	Ottoni et al. (2020)	Technology	Routing for e-waste reverse logistics system	Analysis of e-waste generation, recycling companies, routing for e-waste valorization in the metropolitan region of Rio de Janeiro (MRRJ)	Thirty-five hotspots were identified and divided into five main routes according to the recycling industries nearby and the local roads	Usage of secondary and estimated data, which were limited by the accuracy of these external sources
2019	Souza (2019)	EWMS	Models for e-waste RLS	Description of the Brazilian e-waste management scenario	- E-waste generation in Brazil is based on estimation methods, which have uncertainties and adopted approaches - Southeast and South regions concentrate more specialized operations for e-waste - E-waste recyclers can only process some e-waste types at a limited capacity in Brazil - Informality plays a huge role in e-waste management recycling chains in Brazil	- Environmental licensing and formalization of some e-waste agents - Efficient implementation of the Sectorial Agreements for e-waste reverse logistics - Expansion of recycling capacity in the country - Inclusion of capacitated cooperatives of waste pickers
	Gouveia et al. (2019)	Social	E-waste risks	Assessment of the occupational exposure to mercury in recycling cooperatives in the metropolitan region of São Paulo	- 4 cooperatives were assessed - Only 14.5% of the 83 samples showed concentrations above the limit of quantification (LOQ) while 53% were between the LOD (limit of detection) and LOQ. - The results were below the occupational reference values, showing that the workers are not exposed to Hg	- Discontinuity of the e-waste processing and the unpredictable occurrence of fluorescent lamps mixed with recyclable materials

	Neto (2019)	EWMS	Review	A mini-review of e-waste management in Brazil	- Most analyzed studies referred to “e-waste management strategies” and “e-waste composition and recovering” - All analyzed studies were published after 2012, probably motivated by the Brazilian Policy on Solid Waste - After 2017, more articles focused on management strategies, reflecting a trend to resolving e-waste management problems - Few studies focused on e-waste’s production forecast, reflecting the difficulty of finding reliable data of certain types of EEE in Brazil	- Brazil lacks proper facilities to extract precious metals from e-waste, and the formal market exports preprocessed waste abroad, reducing the profitability of the enterprise - the lack of control over the informal market has already begun to undertake the extraction of precious metals from e-waste - Concentration of recycling industry in southern and south-eastern Brazil - Difficulties in transporting from distant areas to recycling centres - Differentiated taxation by Brazilian states
	Silva et al. (2019)	Technology	E-waste recycling	Analysis of mechanical processing of WPCB to concentrate metal content and reduce costs of the subsequent recovery of copper, tin, and lead	- 10.7% of the obsolete WPCB was comprised of magnetic materials - The milled WPCB evaluated consisted of 50% of soluble (metal) materials and 50% of insoluble (ceramic and polymer) materials. - The metals content in the residue was 18.8% of copper, 3.4% of lead, and 1.3% of tin - Enrichment of copper (from 43±11% to 68±5%), tin (from 10±3% to 17±1%), and lead (from 4±1% to 6.4±0.5%) - The zig-zag classifier has shown to be a sustainable alternative for the concentration of metals from WPCB	- All recycling techniques have limitations, but mechanical preprocessing may increase metal recovery efficiency

	Caetano et al. (2019)	Social	E-waste risks	Evaluation of a methodology to analyze environmental and occupational health risks in e-waste management organizations	- Most significant environmental impacts and occupational risks are associated with e-waste sorting and disassembly - Potential environmental impacts are associated with e-waste transportation and coproducts - Accident risks represented 69% of the sum of all risk levels associated with occupational health	- E-waste management organizations in Brazil fail to recognize the importance of appropriately addressing risks associated with their processes and activities - Need to adopt control measures to protect workers in e-waste organizations - Use of hoods as protection during equipment operation, staff training, and use of personal protective equipment (PPE) have to be adopted in such organizations
	Ferreira et al. (2019)	Social	Social inclusion	Assessment of the inclusion of cooperatives of recyclable waste pickers in the e-waste market in Brazil	- There is a clear barrier in the access of the waste pickers' cooperatives in the market - The government envisioned the inclusion of waste pickers in the reverse logistics but did not promote concrete actions for such inclusion to occur	Challenges faced by cooperatives within the e-waste market: '- Achieving partnership with companies - Competition with companies in the area - Minimal e-waste volumes are needed to negotiate good selling prices - Lack of knowledge about the Brazilian e-waste regulation
	Azevedo et al. (2019)	EWMS	Economic analysis	Economic analysis of the current e-waste management system in Brazil	- 10,000–15,000 workers are required to operate the entire RLS at full capacity, covering 100% of the national territory - A management entity is not able to monopolize this market, as the recycling companies can informally separate e-waste and export it - If the producers/importers pay for the RLS and complete recycling for precious metals recovery, the entire system will become self-sustaining (no government investment and consumer charges)	- In Brazil, there is no possibility of using recovered metals in the electronics industry because the country does not manufacture integrated electronic circuits that could be used in the production of electronics

	Dieste et al. (2019)	EWMS	Models for e-waste RLS	Propose a framework to indicate the most suitable scheme for e-waste reverse logistics for Brazil according to the models used in European countries	- European collective schemes can be divided into two main models: National Collective scheme (NC) and Clearing House model (CH) - NC Model: schemes are not competing between them since they are in charge of the collection of diverse e-waste categories and are more efficient - CH Model: schemes compete between them as they can gather the same e-waste categories and have low logistics efficiency - The most suitable model for Brazil is the National Collective - Three-level model for Brazil: federal (guidelines), state (model to be adopted) and cities (operational) scopes	E-waste collection and reverse logistics need to be deepened and studied at the moment of the decision-making because e-waste management usually needs the adoption of immediate actions to solve the problem
	Abbondanza & Souza (2019)	EWMS	E-waste generation	Development and applying an e-waste estimation method in São José dos Campos	- Lifespan distributions are most desirable for e-waste estimation studies than discrete averages - Lifespan profiles in the city are considerably different from previous values adopted in other Brazilian studies - Significant variations of lifespan profiles for different e-waste types among the Zones of the city, reflecting the socioeconomic differences	- The required effort and workforce to apply a survey comprehending a representative sample of the population may take several months - Uncertainties on the replies, as they rely on the memory of interviewees for certain types of EEEs acquired many years ago (e.g., refrigerators)
2018	Dias et al. (2018a)	Social	E-waste risks	Lead hazard evaluation for cathode ray tube monitors in Brazil	- All assessed samples are hazardous due to lead leaching - The CRT panel is lead-free, while the CRT funnel and neck have about 20% of lead oxide in their composition - Vacuum atmosphere and the addition of 5% carbon graphite as a reducing agent are optimum conditions to turn the CRT into a non-hazardous waste	- CRT monitors are hazardous waste and that should not be discarded in non-controlled landfills - This study only analyzed lead values. Future studies could assess the hazardousness potential of other elements such as barium and strontium

	Augusto et al. (2018)	EWMS	Models for e-waste RLS	The impact of cooperation on the implementation of the 'descarte on' e-waste reverse logistics pilot project in Brazil	- E-waste RL can be effective in Brazil with the cooperation/partnership among the actors, with a proposal that presents opportunities for all actors and minimised risks - A favourable aspect was the participation of the retailers in the project, which for many years rejected to join RL initiatives in Brazil - WEEE collections were below the expected volumes, showing that cooperation has to occur among all RL members including the final consumer	The consumer needs to be encouraged and made aware of the benefits of proper disposal, not only in the collection phase but from the discussion and implementation of the project
	Dias et al. (2018b)	Technology	E-waste recycling	Analysis of e-waste processing based on 134 recycling companies active in Brazil	- The Brazilian government does not have control over the number of active e-waste recycling companies in Brazil - 89% of the Brazilian recycling companies only undertake the pretreatment phase in the recycling process (sorting and dismantling) and that at least 92% dismantle it manually - More complex e-waste is still shipped abroad for foreign companies - The revenue generated by the e-waste recycling market in Brazil can financially support up to five agents involved in the e-waste flow	High e-waste generation and the inefficient recycling system are critical issues in Brazil
	Afonso (2018)	Technology	E-waste recycling	Description of the technological, environmental, socio-cultural, economic and health challenges of e-waste in Brazil	- An effective measure to address the e-waste problem is to focus on its origin through conscious consumption practices - Recycling in Brazil is very incipient and not organized in scale, resulting in the export of items that have high added value - Almost 90% of the e-waste recycling companies in Brazil only carry out the pre-treatment phase	The biggest challenges: efficient reverse logistics systems with high capillarity and formalizing the informal chain

2017	Echegaray & Hansstein (2017)	Social	Consumer behaviour	Discussion of determinants of consumer intentions and behaviour towards e-waste recycling in the major metropolitan areas of Brazil	- Most respondents hold a positive intention towards e-waste recycling (mostly female, middle-aged individuals from lower-income groups, and residents of the South-east region) - Only a minority of respondents adopts adequate recycling practices connected to e-waste	- E-waste legal arrangements remain largely unfamiliar to consumers and poorly enforced among both manufacturers and local authorities - Lack of formal and continuous feedback instruments to provide all stakeholders with information about their respective roles and possible sanctions
	Azevedo et al. (2017)	EWMS	Economic analysis	Analysis of the costs and the possible financial gains of e-waste reverse logistics proposed by Law in Minas Gerais	- The proposed logistical model in Minas Gerais is profitable - The installation of industries for the processing of printed circuit boards in Brazil will increase earnings as legal export costs, environmental taxes, and charges will be replaced by environmental taxes and charges in Brazil and maritime freight costs are eliminated	- Exaggerated number of collection centres and e-waste disposal at the cities in the proposed model - The main difficulty for implementing e-waste recycling processes in Brazil is the collection system (dependent on the cooperation of consumers, industry, distributors, and the government)
	Caiado et al. (2017)	EWMS	E-waste Reverse Logistics credits	Characterization of the Brazilian market of reverse logistic credits (RLC) as an analogy with the existing carbon credit market	- Most of the stakeholders agree that the reverse logistics credit market is a possibility, but currently, there are multiple obstacles to its implementation. - The comparison of RLC with the carbon credit market showed many aspects to be developed before the RLC market becomes a reality	The Brazilian RLC market still does not have any legal support to work on, no organization to control and audit the market, and no support from the government
	Moura et al. (2017)	Social	Consumer behaviour	Analysis of the relationships between Brazilian institutional users (IUs) and technical assistance (TAs) regarding their electronic devices and e-waste in Blumenau	- Exchange or disposal was mostly related to the end-of-use of EEEs and the difficulty in elimination (IUs and TAs stock their waste in the workplace or dispose of them in the municipal solid waste collection) - The study identified an increasing trend for informal e-waste recycling companies - E-waste reverse logistics system should include electronic institutional users and technical assistances	- The importance of knowing how and where to dispose of e-waste is a challenge to be managed - High amount of e-waste being sent to the municipal solid waste system or stored in 2015

	Lima et al. (2017)	EWMS	E-waste laws	Description of three Brazilian government's efforts to support e-waste recycling facilities to comply with environmental sound practices	- Law 12.305/2010 is a legal framework that determines the guidelines, goals, responsibilities and actions to integrate solid waste management - The technical standard ABNT NBR 16156/2013 is a tool to discipline the best practices of organization and management of an enterprise that performs e-waste recycling - The SIBRATEC program (2015) provided technological support for small and medium-sized enterprises to suit the requirements of ABNT NBR 16156	The assessed WEEE company in SIBRATEC program presented some challenges that could compromise its efficiency, as the accumulation of unnecessary materials, no access control in the areas, no adequacy on weighing method, among others
	Ghisolfi et al. (2017)	Social	Social inclusion	Design of a closed cycle model to manage the reverse logistics of desktop and laptop waste including waste pickers within the e-waste management system	- Even in the absence of bargaining power, the formalization of waste pickers occurs due to legal incentives - All the efforts made in the structure will be useless if the necessary raw recycling material is not collected in sufficient volume - Cooperatives should work with a varied e-waste portfolio to ensure bargaining power - Steel is the material with the largest decrease in acquisition rate of raw material	- Brazil still lacks technology for the recycling of high value-added components (such as printed circuit boards) - Inefficient waste sorting and disputes with private companies that compete with cooperatives are some of the reasons for low efficiency in the e-waste collection process
	Panizzon et al. (2017)	EWMS	E-waste generation (Universities)	Evaluation of the electrical and electronic equipment waste (WEEE) generation in a private university	- The main e-waste generated by the institution was Information technology (IT) and telecommunications equipment (48.2%), large household appliances (14.4%), monitoring and control instruments (13.3%), electrical and electronic tools (10.9%) and consumer equipment (9.8%) - the majority of WEEE was generated by the university administration (29.3%) and the computer classrooms (17.3%) - Biology and Exact Sciences have EEEs with a longer life cycle, resulting in smaller waste generation	Great complexity in WEEE management in higher education institutions, mostly due to the considerable diversity, increasing the recycling complexity

	Paes et al. (2017)	EWMS	Models for e-waste (Universities)	Proposal of an e-waste management model for public education institutions through Action Research	- Action research is an adequate management tool for public institutions looking to deal with e-waste issues - 2 improvement cycles were conducted: at the university warehouse and other sectors within the institution - 474 e-waste units were adequately treated and disposed of	the university warehouse is at full capacity and unable to receive additional electronic equipment to be further disposed of
	Araujo et al. (2017)	EWMS	E-waste generation	Evaluation of the e-waste generation on Fernando de Noronha Island	- 1.3 tons of e-waste generated in one year - Mobile phones, televisions, computers in general, and refrigerators were the most found domestic equipment - These goods are quickly exchanged due to the lack of technical assistance on the island - Monthly income and education level are related to recycling behaviour variables - Population and government treat e-waste as ordinary waste, ignoring its contaminant potential	- Despite the existence of relevant e-waste legislation, additional efforts will be required by the government to properly manage e-waste on the island
	Campolina et al. (2017)	Technology	Environmental analysis	Study the environmental aspects of e-waste plastic recycling on large scale in a Brazilian company	- When compared to the production of virgin ABS and HIPS, the recycling processes showed a reduction in energy consumption by approximately 90%for both plastics and a reduction in CO2 emissions by approximately 84% for HIPS and 87% for ABS - The plastics recycled by the company retain over 90% of their virgin mechanical properties	Only one company in Brazil that operates e-waste plastic recycling on a large scale
	Neto (2017)	EWMS	Economic-environmental analysis	Assessment of the economic and environmental advantages of e-waste reverse logistics manufacturers and recyclers in Brazil and Switzerland	- The e-waste reverses logistics by three EEE manufacturers located in Brazil and recyclers resulted in an annual economic gain for the chain of US$ 3,501,417. - Significant environmental impact of 3.5 × 108 kg reduction in abiotic, abiotic, water and air components, with the adoption of e-waste reverse logistics - The main recycling activity is that of polymers, which requires a simpler technology	- E-waste recycling and reuse processes in Brazil are decentralized and the development of a cooperation network is complex - The main barrier to adopting e-waste reverse logistics for recycling and reuse in Brazil is the lack of technology for PCB recycling and reuse, which is carried out by foreign companies

2016	Demajorovic et al. (2016)	EWMS	Models for e-waste RLS	Discussion of challenges and opportunities for the implementation of the Brazilian reverse logistics model for computers and cell phones	- The Brazilian government is active in defining incentives, but not in inspecting the industry - Another organization will be created to audit all the companies in the reverse process, as well as the results obtained - An embedded fee to cover RL costs will be charged at product purchase	- Conflicts inside the chain itself and the low willingness of manufacturers and retailers with costs sharing - Low consciousness of the population and the difficulties in adjusting taxation - The possibility of double taxation represents a political cost - An increase in costs of final products may stimulate consumers to purchase products in the grey market - Brazil´s huge territory makes collecting waste even more difficult outside big urban areas
	Echegaray (2016)	Social	Consumer behaviour	Consumers' reactions to product obsolescence in emerging markets in Brazil	- Consumers have experienced a shortened product lifespan over time and this fails to fuel consumer dissatisfaction - Technical failure is far surpassed by subjective obsolescence as a motive for rapid product replacement - Brazilians naturalize obsolescence by adjusting downwardly their product lifespan management behaviors	- Consumers exhibit a lack of awareness of both the importance of product longevity and the negative effects of replacing products - Consumers from developing societies may embrace product obsolescence as proof of their successful market inclusion
	Guarnieri et al. (2016)	EWMS	Governance and decision-making	Analysis of electronic waste reverse logistics decisions using Strategic Options Development Analysis methodology in Brazil	- Four categories of actions to be implemented: strategic, environmental, economic and social - Recommendations: environmental education; greater producers involvement; more e-waste collection points; tax incentives; effective control by the Government to ensure the system effectiveness	- Few people interviewed (eight people engaged in companies or institutions that deal with e-waste in Brazil)

	Polzer et al. (2016)	EWMS	E-waste laws	Analysis of the current situation of the reverse logistics schemes in Brazil (including e-waste) and the importance of the Brazilian Policy of Solid Waste	- Brazilian cities can use the European extended producer responsibility (EPR) schemes as parameters to set up the guidelines in short and long terms - The EPR regulation and economic instruments can promote diverting of waste from landfills to reusing, recycling and recovering treatments	- Lacking the political will to implement aspects of the Law regarding waste management - The cities need not only increase the number of e-waste delivery points but also help recycling companies being able to disassemble the components
	Souza et al. (2016)	EWMS	Models for e-waste RLS	Sustainability assessment and prioritisation of e-waste management options in the metropolitan region of Rio de Janeiro	Hybrid e-waste collection scheme with delivery points at shops, metro stations and neighbourhood centres; a pre-treatment phase with the involvement of private companies, cooperatives and social enterprises; and full recycling of all components in the country	The methodological approach does not guarantee as precise results as could be obtained with statistical inference and a larger sample of experts
2015	Schroeder et al. (2015)	Technology	E-waste recycling	Description of recycling and reuse processes of Printed Circuit Board in Brazil	- Brazil needs to invest in new technologies to recycle and reuse the national e-waste - Company A: manufacturing of equipment and components for the computers in São Paulo. PCB is size-reduced. - Company B: PCB is separated and classified into different materials types, and sent for recycling and reuse abroad (Company C) - Company C: PCB is fully recycled and precious metals are recovered	- E-waste recycling and reuse are decentralized - Several companies in Brazil collect e-waste but do not have the right technology to reuse and recycle the e-waste components - Waste PCB recovery demands a structured plan of the entire network and it increases its complexity
	Silva et al. (2015)	Technology	E-waste recycling	Description of Rematronic Project to recover precious metals from electronic waste in Brazil	- Hydrometallurgy/biohydrometallurgy adopted in REMATRONIC demand less infrastructure and investment than pyrometallurgy - Development of small local plants as a viable option, and this technology supports a low volume of PCBs - High-level jobs must be created in Brazil, in the field of material recovery from e-waste with this project	- Biometallurgical process has great potential to leach metals from PCBs. But there are only limited laboratory studies for PCBs processing through Biometallurgical routes - Only a very small portion of e-waste has been recycled

	Rodrigues et al. (2015)	EWMS	E-waste generation	Evaluation of e-waste generation from households: Proposal of method and application to the city of São Paulo, Brazil	- Total EEE: 71.9 million units - EEE out of service: 8.8 million (12.2%) - 18.2 EEE/household and 5.3 EEE/inhabitant - 72.6% of households store EEE out of service - Annual e-waste per capita: 4.8 kg/inhabitant - Potential of generated waste based on out-of-service EEE: 2.9 to 6.0 kg/inhabitant.year	- Possibility of underestimation of values (respondents' memory bias regarding discard)
	Araujo et al. (2015)	Technology	E-waste tracking	Cost assessment and benefits of using RFID in reverse logistics of waste electrical & Electronic equipment (WEEE)	- RFID technology in e-waste reverse logistics increases the potential for surveillance practices and contributes to better performance of administrative structures of e-waste - Need for the reorganization of the production of goods, research/innovation in e-waste management strategies, combining economic with environmental efficiency	The low cost of inadequate e-waste disposal generates a significant divergence between the private cost and the social cost
	Correia et al. (2015)	EWMS	E-waste laws	Comparative analysis of regulatory instruments in reverse logistics for e-wastes in Brazil, Japan, European Union members, USA and China	- The largest number of e-waste laws were not decisive to improve the e-waste collection and recycling rates - Countries with few regulatory instruments (Japan and European Union members) were the ones that stood out for their high e-waste collection and recycling rates	The Brazilian e-waste law was considered relatively new for conclusive analysis with the researched data to demonstrate the collection and recycling rates
	Silvas et al. (2015)	Technology	E-waste recycling	Development of a new combined route (physical and hydrometallurgical) to recycle printed circuit boards (PCBs) from printers to recover copper	- The metallic fraction corresponded to 44.0 wt.% (mostly copper with 32.5wt.%), the polymeric to 28.5 wt.% and the ceramic to 27.5 wt.% - On sulfuric leaching 90 wt.% of Al, 40 wt.% of Zn and 8.6 wt.% of Sn were extracted, whereas on oxidant leaching tests the extraction percentage of Cu was 100 wt.%, of Zn 60 wt.% and Al 10 wt.% - At the end of the hydrometallurgical processing, 100% of copper extraction was obtained and the recovery factor was 98.46%, which corresponds to 32 kg of Cu in 100 kg of PCB	Temperature can be a limiting factor during the leaching process

	Souza et al. (2015)	EWMS	Environmental analysis	Definition of sustainability impact categories based on stakeholder perspectives and its application in a proposed Brazilian WEEE reverse logistics system (RLS) model	- Causal mapping and the involvement of stakeholders has revealed some potential innovative impact categories in the Brazilian WEEE RLS - Endpoint impact categories reflect best the essential sustainability concerns, but their measurement is problematic. Midpoint impact categories are more operational, but they need to be refined - This methodology has the potential to facilitate consultation with stakeholders in SLCA modelling	Some remaining methodological issues: the identification and involvement of all relevant stakeholders, the definition of endpoint and midpoint levels, and the qualitative evaluation of potential sets of impact categories

Appendix B. WPCB reverse logistics agents considered in this study selected from the list of the fist phase of DATARE PROJECT

STATE	ID	RECYCLER	CITY	SHARE CAPITAL*	STAGE
AM	76	GEODIS GERENCIAMENTO DE FRETES DO BRASIL LTDA - Manaus	Manaus	-	Storage, transport, exportation
AM	129	LORENE IMPORTACAO E EXPORTACAO LTDA - Manaus AM	Manaus	-	Collection, transport, storage, processing, sell to exportation
AM	249	UMICORE - COIMPA INDUSTRIAL LTDA	Manaus	R$ 209.667.240,40	Collection, transport, storage, repairing, processing, sell to exportation
BA	126	LORENE IMPORTACAO E EXPORTACAO LTDA - Salvador BA	Salvador	-	Collection, transport, storage, processing, sell to exportation
ES	105	GRI KOLETA - GERENCIAMENTO DE RESIDUOS INDUSTRIAIS S.A. - Vila Velha	Vila Velha	-	Collection, transport, storage, processing, sell to exportation
ES	133	MARCA AMBIENTAL - MARCA CONSTRUTORA E SERVICOS LTDA - Matriz - Cariacica ES	Cariacica	R$ 9.600.000,00	Collection, transport, processing
GO	128	LORENE IMPORTACAO E EXPORTACAO LTDA - Aparecida de Goiânio GO	Aparecida de Goiania	-	Collection, transport, storage, processing, sell to exportation
MG	119	LORENE IMPORTACAO E EXPORTACAO LTDA - Belo Horizonte MG	Belo Horizonte	-	Collection, transport, storage, processing, sell to exportation
MG	120	LORENE IMPORTACAO E EXPORTACAO LTDA - Betim MG	Betim	-	Collection, transport, storage, processing, sell to exportation
PE	122	LORENE IMPORTACAO E EXPORTACAO LTDA - Recife PE	Recife	-	Collection, transport, storage, processing, sell to exportation
PE	208	Revert Brasil Soluções Ambientais - MATRIZ	Recife	R$ 4.331.000,00	Collection, transport, processing

PE	232	Stericycle Gestao Ambiental LTDA	Recife	R$ 410.844.639,00	Collection, transport, storage, repairing, processing, sell to exportation
PR	3	AMBSERV TRATAMENTO DE RESIDUOS LTDA	São José dos Pinhais	R$ 1.000.000,00	Collection, transport, processing
PR	54	ESSENCIS SOLUCOES AMBIENTAIS S.A. - CSA SERVICOS AMBIENTAIS - Curitiba	Curitiba	-	Collection, transport, storage, processing, sell to exportation
PR	73	GEODIS LOGISTICA DO BRASIL LTDA - Curitiba	Curitiba	-	Storage, transport, exportation
PR	91	HAMAYA DO BRASIL COMERCIO DE PRODUTOS RECICLAVEIS LTDA	Fazenda Rio Grande	R$ 1.272.000,00	Collection, transport, storage, processing, sell to exportation
PR	121	LORENE IMPORTACAO E EXPORTACAO LTDA - Curitiba PR	Curitiba	-	Collection, transport, storage, processing, sell to exportation
PR	211	Sabia Ecologico Transportes de Lixo Eireli	Nova Esperança do Sudoeste	R$ 4.700.000,00	Collection, transport, processing
RJ	20	COBREMAX INDUSTRIA E COMERCIO LTDA	Rio de Janeiro	R$ 20.000.000,00	Collection, transport, processing
RJ	59	ESSENCIS SOLUCOES AMBIENTAIS S.A. - Magé	Magé	-	Collection, transport, storage, processing, sell to exportation
RJ	80	GEODIS GERENCIAMENTO DE FRETES DO BRASIL LTDA - Rio de Janeiro	Rio de Janeiro	R$ 4.860.000.000,00	Storage, transport, exportation
RJ	102	GRI KOLETA - GERENCIAMENTO DE RESIDUOS INDUSTRIAIS S.A. - Rio de Janeiro	Rio de Janeiro	-	Collection, transport, storage, processing, sell to exportation
RJ	116	LORENE IMPORTACAO E EXPORTACAO LTDA - Rio de Janeiro RJ 01	Rio de Janeiro	-	Collection, transport, storage, processing, sell to exportation
RJ	125	LORENE IMPORTACAO E EXPORTACAO LTDA - Rio de Janeiro RJ 02 - Sucat Davi Comércio de Sucatas	Rio de Janeiro	-	Collection, transport, storage, processing, sell to exportation

RS	123	LORENE IMPORTACAO E EXPORTACAO LTDA - Porto Alegre RS	Porto Alegre	-	Collection, transport, storage, processing, sell to exportation
SC	127	LORENE IMPORTACAO E EXPORTACAO LTDA - Palhoca SC	Palhoca	-	Collection, transport, storage, processing, sell to exportation
SP	7	BELMONT TRADING COMERCIAL EXPORTADORA LTDA	Campinas	R$ 1.260.499,00	Collection, transport, repairing, processing, storage
SP	32	ECOASSIST SERVICOS SUSTENTAVEIS E PARTICIPACOES S.A.	São Paulo	R$ 1.000.000,00	Collection, transport, repairing, processing, storage
SP	55	ESSENCIS SOLUCOES AMBIENTAIS S.A. - Jaguaré (MATRIZ)	São Paulo	R$ 129.195.979,00	Collection, transport, storage, processing, sell to exportation
SP	55	ESSENCIS SOLUCOES AMBIENTAIS S.A. - Jaguaré (MATRIZ)	São Paulo	R$ 129.195.979,00	Collection, transport, storage, processing, sell to exportation
SP	56	ESSENCIS SOLUCOES AMBIENTAIS S.A. - Vila Brasilândia	São Paulo	-	Collection, transport, storage, processing, sell to exportation
SP	57	ESSENCIS ECOSSISTEMA LTDA - São José dos Campos	São José dos Campos	-	Collection, transport, storage, processing, sell to exportation
SP	58	CONSORCIO PLANESAN - Essencis - Caieras	Caieiras	-	Collection, transport, storage, processing, sell to exportation
SP	61	FBM FUNDICAO BRASILEIRA DE METAIS LTDA	São Paulo	R$ 3.200.000,00	Collection, transport, processing
SP	62	INDUSTRIA FOX ECONOMIA CIRCULAR LTDA	Cabreúva	R$ 20.000.000,00	Collection, transport, storage, repairing, processing, sell to exportation
SP	72	GEODIS LOGISTICA DO BRASIL LTDA.	Jundiaí	R$ 10.150.377,00	Storage, transport, exportation
SP	75	GEODIS GERENCIAMENTO DE FRETES DO BRASIL LTDA - São Paulo	São Paulo	R$ 38.203.670,00	Storage, transport, exportation
SP	69	GEODIS SOLUCOES GLOBAIS DE LOGISTICA DO BRASIL LTDA - Hortolândia	Hortolândia	-	Storage, transport, exportation

SP	71	GEODIS SOLUCOES GLOBAIS DE LOGISTICA DO BRASIL LTDA - Campinas	Campinas	-	Storage, transport, exportation
SP	77	GEODIS GERENCIAMENTO DE FRETES DO BRASIL LTDA - Santos	Santos	-	Storage, transport, exportation
SP	78	GEODIS GERENCIAMENTO DE FRETES DO BRASIL LTDA - Campinas	Campinas	-	Storage, transport, exportation
SP	88	GM&C SOLUCOES EM LOGISTICA REVERSA E RECICLAGEM LTDA	São José dos Campos	R$ 1.000.000,00	Collection, transport, storage, repairing, processing, sell to exportation
SP	97	ITRENEW BRASIL COMERCIO DE EQUIPAMENTOS DE INFORMATICA E SERVICOS LTDA.	Barueri	R$ 8.180.000,00	Repairing, processing, storage
SP	103	GRI KOLETA - GERENCIAMENTO DE RESIDUOS INDUSTRIAIS S.A. - São Paulo	São Paulo	R$ 101.016.533,00	Collection, transport, storage, processing, sell to exportation
SP	114	LORENE IMPORTACAO E EXPORTACAO LTDA - São Paulo - Matriz	São Paulo	R$ 38.099.220,00	Collection, transport, storage, processing, sell to exportation
SP	115	LORENE IMPORTACAO E EXPORTACAO LTDA - Guarulhos SP 01	Guarulhos	-	Collection, transport, storage, processing, sell to exportation
SP	117	LORENE IMPORTACAO E EXPORTACAO LTDA - Santa Isabel SP	Santa Isabel	-	Collection, transport, storage, processing, sell to exportation
SP	118	LORENE IMPORTACAO E EXPORTACAO LTDA - Guarulhos SP 02	Guarulhos	-	Collection, transport, storage, processing, sell to exportation
SP	124	LORENE IMPORTACAO E EXPORTACAO LTDA - Ribeirão Preto SP	Ribeirão Preto	-	Collection, transport, storage, processing, sell to exportation

SP	168	RBM - Recuperadora Brasileira de Metais LTDA MATRIZ	Caieiras	R$ 30.000.000,00	Storage, processing, sell to exportation
SP	196	Reciclo Inteligência Ambiental S/A	São Paulo	R$ 1.280.000,00	Collection, transport, storage, repairing, processing, sell to exportation
SP	203	RE-TECK	Indaiatuba	R$ 12.414.252,00	Collection, transport, storage, repairing, processing, sell to exportation
SP	212	Salmeron Ambiental LTDA	Sorocaba	R$ 2.750.000,00	Collection, transport, storage, repairing, processing, sell to exportation
SP	222	Silcon Ambiental LTDA MATRIZ	São Paulo	R$ 3.144.849,00	Collection, transport, storage, repairing, processing, sell to exportation
SP	227	Flextronics International Tecnologia LTDA MATRIZ	Sorocaba	R$ 1.319.734.275,00	Storage, repairing
SP	246	Umicore Brasil Ltda.	Americana	-	Collection, transport, storage, repairing, processing, sell to exportation
SP	247	Umicore Brasil Ltda.	Guarulhos	-	Collection, transport, storage, repairing, processing, sell to exportation

***** *The usage of "-" in the shared capital means that the company is a subsidiary of a holding company that has share capital equal to or higher than R$ 1.000.000,00, equivalent to US$ 186,198.90 in first-quarter 2021*

Source: Filtered from the original list of e-waste reverse logistics agents of the first phase of DATARE PROJECT (CETEM, 2021)