

School of Mining Engineering



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

**FINANCIAL VALUATION OF RECOVERING
VALUABLE METALS FROM E-WASTE IN SOUTH
AFRICA: AN ASSESSMENT OF WASTE PRINTED
CIRCUIT BOARDS**

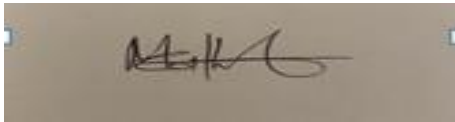
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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2024

DECLARATION

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30 September 2024

“Those who complete the course will do so only because they do not, as fatigue sets in, convince themselves that the road ahead is still too long, the inclines too steep, the loneliness impossible to bear and the prize itself of doubtful value.”

President Thabo Mvuyelwa Mbeki

ABSTRACT

As the world's population is growing more rapidly, more mineral resources are needed for the development of economies. The recovery of metals from waste electrical and electronic equipment (EEE) has the potential to supplement the current metal production levels from primary mining and create socio-economic opportunities for countries. The purpose of this research was to assess the feasibility of recovering metals from e-waste with a focus on Printed Circuit Boards (PCBs). A Discounted Cash Flow (DCF) analysis was conducted to assess the economic feasibility of 1) exporting of PCBs and 2) commissioning of pyrometallurgical plant to process waste PCBs in South Africa. The study employed a mixed method approach. Face-to-face and telephonic interviews were conducted to collect primary data, and this was supplemented by secondary data from desktop review of past work.

The DCF results on the exporting of PCBs showed a positive NPV on all three different grades of PCBs. An NPV of R436.89 million, R319.10 million and R163.83 million for the high grade, medium grade and low grade PCBs was calculated respectively. The NPV for the option of setting up a refining plant are R3 446.85 million, R1 590 million and R1 125.78 million and for all options, an IRR of more than 200% for the high grade PCBs, medium grade PCBs and low grade PCBs was calculated respectively. Whilst the results show the economic feasibility of setting up a refining plant to recover valuable metals such as gold and copper, the operating costs may have been underestimated because the assumption of the inputs was made from information obtained from interviews and literature. There is a need to improve the reliability of input parameters, as such, further research is recommended on accurate volumes of PCBs generated and operating cost estimates.

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LIST OF ABBREVIATIONS AND SYMBOLS

CBA	Cost and Benefit Analysis
CEA	Cost Effective Analysis
CMA	Cost Minimisation Analysis
CUA	Cost Utility Analysis
DCF	Discounted Cash Flow
DEDAT	Department of Economic Development and Tourism
EEE	Electrical and Electronic Equipment
ERA	E-Waste Recycling Authority
EWASA	eWaste Association of South Africa
E-Waste	Electronic and Electrical Waste
EU	European Union
IRR	Internal Rate of Return
NPV	Net Present Value
PCBs	Printed Circuit Boards
SADC	Southern African Development Community
StEP	Solving the E-waste Problem
TM	Traditional Mining

UM	Urban Mining
UNU	United Nations University

CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Research Background

As the world's population is growing more rapidly, more mineral resources are needed for the development of economies. The global mineral demand is also driven by growth in per-capita consumption as the need to enhance the standard of living of the population increases (Forti et al., 2020; Kesler, 2007; Park et al., 2017). Figure 1.1 shows per capita consumption of electronic waste (e-waste). Per capita consumption is defined as the quantity of goods and services used by each person (Jain et al., 2016). It is reported that higher levels of disposable incomes, growing urbanisation and mobility, and industrialisation in some parts of the world have contributed to the growing amounts of e-waste. Figure 1.1 shows per capita consumption of waste EEE. As can be seen, the waste EEE has been increasing alongside population growth. The growth of e-waste stream is further caused by short life span and less repairs.

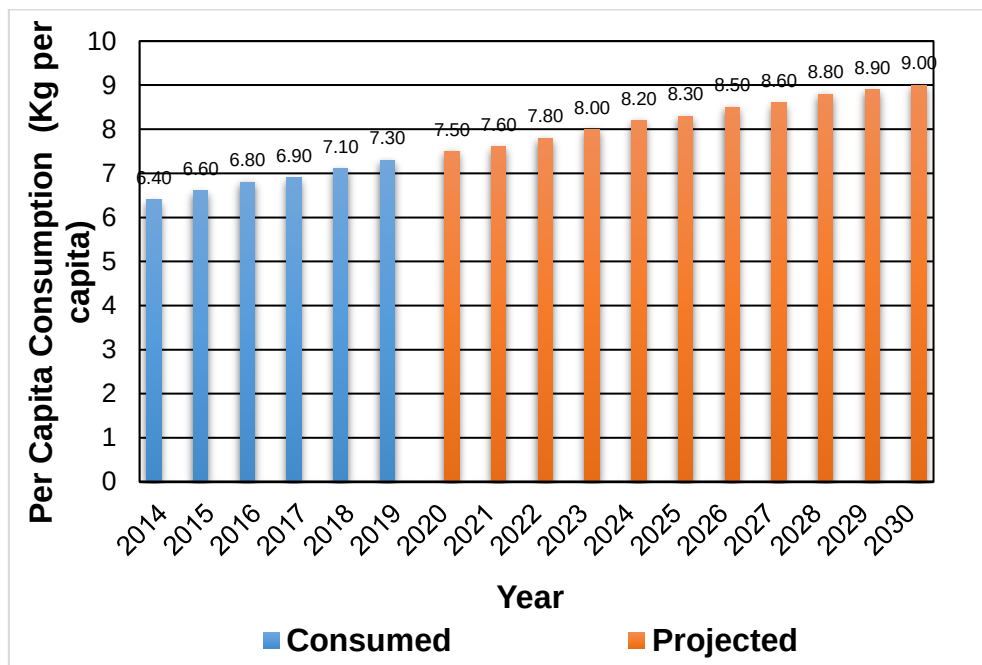


Figure 1.1: Consumed and Projected Volumes of waste EEE Per Capita from 2014 to 2030 (Balde et al., 2017)

The e-waste stream generates valuable material comprising of precious, base, critical and non-critical metals which could be utilised as secondary materials (Forti et al., 2020; World Economic Forum, 2019). As low cost and easy to extract rich mineral resources are being depleted, new sources of supply of minerals are needed (Kesler, 2007; Sibley, 2011). To this effect, it has become important that accurate reporting of a country's mineral resources include both primary and secondary resources (Sibley, 2011). The primary resources are defined as non-renewable resources that need to be mined using either surface or underground mining method or both. The secondary resources include mineral resources which have been mined already and are accumulating as direct mine waste (i.e., waste dumps, tailings and slag) and/or waste produced from end-products (i.e., for example e-waste). The e-waste includes all products which have reached their end of their product lifecycle or obsolete EEE like computers, electronic gadgets, fax machines, printers, mobile phones and household products (Koloseni and Shimba, 2012).

With the increased application of technology, the amount of EEE has increased substantially. This has been accompanied by the waste generated from EEE annually. Figure 1.2 shows the volumes of e-waste that have been generated between 2014 and 2019 along with projected volumes from 2020 to 2030.

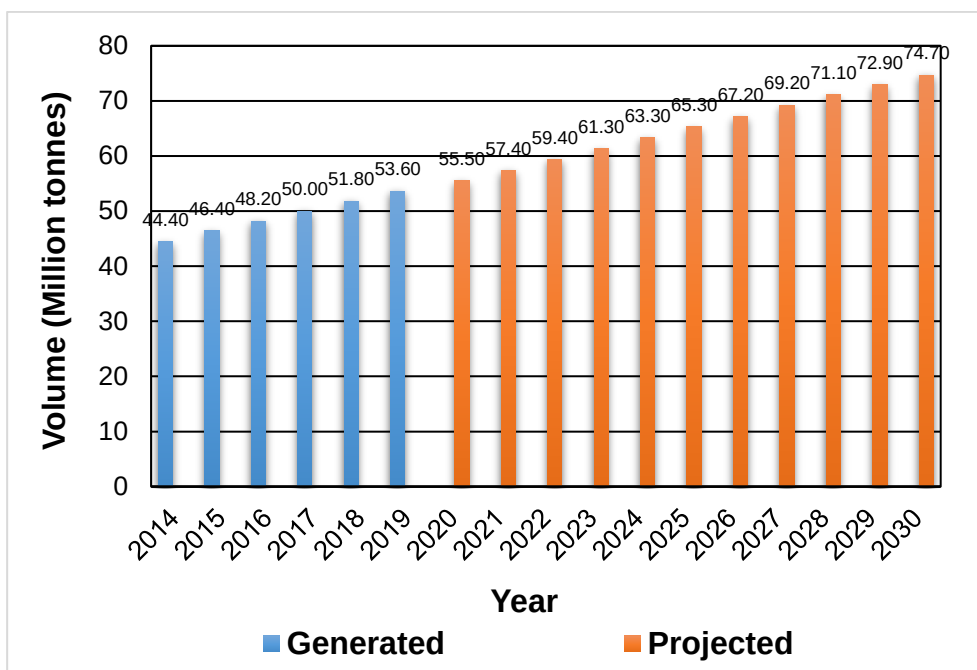


Figure 1.2: Generated and Projected Volumes of waste EEE from 2014 to 2030 (Balde et al., 2017)

From figure 1.2 the volume of e-waste is increasing rapidly across the world. As the world is developing, the demand for new EEE increases which leads to higher rate of consumption of EEE thus causing higher production levels of e-waste. In 2014, an estimated 44.4 million tonnes of e-waste were produced around the world. The volume of e-waste rose to 53.6 million tonnes in 2019. It is reported that an estimated 74.7 million tonnes of e-waste would be created in 2030. The amount of e-waste created globally was estimated to grow at a rate ranging from 3% to 5% annually (Cucchiella et al., 2015).

In 2019, Asia, America, Europe, Africa and Oceania generated 24.9 million tonnes, 13.1 million tonnes, 12 million tonnes, 2.9 million tonnes, and 0.7 million tonnes respectively. According to Forti et al (2020), in 2019 only 17.4% (9.3 million tonnes) of the total amount of e-waste produced globally were collected to recover valuable metals and the remaining was sent to landfills and/or thrown into residual waste in low-income countries. In the same year, Europe achieved the highest recycling rate of 42.5%, Asia at

11.7%, America at 9.4% and Oceania 8.8%. Africa achieved the lowest recycling rate at 0.9% in the same year (Forti et al., 2020). Based on this data, it is evident that the total volume of e-waste recycled is considerably smaller than the volumes of e-waste generated.

In 2019, the amount of e-waste produced was valued at around \$57 billion. The e-waste fraction has the potential of reaching 120 million tonnes annual production in 2050 (United Nations Environment Programme, 2019). As such, there is an emerging trend that recycling and trade of materials from e-waste will also continue to rise because of increasing commodity prices, relatively low costs of labour associated with recycling and a high demand for materials (Nakamura and Halada, 2015; World Economic Forum, 2019). E-waste offers an opportunity for the extraction of metals to boost current production levels (Brunner and Rechberger, 2004; United Nations Environment programme, 2010). Each year, electronics utilises about 300 tonnes of gold thus making e-waste an important source of metals (Hagelucken and Corti, 2010).

The production of electric and electronic equipment requires access and availability of huge quantities of non-renewable resources including precious metals. Printed circuit boards (PCBs) are the most precious components of e-waste and are sources of base and precious metals such as gold, platinum, palladium, silver and copper, and can become a renewable resource that can supply recycled metals for new production at the end of its life. Recycling of these obsolete PCBs will help recover metals, energy, and mitigate their hazardous effect on the environment copper (Abdelbasir, et al., 2018; Lydall, et al., 2017).

The large volumes of e-waste being produced may lead to environmental degradation and disposal problems. Also, the increasing volumes present an economic opportunity to recover valuable metals and contribute to the economy. Therefore, the treatment of this waste stream gives an opportunity to assess the economic potential and reduce the environmental impact.

1.2 Problem Statement

The extraction of metals from e-waste has the potential to supplement the current metal production levels in South Africa and create employment opportunities for communities. In 2016 South Africa generated an estimated 300 000 tonnes of e-waste. Table 1.1 presents the e-waste production estimates in South Africa. As per the estimates, the volumes of e-waste created by the country differs, however hovers around 300 000 tonnes. South Africa also currently lacks the correct records on the type, tonnages and rate of e-waste generated, in circulation, processed, and exported (Lydall et al., 2017). E-waste stream is a richer source of metals, particularly the PCBs accounting for more than 80% of precious metals with copper accounting for about 14% (Khaliq et al., 2014). The recycling of PCBs presents the benefits of recovering valuable metals and the environment and health benefits (Golev, et al., 2016).

**Table 1.1 E-waste Production Estimates between 2013 and 2024 in
South Africa (GreenCape, 2022)**

Data Source	Year	Generated (Tonnes / Year)	Projected 2020 (Tonnes / Year)	Projected 2024 (Tonnes / Year)
ERA (2018)	2018	360 000	370 301	390 189
DEDAT (2016)	2015	-	585 953	617 424
EWASA (2016)	2015	322 000	346 353	364 955
Lydall et al. (2017)	2017	74 923	78 202	82 403
StEP (2013)	2012	339 310	382 047	402 566
UNU (2018)	2016	321 000	340 087	358 352

It was stated that, only about 25 100 tonnes of the 360 000 tonnes produced were collected for the recovery of metals. This leaves about 334 900 tonnes (approximately 93%) of e-waste sent to landfill (GreenCape, 2019). It is further estimated that of the 25 100 tonnes collected, about 2 730 tonnes are processed in South Africa and the rest are exported to countries such as India, China and Germany. The balance that is not recovered or exported is sent to landfill for disposal (GreenCape, 2019). These landfill sites are

reaching their full capacities, and they pose health risks to surrounding communities because of the negative impacts on the environment (GreenCape, 2019). There is therefore a need to find solutions considering the economic opportunities presented by e-waste processing. Companies' participation across the e-waste value chain in South Africa are listed in Table 1.2.

**Table 1.2: Companies Participation across the E-waste Value Chain
in South Africa (Lydall et al., 2017)**

Company	Collection	Dismantling	Pre-processing	Processing
Africa E-Waste	•	•		
Bolunga Electronic Waste	•	•		
Cape E-Waste	•	•		
Desco Electronic Recyclers	•	•	•	
Effortless Computer Recycling	•	•		
Electronic Cemetery	•	•		
eWaste Africa	•		•	
E-waste Technologies	•	•		
Inca Metals	•	•		
Indalo Resources	•	•		
Just PC	•	•		
Javco			•	
Metrex	•	•		
Rand Refinery				•
Reclam	•	•		
RecLite	•	•	•	
SA Metals Group	•	•	•	
SA Precious Metals				•
Sibanye Recycling	•	•	•	
Sims Recycling	•	•	•	
Sindawonye	•	•	•	
SmartMatta (Re-Ethical)	•			
Tshwane Electronic Waste	•	•		
Universal Recycling Company	•		•	
Virgin Earth	•	•		
Waste Plan	•			

Almost all the companies are engaged in the collection of e-waste and no single company is involved in all stages of the value chain. Most companies are active in the collection and dismantling stages and sell their outputs to a few companies in the pre-processing and processing stages (Lydall et al., 2017).

According to E-waste Recycling South Africa (2018), of the total e-waste, South Africa generates between 7 000 tonnes and 10 000 tonnes of PCBs annually. Printed circuit boards (PCBs) are the most precious components of e-waste and are sources of base and precious metals such as gold, platinum, palladium, silver and copper, and can become a renewable resource that can supply recycled metals for new production at the end of its life. Recycling of these obsolete PCBs will help recover metals, energy, and mitigate their hazardous effect on the environment copper (Abdelbasir, et al., 2018; Lydall, et al., 2017).

1.3 Research Aim and Objectives

The purpose of this research was to evaluate the economic feasibility of recovering valuable metals from e-waste in South Africa. The research was centred on printed circuit boards (PCBs). According to Lydall, et al. (2017), the focus of the recovery of valuable metals from e-waste has mainly been on ferrous and non-ferrous metals, specifically copper because of existing processing methods and technologies. There has been less focus on the recovery of precious metals, and this attributed to the limited technology and lack of investment in research and development, which results in the export of complex fractions like PCBs. The PCBs contain numerous metals such as gold, copper, palladium, platinum and silver (GreenCape, 2019; Lydall, et al., 2017). These are important minerals and find use in many applications. Against the economic potential of PCBs, the objectives of the research were to:

- Provide an overview of the e-waste value chain and the current state of recycling in South Africa;
- Analyse the material flow of PCBs to estimate volumes and metal recovery rates;
- Perform a discounted cash flow (DCF) analysis of recovering valuable metals contained PCBs; and
- Assess the costs and benefits of establishing a recycling plant in South Africa.

1.4 Research Motivation

Since the diamonds were first discovered in the 1870s, mining in South Africa has predominantly comprised of primary mining as a source of minerals and metals. South Africa is well endowed with major deposits of gold, chrome, coal, platinum group metals (PGMs), iron ore, copper and manganese. South Africa's mineral wealth is valued to be around 2.4 trillion US Dollars (The World Bank, 2019). While South Africa still holds a significant comparative advantage, the performance of the mining industry has declined amid technical and social challenges. South Africa has seen a notable decrease in the production of gold over the years. An estimated 100 tonnes of gold were produced in 2021 as compared to 189 tonnes of gold produced in 2010 (Statista, 2022). With e-waste being a potential supply of important metals, it provides opportunities to boost the gold production outputs thereby generating revenue and providing opportunities for employment, skills development and the establishment of small and medium processing plants that may contribute towards the implementation of the beneficiation strategy of South Africa.

1.5 Report Structure

The research is divided into five sections. The structure is presented below:

Chapter 1 gives the research background on the recovery of metals from e-waste with a focus on waste PCBs, including the problem statement, followed by the research aims and objectives, and research motivation. Chapter 2 gives an overview of the linkage between urban mining and e-waste from an international perspective and the South African context. The chapter also covers the status of e-waste production and processing in South Africa including the structure of the value chain, drivers, opportunities, challenges, e-waste policy and legislation.

Chapter 3 covers the methodology adopted and utilised to complete this research. The research approach, data sources, data gathering, data analysis and ethical clearance are also covered in the chapter. Chapter 4 presents the analysis together with the discussion of the results obtained from the research. This includes the current state of recycling in South Africa, e-waste value chain, material flow of PCBs, economic valuation and it presents of the DCF model to assess the viability of recycling metals from PCBs. Chapter 5 concludes this research and also give suggestions for further research and limitations of findings.

CHAPTER 2: OVERVIEW OF URBAN MINING AND THE E-WASTE INDUSTRY

2.1 Introduction

This chapter intends to give an overview of the concept of urban mining (UM), which is the process of recovering metals from materials which are no longer in use. The intention is to present the link between UM to primary mining as an alternative method to extract metals from mineral deposit and a complement to primary mining. This chapter further gives an overview of e-waste, its value chain, drivers, opportunities, and challenges and looks at legislation from the global perspective and the local South African perspective.

2.2 Overview of Urban Mining

2.2.1 What is urban mining?

UM is defined as a “process of recovering the compounds and materials from products and buildings which have reached their end of life” and it is alternatively called the recycling of waste (Park et al, 2017; World Resource Forum, 2012). The concept of UM was invented half a century ago by an urbanist Jane Jacobs (1969) and was developed through several stages involving different sectors such from mineral, environment, waste management and urban metabolic sectors (Nascimento and Xavier, 2018; Xue, 2018). Jane Jacobs stated that “in the highly developed economies of the future, it is probable that cities will become huge, rich and diverse mines of raw materials” (Johansson et al., 2013). Metallurgists later paid attention to the concept of UM fascinated by the vast amount of metals that could be recovered from secondary resources (Xue, 2018). These cities called ‘urban mines’ contains significant amounts of secondary materials such as e-waste that continue to accumulate as waste (Mogilska et al., 2012). The ‘urban

mines' will continue to grow because of on-going technological innovations, short lifecycle of EEE and increasing demand (Van Eygen et al., 2016).

Yang and Li (1985) reported that the period from 1960 to 1980 saw the industrialised economies investing into the recycling of scrap to recover metals, where in America the amount of metals such as aluminium (Al), copper (Cu), lead (Pb) and titanium (Ti) exceeded that produced by primary metal production methods. It was noted by Nanjo (1987), as early as the 1980s that grades of rare earth elements (REEs) found in industrial equipment exceed grades in primary mines (Nakamura and Halada, 2015; Nanjo, 1987). He further argues that the re-use of these metals requires less energy than that required to smelt and refine raw ores, as they are found in refined metal form. Nanjo (1987) also called the massive accumulation of industrial products 'urban mines'. Nishiyama (1993) also noted that the amount of metals that had already been extracted exceeds that of in-situ reserves (Nakamura and Halada, 2015; Nishiyama, 1993). For example, the secondary resources of lead (Pb), silver (Ag), gold (Au), zinc (Zn) and copper (Cu) account for 72%, 70%, 69%, 60% and 48% of the total known primary resources as shown in Figure 2.1 (Nakamura and Halada, 2015). On surface stock includes, namely, waste dumps, tailings, slag, and e-waste.

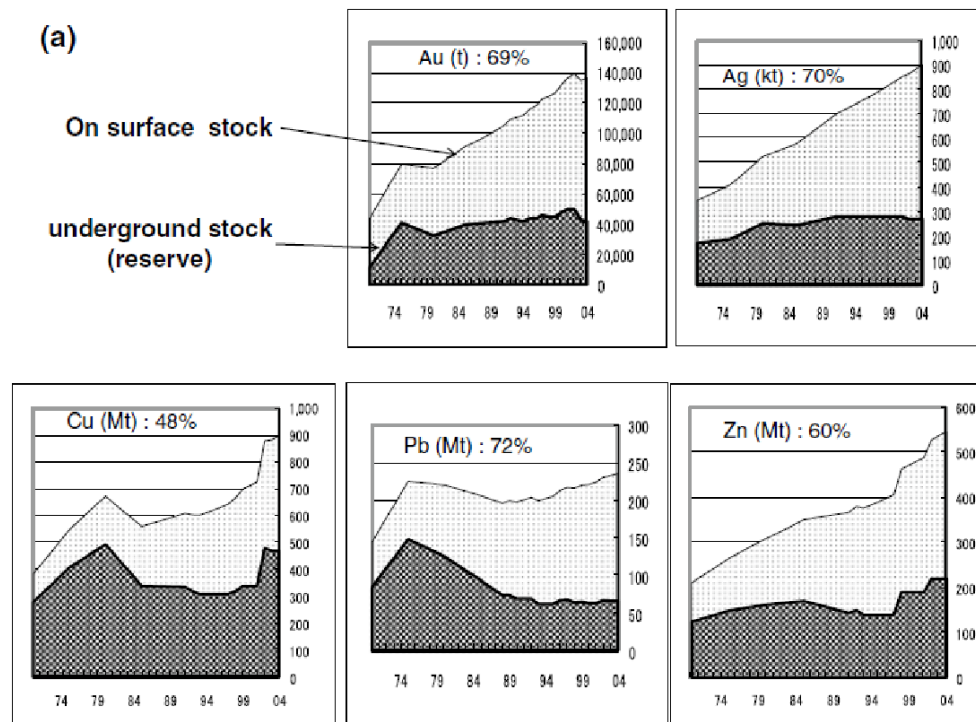


Figure 2.1: Primary Resource (underground stock) and Secondary Resources (on-surface stock) of Au, Ag, Cu, Pb and Zn (Nakamura and Halada, 2015)

2.2.2 Comparison between urban mining and primary mining

UM differs from primary mining in a sense that, it involves the recovery of metals from secondary resources generated by social consumption and industrial production processes, while primary mining entails the extraction of metals from geological deposits formed millions of years ago (Xue, 2018). Exploration in UM involves material flow analysis (MFA) which includes processing of economic and social data (Xue, 2018). On the contrast, exploration in primary mining involves the search for minerals either at or below the surface of the earth (Balasubramanian, 2016). In primary mining, the mining activity happens at a fixed location whereas in UM the value chain involves the collection obsolete products from individuals, households and businesses across the world (Environmental Law Alliance Worldwide, 2010; Hagelucken and Corti, 2010). UM aims to provide solutions by managing today's waste as well as to anticipate and extract value from

tomorrow's waste, while primary mining aims to meet the future demand for raw materials through exploration, mining, concentration and refining of metals (Espinoza et al., 2020; Muller et al., 2017). The UM value chain is shown in Figure 2.2.

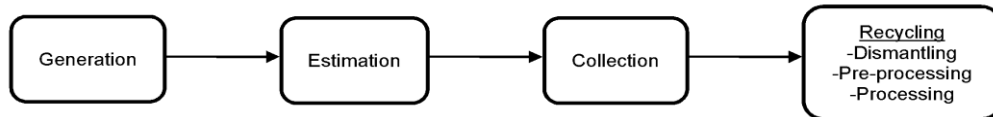


Figure 2.2: Urban Mining Value Chain (Yanyan, 2018)

The value chain starts with the generation of waste, estimation of volumes of waste, and then followed by recycling of metals which includes, after collection, dismantling, pre-processing, and processing (Xue, 2018).

In primary mining, the process starts with exploration which is the process of searching for mineral deposits that are economically viable to warrant extraction. The mineral ore is then extracted from the ground using specialized heavy equipment and machinery and different modes of transporting the ore to processing plants are used (Balasubramanian, 2016). Mining is then followed by size reduction methods (crushing and grinding) and beneficiation of mineral ore, which entails transforming and upgrading of mined mineral ore (Environmental law Alliance Worldwide, 2010; Wills, 2007).

The metal recovery methods includes both hydrometallurgical and pyrometallurgical processes which are common methods used in primary mining depending on the mineral of interest (Xue, 2018). The concentration and extraction of metals are followed by the smelting and refining of the metals extracted from the ore. The semi-finished and fabricated products are then produced, with the last stage in primary mining value chain involving the production of high value finished products as shown in Figure

2.3. Mineral and metal extraction from primary mining is labour and energy intensive than in UM (Nakamura and Halada, 2015; Xue, 2018).

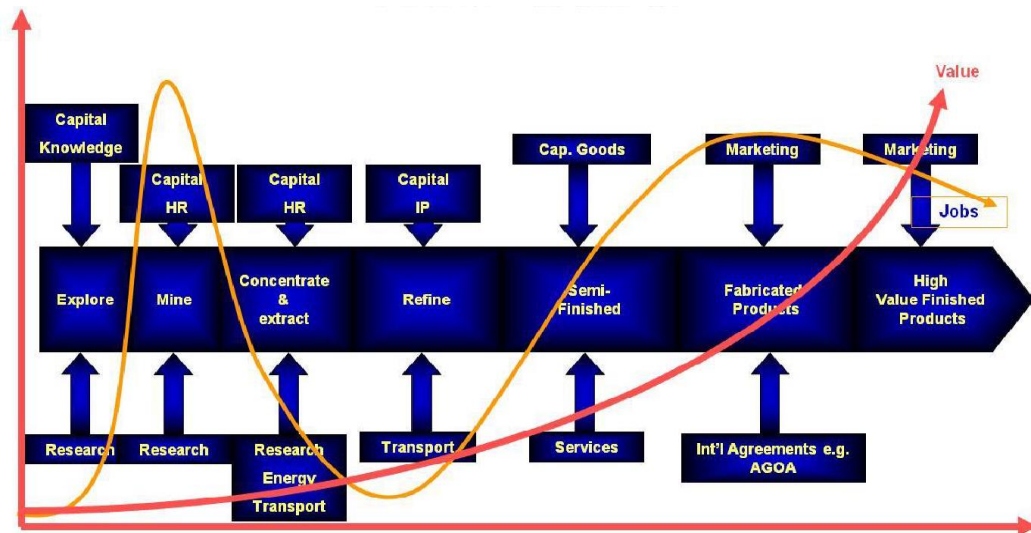


Figure 2.3: Primary Mining Value Chain (Leeuw, 2012)

Another difference between the two is that the sources of raw materials are distributed differently in UM and primary mining. In UM, the supply of raw materials is distributed globally because EEE components and parts are currently used and later disposed of as waste (Espinoza et al., 2020). However, the concentration of raw materials in primary mining can be found in certain places.

The composition of UM is different than that of primary mining where approximately 60 different elements are closely connected in complex products requiring metallurgical processes to recover the valuable metals safely and efficiently (Hagelucken and Corti, 2010). These valuable metals could be recovered and used as inputs for new products and goods (World Economic Forum, 2019).

2.2.3 Drivers of urban mining

The general drivers of UM are environmental concerns, energy and resource conservation and economic value. These are discussed in detail below.

- Environmental concerns

E-waste is categorised as hazardous waste and most of it ends up in landfill sites (Khaliq et al., 2014). Disposing of e-waste in landfill sites, acid leaching and open burning causes environmental pollution which leads to contamination of water, soil and release of toxic gases. It is therefore important to process the waste to prevent and minimise the environmental pollution and to ensure resource management (Khaliq et al., 2014).

- Energy and resource conservation

One of the major benefits of recycling e-waste is the saving of energy. Less energy is required to process e-waste than minerals from primary deposits. The recovery of lead, aluminium, iron and steel, zinc, copper, plastic and paper save up to 65%, 95%, 74%, 60%, 85%, 80% and 64% over primary deposits respectively (Khaliq et al., 2014). The treatment of e-waste could lessen the burden on primary mining as a source of metals, thus conserving the energy that is consumed. E-waste contains richer grades of metals than primary deposits, which is about 17 times than that of primary deposits (Khaliq et al., 2014).

- Economic value

E-waste stream is a richer source of metals, particularly the PCBs accounting for more than 80% of precious metals with copper accounting for about 14% (Khaliq et al., 2014). Therefore, the recycling of e-waste makes it one of the major economic drivers because of their inherent value.

2.3 Global E-waste Industry

2.3.1 Definition and composition of e-waste

Several definitions have been used to define e-waste globally. The widely used definition of e-waste includes all electrical and electronic equipment that have reached their product lifecycle like fax machines, household products, computers, mobile phones and printers (Basel Action Network, 2002; Koloseni et al., 2012). The Organisation for Economic Cooperation and Development (OECD) (2001) defines e-waste as any electrical equipment that has reached its lifespan. Balde et al (2014) refer to e-waste as “all items of EEE and its parts that have been discarded by its owner as waste without any further intent of re-use”.

The commonly accepted definition of e-waste is by the European Commission Directive (2002) which defines e-waste as “electrical and electronic equipment waste which includes all components, sub-assemblies and consumables, which are part of the product at the time of discarding”. According to Lydall et al (2017) globally e-waste is classified into six different categories as indicated in Table 2.1

The six different categories of e-waste include screens and monitors, temperature exchange equipment, lamps, large electrical equipment, small electrical equipment, telecommunication equipment and small information technology. Table 2.1 indicates the definition of each category.

Table 2.1: Category of e-waste (Lydall et al., 2017)

Category	Definition
Temperature exchange equipment	Also referred to as cooling equipment. Encompasses refrigerators, freezers, air conditioners, and heat pumps.
Screens and monitors	Equipment containing screens having a surface greater than 100 cm ² . Includes televisions, monitors, laptops, notebooks and tablets.
Lamps	Typical equipment comprises fluorescent lamps, compact fluorescent lamps (CFLs), high intensity discharge lamps (HIDLs), and light emitting diode (LED) lamps.
Large equipment	Typical equipment comprises washing machines, clothes driers, dish washing machines, electric stoves, large printing machines, copying equipment, and photovoltaic panels.
Small equipment	Typical equipment comprises vacuum cleaners, microwaves, ventilation equipment, toasters, electric kettles, shavers, scales, calculators, radio sets, video cameras, electric and electronic toys, and small electric tools, small medical devices, and small monitoring and control equipment.
Small IT and telecommunication equipment	External dimensions of such equipment are less than 50 cm and typically include items such as mobile phones, GPS, pocket calculators, routers, personal computers (PCs), printers and telephones.

The e-waste composition is mainly based on the manufacturer, type of electronic device, model, date of manufacture and age of scrap (Abdelbasir et al, 2018; Mmereki et al, 2016). About 1000 different materials are contained in e-waste where some are valuable and highly toxic (Ghimere and Ariya, 2020; Sahu and Agrawal, 2008). Information technology (IT) scrap and telecommunication systems have higher metals content than household equipments scrap (Chancerel et al., 2009; Mmereki et al., 2016).

For instance, mobile phones comprise of about 40 elements like silver (Ag), gold (Au), platinum (Pt), palladium (Pd), zinc (Zn), nickel (Ni), copper (Cu), tin (Sn), aluminium (Al) and iron (Fe). The associated toxic elements include lead (Pb), arsenic (As), mercury (Hg), beryllium (Be), cadmium (Cd), indium

(In) and antimony (Sb) with halogens such as chlorine (Cl), fluorine (F) and bromine (Br). The mobile phones also made up of organic fluid and plastics (Ghimire and Ariya, 2020).

On the other hand, large household appliances contain metals (stainless steel, aluminium, copper, steel and their alloys), organic materials, plastics, fillers, stabilisers, additives, inert materials, fillers, low value PCBs and stabilizers (Lydall et al., 2017). Circuit boards in electronic equipment contain elements like Hg, Cd, As Cr, Pb and other toxic chemicals which are harmful to the environment (Mmereki et al., 2016; Abdelbasir et al., 2018). Typical amounts of different elements in various EEE and e-waste from various sources are shown in Table 2.2.

Table 2.2: Material Composition in Different Types of EEE and E-waste (Ghimire and Ariya, 2020)

EEE/E-Waste	Content (%w/w)								Content (ppm)		
	Fe	Cu	Al	Pb	Ni	Sn	Plastics	Glass	Ag	Au	Pd
TV Boards	28	10	10	1	0.03	1.4	28	6	280	17	10
PC Boards	7	20	5	1.5	1	2.9	23	18	1000	250	110
Cell phone	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	-
PCBs scrap	-	10	7	1.2	0.85	-	-	-	280	110	-
			"- " indicate data unavailable; PCB - printed circuit boards, %w/w – percentage weight per weight, ppm – parts per million								

2.3.2 E-waste value chain

The process of treating e-waste makes it possible to recover metals required to produce EEE (Torres et al, 2016). The e-waste value chain is made up of four main stages, namely, collection, dismantling, pre-processing and processing as shown in Figure 2.4 (Khaliq et al; 2014, Torres et al., 2016). The value chain produces separated fractions and parts that can be sold for re-use or could be used as raw materials for downstream processes (Torres et al, 2016).

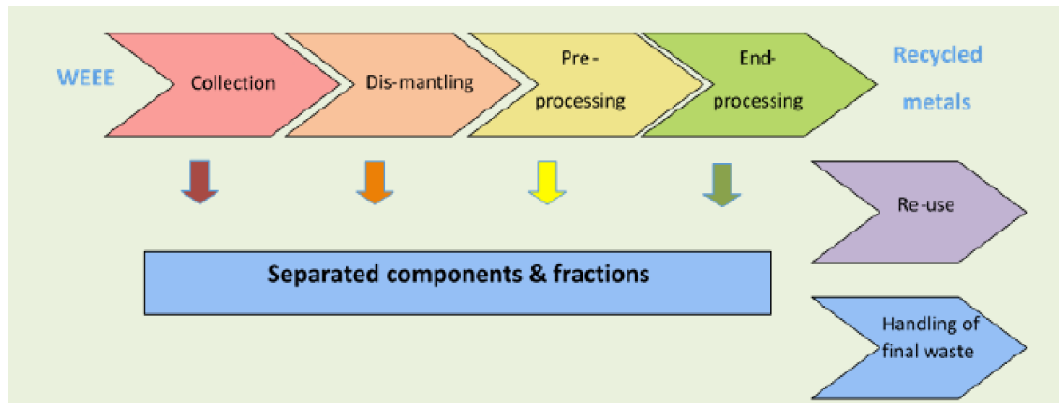


Figure 2.4: E-Waste Value Chain (Torres et al., 2016)

The first stage in the value chain of e-waste is the collection stage and is the stage that determines the amount of waste coming into the value chain (Ottiger et al., 2019). The collection of e-waste is facilitated by government policies, public awareness, installed collection facilities at public places (Khaliq et al., 2014) and dedicated companies involved in e-waste collection and informal companies specializing in waste picking (Ottiger et al., 2019). This stage requires low levels of capital investment and technology.

The second stage in the value chain is the dismantling stage, which utilises liberation and sorting methods to get different components or fractions for the recovery processes (Meskers et al., 2009). Individual components are manually dismantled and liberated from other components, and further

broken down into materials through mechanical processing using mills (Khaliq et al., 2014). Manual dismantling is important to prevent contamination of components and fractions and to further separate hazardous materials from valuable materials (Ottiger et al., 2019).

The third stage of e-waste value chain is pre-processing stage, where the techniques like dismantling used in mineral processing are then used in this stage to separate the metals from non-metals. Techniques used include screening, magnetic, eddy current and density separation (Khaliq et al., 2014). This stage produces three main streams of materials, namely, ferrous fractions to be treated at the steel plant, aluminium fraction for aluminium refiners or smelters, and copper, lead, zinc, PCBs and other precious metal fractions which are then treated separately in integrated non-ferrous metal smelters (Meskers et al., 2009). Two things can happen if the different streams are not properly constituted, namely, the creation of difficult or non-recyclable fractions and the loss of material resources because of technical or chemical limitations of end-processing methods.

The final stage in the e-waste value chain is called the end processing. The final metal recovery takes place in this stage (Khaliq et al., 2014; Meskers et al., 2009). Various metallurgical processes can be utilised to further process the metallic fraction of e-waste to separate or recover metals or elements (Khaliq et al., 2014). Metallurgical processes used include pyrometallurgy, hydrometallurgy, biometallurgy and electrometallurgy or their combination. The main processes used for the processing of e-waste are pyrometallurgy and hydrometallurgy. Electrometallurgy is mainly employed for selected metals and biometallurgy is only used on a laboratory scale (Khaliq et al., 2014).

Hydrometallurgy is a branch of extractive metallurgy concerned with the extraction of base and metallic minerals using aqueous solutions at much lower temperatures (Gupta, 2003; Lydall et al., 2017). This process is a promising option to be used to extract valuable metals contained in e-waste,

because of its possible for high recovery rates, moderately low capital investment, suitability for small scale application, reduced impact on the environmental, (Lydall et al., 2017).

Pyrometallurgy uses high temperatures and processes for the extraction and refining of metals (Gupta, 2003; Lydall et al., 2017). Pyrometallurgical processes utilises more energy and are costly to operate than hydrometallurgical processes. Pre-processing of e-waste is not always needed for pyrometallurgical processes than it is required for hydrometallurgical processes (Khaliq et al., 2014). Pyrometallurgical processes require a feed grade which is higher in metal content and the processes generate harmful gases that need cleaning of the air. Pyrometallurgical processes include incineration, smelting, combustion, pyrolysis, and molten salts processes. The selection and choice of method differs and is dictated by the type of e-waste, plant operating parameters and the size and shape of the feed materials (Lydall et al., 2017).

2.3.3 Status of e-waste production and processing

E-waste is reported as one of the rapidly increasing waste fractions globally because of the rapidly advancing technologies, shorter product lifespan and increasing demand for electronics (Statista, 2022). By 2019, the global production of e-waste was about 53.6 million tonnes globally with Asia accounting for almost half of the global e-waste volumes (Forti et al, 2020; Statista, 2022). E-waste generation grew by about 60% between 2010 and 2019 (Statista, 2022). Table 2.3 indicates the volumes of e-waste produced per continent in 2019.

Table 2.3: E-waste Generated in 2019 (Statista, 2022)

Continent	E-waste Generated (million tonnes)
Asia	24.90
America	13.10
Europe	12.00
Africa	2.90
Oceania	0.70

The value of metals like gold, palladium, silver and copper, in e-waste was valued at around \$57 billion (Balde et al., 2020; Statista, 2022). The e-waste stream has the potential of reaching 120 million tonnes annually in 2050 if left unprocessed (United Nations Environment Programme, 2019).

2.3.4 Challenges and opportunities

The global challenges of e-waste are the unknown quantities of e-waste, lack of safety (Bazargnan et al., 2012) and gaps in existing legal frameworks, extended producer responsibility (EPR) implementation, consumer behaviour and transformation of the informal sector (Murthy and Ramakrishna, 2022). These are discussed in detail below.

- Unknown quantities

Monitoring the e-waste quantities at an international level is the most essential step in addressing the challenges brought by e-waste. A lot of industrialised economies have established various regulations and guidelines on the management of e-waste. However, most e-waste gets exported to developing countries through semi-formal or illegal routes thus making it difficult to quantify the volumes exported (Bazargnan et al., 2012). With e-waste containing various toxic elements, the exporting of such waste is akin to sending of toxic waste to countries that are less developed.

- Lack of technological advancement

The lack of advanced technology, infrastructure and facilities in developing countries makes it challenging to properly process e-waste because the people resort to the use of unsafe treatment processes such as manual dismantling, acid leaching and incineration (Bazargnan et al., 2012). This further poses risks to people and the environment as they release various toxic pollutants.

- Gaps in existing legislation

Globally, there is not a common regulation that governs e-waste management. This leads to confusion in terms of policies (Murthy and Ramakrishna, 2021).

- Implementation of EPR

The EPR policy in OECD nations is different from that of non-OECD, thus creating confusion on how to manage e-waste (Murthy and Ramakrishna, 2021). Therefore, stakeholders in these countries lack awareness concerning roles and responsibilities in managing EEE value chain. EPR is defined as policy that prevents pollution by focusing on the entire production systems than the individual production system (Department of Environmental Affairs and Tourism, 2005; World Bank Group, 2012). The policy helps to encourage producers to design products with a longer lifespan, environmentally friendly, and can be easily treated for the recovery of metals (The World Bank Group, 2012).

- Consumer behaviour

There is a lack of knowledge amongst consumers in terms of their responsibilities in handling and disposing e-waste. Awareness programmes

are needed to inform users on the harmful effects of disposing off e-waste illegally (Murthy and Ramakrishna, 2021).

- Informal sector transformation

Women and children are mostly used for dismantling of e-waste components. Various diseases and environmental harm are caused using unsafe methods for treating e-waste (Murthy and Ramakrishna, 2021).

2.4 E-waste Industry in South Africa

2.4.1 Definition of e-waste

In South Africa, e-waste is referring to all EEE using electrical power supply and usually discarded once it has reached its end of life by the original owner (Lydall et al., 2017). In South Africa two more groupings to the categorization off e-waste are added, namely, security and health care, and mixed waste electrical and electronic equipment. In South Africa E-waste is categorised as hazardous waste because of toxic materials contained in e-waste (GreenCape, 2020).

2.4.2 Structure of e-waste value chain and industry

South Africa's e-waste value chain, as it is globally, comprises collection, dismantling, pre-processing and processing stage as shown in Figure 2.5. (Lydall et al, 2017). South Africa has over more than legal business enterprises operating along the e-waste value chain. A lot of these businesses operate in the early stages of the value chain with only a few involved in the final stages (GreenCape, 2019; Lydall et al., 2017).



Figure 2.5: Typical Four Stage E-waste Value Chain (Lydall et al., 2017)

The collection stage is the first stage in the e-waste value chain and determines the amount of material available for processing. It entails sourcing and transporting of the e-waste from source to processing sites. The collection of e-waste in South Africa is done by multiple stakeholders through informal and formal routes at different volumes (Lydall et al., 2017; Sadan, 2019).

Informal e-waste collectors in South Africa are known as waste pickers. These comprise of unlicensed and unregistered persons collecting different waste from malls, refuse bins and municipal landfill sites, across the inner cities for sale to early stage processors. About 25% of the total amount e-waste collected in South is collected by more than 100 00 informal waste collectors (GreenCape, 2019).

The collection stage is followed by the dismantling stage which is the process of breaking down e-waste into small fractions and components or materials such as PCBs, ferrous and non-ferrous metals, and other precious metals for downstream processing. The stage involves manual dismantling of e-waste employing hand tools like grinders, hammers, drills, screwdrivers, scissors, pliers, and cutters (Sadan, 2019). Several South African companies are involved in this stage and an increase in the number of such companies has been reported over the years because of rising volumes of collected. These companies are engaged with the collection, dismantling, classifying and sorting collected e-waste, selling of individual e-waste fractions and components locally and international market for

subsequent pre-processing and processing. The final waste produced by this stage is then sent to landfill sites (Lydall et al., 2017).

It is reported that a number of these companies are refurbishing and selling selected e-waste (particularly ICT equipment) which makes about 60% of their revenue. The difference between refurbishment and recycling is that refurbishment involves the selling of products that were taken back to a manufacturer or a seller where they are tested and certified before they are sold. On the other hand, recycling is the process of making new products by using waste materials (Dlila, 2024). These companies treat between 10 tonnes and 500 tonnes of e-waste annually (Salhofer et al., 2017; Lydall et al., 2017). Small to medium sized business enterprises end their operation at this stage. The key features of companies involved in the dismantling stage Lydall et al., 2017):

- These are licensed small to medium sized companies engaged in the recycling of e-waste;
- Their primary business is to collect, dismantle and refurbish e-waste components and subsequent selling of such components ;
- Have agreements with large processors engaged in the processing of e-waste fractions produced before selling them locally and in the international market;
- Refurbishment activity accounts about 60% of their revenue with recycling accounting for the remaining 40% of the revenue they generate;

- These are niche operators based in specific areas or involved in specific e-waste fractions;
- Generate revenue of between R1 million and R10 million per annum; and
- Have a workforce of between 2 to 5 people.

Pre-processing stage liberates complex and multi-material fractions into individual components by applying force to separate valuable metals and non-metals fractions for further processing. The purpose of this stage is preparation for transport, material liberation and separation (Sadan, 2019). The methods and technology used in this stage are like those used in mineral processing, such as balers, shears, shredder, granulators, pulverisers and separators. Equipment selection and treatment methods to be used have an effect on the quantity and quality of the feed going to metal recovery and the quantity of final waste going to the landfill sites (Lydall et al., 2017; Sadan, 2019).

There are two main activities involved in the pre-processing stage and these are liberation and separation. Liberation is a size reduction process (comminution) which includes hammering, crushing, grinding or shredding (Wills, 2007). Liberation processes produce a mix of broken pieces with different sizes distribution as well as chemical and physical properties. The chemical properties determine the metallurgical processing route to be followed, while the physical properties influence the separation technique to be used. The product from liberation is first screened and de-dusted prior to separation process (Lydall et al., 2017, Wills, 2007).

Separation can be conducted in dry or wet conditions. The process takes advantage of the difference in density, magnetic, visual, electrostatic or other properties of the e-waste output from liberation. Dry processes include

high intensity magnetic separators, laser and sensor sorters, Eddy current, rotating or vibrating screens and electrostatic separators. Wet technologies include hydro cyclones, jigs, tables, sink-float separators. This stage produces input material for the processing and metal recovery stage (Lydall et al., 2017, Sadan, 2019). This stage produces precious metals, ferrous and non-ferrous metals, glass cullet and plastics (Salhofer et al., 2017).

South Africa has well established pre-processing systems in place despite relatively low percentage of e-waste recycling and there are considerably less companies actively involved in pre-processing stage than in the dismantling stage (Salhofer et al., 2017). The pre-processing firms own large number of trucks, storage areas and pre-processing areas. They operate in different geographic locations and are supported either their operations in other provinces or by having strategic partnerships with smaller recycling businesses. These companies process between 1000 tonnes and 5000 tonnes of e-waste per annum. These companies employ over 100 people (Salhofer et al., 2017).

The final stage is the processing or metal recovery stage. This stage involves the recovery of metals by treating the fractions from the pre-processing stage, through smelting and refining plants using hydrometallurgy or pyrometallurgy or electrometallurgy or biochemical methods or their combinations (Khaliq et al., 2014; Salhofer et al., 2017).

Although South Africa has an established market for the recovery of ferrous and non-ferrous metals from e-waste scrap, as in the case with many international e-waste markets, the final processing of e-waste processing is still limited. South Africa had only two companies that were involved in the small-scale extraction of precious metals from obsolete PCBs, namely, SA Precious Metals and Rand Refinery (Lydall et al., 2017; Salhofer et al., 2014). The two companies have since discontinued the processing of PCBs due to economies of scale and higher selling prices of PCBs in the export market (Lydall et al., 2017). Currently, none of the pre-processors are

involved in the final metal recovery stage because of the specialized nature of the plants and technologies required, high levels of capital investment needed, the cyclical nature of the end user market for final products, and the lack of sufficient and stable volumes of e-waste generated in South Africa and the sub-region (Lydall et al., 2017).

2.4.3 Drivers and opportunities in the e-waste industry

E-waste contains fractions that are composed of toxic elements such as mercury, cadmium, lead and arsenic. Tsydenova and Bengtsson (2011) noted that e-waste material can pose risks to the human life and the environment if not treated properly. The drivers of e-waste in South Africa include negative externalities such as health, safety and environmental effects, increasing cost of landfill, limited landfill space, and positive externalities such as revenue potential, job creation, and energy and resource conservation.

- Health, safety and environmental effects

Park et al (2017) indicated that the recycling of e-waste presents an opportunity to reduce the flow of waste into landfill. South Africa has two main categories of e-waste namely, hazardous and general waste. Hazardous waste refers to waste that has a potential to create major threats the environment and public health because of its inherent chemical, physical and toxicological characteristics. General waste does not create major threats to the environment or health of the public or the environment (Department of Environmental Affairs, 2012). Inappropriate management and disposal of e-waste could cause the release of dangerous toxins and contaminants into the air and leaching out of particulates, thus endangering human and aquatic life (Ichikowitz and Hattingh, 2020).

- Increasing cost of landfilling

The cost of disposing of waste into landfill sites are on the rise. The cost differs between municipalities, however, ranges from R164.00 to R556.00 per tonne of waste (GreenCape, 2019). Department of Environmental Affairs (DEA) (2011) estimated about 90.2 million tonnes (90%) of generated waste was sent to landfill and only about 10 million tonnes (10%) was recycled in 2011. GreenCape (2019) reported that South Africa disposed of about 335 000 tonnes of e-waste which had a potential to generate between R438 million and R548 million if it were collected and processed. Due to the high cost of disposal, alternative landfill solutions are needed. DEA is assessing the possibility of implementing landfill tax which will increase the overall disposal costs. This intervention is underscored by the need to encourage landfill diversion (GreenCape, 2019).

- Limited landfill space

South Africa is struggling with a shortage of suitable landfill sites for waste disposal. GreenCape (2019) reported that it has been a challenge to find new suitable landfill sites as the older ones are becoming full. Cost-effective waste treatment technologies are therefore required to reduce the disposal of waste into landfill. Some municipalities are expected to run out of landfill space in less than 10 years (Eberhard, 2018). Such municipalities include the City of Cape Town and City of Johannesburg (Department of Environmental Affairs, 2018). The development of new landfill areas is complex and could take seven years or longer. For example, the City of Tshwane has serious challenges after closing two of its landfill sites in 2013 and 2014. This means the municipality has to divert waste to other sites further away, thus increasing transport costs and significantly reducing the lifespan of these landfill sites. Onderstepoort landfill is one of the landfill sites where a higher percentage of the waste was directed to, and it is estimated to reach its capacity (Eberhard, 2018). As of August 2021, South

Africa has banned the land filling of all hazardous e-waste and municipalities are required to implement the ban.

- Revenue potential

Quantities of valuable metals found in e-waste can generate profit when recycled. The treatment of e-waste to extract and recover metals is one of the most important economic drivers of e-waste because of their inherent value. For example, one tonne of PCBs can contain between 0.08 tonnes of gold and 1.5 tonnes of gold, and about 0.16 tonnes of copper and 0.21 tonnes of copper, thus making the PCBs the most profitable fractions of e-waste (Bazargan et al., 2012). South Africa exports its PCBs fraction to markets such as China, Germany and India for further processing. Processing of this high value fraction of e-waste could unlock economic opportunities. South Africa generates about 335 000 tonnes of e-waste per year at a price of approximately R438 million to R548 million (GreenCape, 2019).

- Job creation

Anderson (2018) suggested that investment into e-waste recycling could lead to the formation of new businesses, employment opportunities and economic growth.

2.4.4 Challenges in the e-waste industry

The challenges experienced in the e-waste industry in South Africa include the lack of reliable data, the lack of technological advancement, access to feedstock, cherry picking and costly licensing e-waste. The challenges are discussed below.

- Lack of reliable data

Balde et al (2017) reported that only 41 countries globally records data on e-waste. South Africa lacks accurate e-waste data on the type, rates, tonnages generated, flow to landfill sites and markets where the fractions are sold to (GreenCape, 2019). South Africa's e-waste database is not well developed and, in most cases, extrapolated and assumed.

- Lack of technological advancement

The lack of technology, infrastructure and proper facilities in most countries lead to employment of old treatment processes such as manual dismantling, incineration, and acid leaching to process e-waste (Bazargan et al., 2012). The use of these old treatment processes poses risks to the environment and people as they release various toxic pollutants. South Africa lacks off-the-shelf technologies to manage and process e-waste. The technologies are only readily accessible in China, Belgium, France, Italy and Germany (Lydall et al., 2017). High capital costs, low volumes of collection and import duties make it challenging to recycle e-waste locally.

- Access to feedstock

The factors impacting on the collection of e-waste are the few collection points, collection points located far from e-waste generators, less public awareness on disposal of e-waste and lack of separation of e-waste from other solid waste fractions (GreenCape, 2019). Additionally, concerns about data safety (i.e., information getting leaked) and emotional attachment to equipment are also considered to contribute to low collection of e-waste from offices and households (GreenCape, 2019).

- Cherry-picking of high value e-waste

It is reported that the cost to collect and treat low value e-waste streams exceed the revenue that can be generated (GreenCape, 2019). Many collectors therefore invest in the picking of e-waste with high metal content such as ICT and consumer electronics. This is expected to change with the introduction of levies as recommended in the Industry Waste Management Plan (IndWMP) (GreenCape, 2019).

- Expensive licensing of e-waste

One of the major challenges impacting businesses engaged in the recycling of e-waste is the time it takes to get the hazardous waste license together with costs needed for Environmental Impact Assessments (EIA) and other investigations (Lydall et al., 2017). It can take up to four years to secure a hazardous waste license and the delay results in companies losing on investment funding.

2.4.5 E-waste policy and legislation

South Africa still lacks specific legislation to manage e-waste (Patil and Ramakashna, 2020). However, there are legislative frameworks that recognise the principles of rehabilitation and environmental protection (Ledwaba and Sosibo, 2016). The legislative frameworks relevant to governing e-waste management are discussed below.

- The Constitution of South Africa

The overarching legislative framework in South Africa which protects and assures that basic human rights are defended is the Constitution of the Republic of South Africa (Ledwaba and Sosibo, 2012). Also, among other things, the Constitution addresses the basic environmental rights (Finlay & Liechti, 2008). The right of all citizens to exist in a safe environment that

does not pose harm to their health is enshrined in the Constitution. With e-waste classified as hazardous, it is important that a proper management of such waste is maintained without causing any harm to people and the environment.

- The National Environmental Management Act: Waste Act

The Waste Act establishes principles for waste management, including prevention, reduction and means to remedy pollution (Finlay & Liechti, 2008). The Act was passed into law in 2008 to control and legalize control the handling of all waste including e-waste (Ledwaba and Sosibo, 2012). The Act emphasizes the principle of waste reduction, re-use, recycle and proper management.

- Hazardous Substance Act

E-waste in South Africa is categorised as hazardous waste. The hazardous Substance Act controls management of hazardous waste and hazardous. The Act also deals with handling, selling and use of hazardous substances (Finlay and Liechti, 2008; Ledwaba and Sosibo, 2012).

- The Occupational Health and Safety Act

The Occupational Health and Safety Act (OHSA) control the health and safety of employees and the general public. The Act ensures that employers are forced to conduct hazards and risk assessments frequently to establish any risks created by the work or material used (Finlay and Liechti, 2008; Ledwaba and Sosibo, 2012).

2.4.6 Definition of PCBs

Printed circuit boards make an integral part of electric and electronic equipment (Szalatkiewicz, 2014). They are the basic component that is

used to assemble electronic items (Abdelbasir, et al., 2018). PCBs are used to connect and hold electronic components together using conductive tracks etched from copper sheets coated onto them (Malikov, et al., 2021). The PCBs are the most precious components of e-waste and are sources of base and precious metals such as gold, platinum, palladium, silver and copper (Abdelbasir, et al., 2018; Lydall, et al., 2017). It is reported that PCBs in some of the equipment makes approximately 22 % of their mass and others contain about 2 % or less of PCBs (Szalatkiewicz, 2014). On average, the e-waste contains about 3 % PCBs.

While PCBs only account between 2 % and 22 % of mass of e-waste, they contain a significant amount of precious metals which can be recovered for economic gain. Recycling of these obsolete PCBs also helps with the mitigation of hazardous effects on the environment resulting from poor disposal of e-waste (Abdelbasir, et al., 2018; Lydall, et al., 2017). In South Africa, PCBs are produced mainly from the recycling of ICT and consumer electronics equipment (Lydall, et al., 2017). Mintek had previously together with Rand Refinery established a pyrometallurgical plant to treat PCBs for the recovery of valuable metals. However, the project had since been closed. It is therefore important to compare the economic benefits of exporting PCBs and commissioning a processing plant.

2.4.7 Composition of PCBs

It is reported that up to 60 valuable and some hazardous elements are contained in PCBs. The different elements can be categorised as metals, non-metals and organic. The composition of these different elements in PCBs depends on the type of PCB (electric or electronic), type of equipment, year of manufacture, and other factors. According to Lydall, et al., (2017), PCBs contain 40% metals, 30% organics and 30% ceramics with a concentration of gold and palladium as high as 250 g/t and 110 g/t respectively. As noted, each individual group represents about 1/3 of the PCB weight (Szalatkiewicz, 2014).

More so, PCBs contain three types of materials such as a non-conducting substrate or laminate, printed conducting tracks, and components mounted on the substrate. The substrate is made up of glass fibre reinforced with epoxy resin or paper reinforced with phenolic resin both filled with brominated flame retardants. The other major elements of PCBs are polymers and industrial plastics which contains polyethylene, polypropylene, epoxies and polyesters (Abdelbasir, et al., 2018).

Copper and tin within PCBs are used as electric current conductor and solder for connections between elements and tracks on the board respectively. Since 2006, the use of lead in solder has been declining and currently lead-free solders comprising of 95.5 % Sn, 3.8 % Ag, 0.7 % Cu; 96.1 % Sn and 2.6 % Ag are used (Abdelbasir et al., 2018; Szalatkiewicz, 2014). Silver is used largely used in solder and contacts. Gold on the other hand is used in electronic components. Palladium is used in multilayer ceramic capacitors and contacts. Metals like Ni, Fe and Cr are also used as construction metals for contracts on board or magnetic cores of transformers and chokes. The non-metals are used as glass fibres (SiO_2 and CaO), fillers in epoxy resin, ceramic packages of electric and electronic devices, and insulators of electronic components, capacitors and resistors. Metal oxides like Al_2O_3 , CaO and MgO are used as fillers for epoxy resin. Organic materials are used as epoxy resin laminate and other substances comprising C, H, O, Br and Cl atoms are used as paint, rubber or PVC electric insulation. Fr-4 laminate filled with brominated fire retardants to decrease its flammability is used in PCB production (Szalatkiewicz, 2014).

2.4.8 PCBs value chain and treatment processes

Lydall et al (2017) indicates that there is no single treatment process that can process all various kinds on waste PCBs because of their complexity, heterogeneous nature, significant difference in volumes of PCBs and different levels of economic development among countries. However, there are three broad stages involved for the recovery of metals from the recycling

of PCBs. The stages include, pre-treatment, size reduction, and metallurgical treatments. Mechanical recycling methods, dismantling and manual sorting are generally classified as pre-treatment techniques. Pre-treatment refers to the compositional analysis and careful dismantling of the toxic parts by thermal or chemical desoldering (Cocchiara, 2019; Lydall et al., 2017). The size reduction stage includes shredding, crushing and screening to reduce the size of the material for easy of handling and processing by downstream processes. Metallurgical treatments used during the recovery and purification of metals include thermal treatment (pyrometallurgy), leaching (hydrometallurgy), electrolysis (electrometallurgy) and biological (biometallurgy) (Abdelbasir, et al., 2018). These treatment methods are discussed below:

- Pyrometallurgy – heat and high temperatures are used for the recovery of metals. This process has been applied for the extraction of precious metals as well as base metals from e-waste (Cui and Zhang, 2008; Marra et al, 2018). Pyrometallurgical techniques include incineration, smelting, dressing, sintering, melting and reactions in gas phase at high temperature (Marra et al, 2018). The prevalent method used for the recovery of metals from e-waste is smelting (Marra et al, 2018). The treatment process involves the feeding and burning of e-waste in blast furnace, incinerators or arc furnace to separate plastics from metals. Metals are then concentrated in a molten bath and further cast as anode for refining of metals to a highest purity level. The slurry residue obtained after refining is rich in precious metals and is treated for their recovery (Marra et al, 2018).
- Hydrometallurgy – hydrometallurgy is the preferred treatment process for the recovery of metals from e-waste than pyrometallurgy. It is preferred because of its predictability and controllability (Marra et al, 2018). The process is appreciated for the high recovery rates, low energy consumption, and non-

emission of gases. However, it produces toxic effluents because of the use of toxic, flammable and corrosive reagents (Cui and Zhang, 2008; Tuncuk et al., 2012). Hydrometallurgy starts with the pre-treatment of the e-waste to liberate the metals from plastics or ceramics and to expose the metals to reagents (Cui and Zhang, 2008). Pre-treatment is followed by leaching of metals into solution using reagents. The metals are then separated in the solution by processes such as solvent extraction, ion exchange and precipitation (Marra et al., 2018; Tunsu and Rategan, 2016). Once the separation of the metals from the leach solution is achieved, refining or purification of metals is conducted by either electro refining, crystallization or chemical reduction (Cui and Zhang, 2008; Marra et al., 2018).

- Biometallurgy – Biometallurgy has two main treatment processes namely bioleaching and biosorption (Marra et al., 2018). Bioleaching is a biotechnological process used for the extraction of metals from a solution by the help of microorganisms. Most used bacteria used for effective recovery of metals from e-waste is acidithiobacillus ferrooxidans (Baniyadi et al., 2019). This technique has already been applied at an industrial scale for the extraction of metals such as gold, copper and small quantities of nickel, cobalt and uranium from primary ores (Rawlings and Johnson, 2007; Wassink and Asselin, 2019). It is now exploited for the extraction of metals from secondary material such as mining waste, contaminated river sludge, fly ash and waste PCBs (Anaya-Garzon et al., 2021). However, the technique is still in its development stage for the extraction of metals from e-waste. Currently there are limited literature studies on e-waste bioleaching as most studies are done at laboratory scale (Marra et al., 2018).

- Biosorption is the process used to recover dissolved metal ions from leach solution. Algae, fungi, yeast and bacteria are used to concentrate leached metal ions in solution. The process has been used successfully for the recovery of metals from liquid effluent (Marra et al., 2018). Biometallurgical techniques are preferred over pyrometallurgy and hydrometallurgy because of the benefits it provides such as safety conditions of operators, operations at low atmospheric pressure and room temperature, lower chemical and energy consumption, lower CO₂ emission, and low capital costs (Dalini et al., 2020). However, the treatment kinetics of biometallurgy are very slow requiring longer time (Marra et al, 2018).
- Electrometallurgy – this technique is generally used towards the end of the value chain. It is a method applied during the purification of metals. Electrometallurgy covers two main routes namely, electrowinning and electrorefining. The working principle of these techniques is based on the electrodeposition of metal ions in aqueous electrolytes or molten salt (Hoffmann, 1992; Sum, 1991; Veit et al., 2005). The processes involve the passing of electrical energy through electrolytic cell containing an electrolyte in which at least two electrodes are inserted. The electrical energy generates a chemical reaction where positively charged metal ions migrate from anode to the cathode for deposition of pure metal (Gupta, 2003).

2.4.9 Economic recovery of PCBs: Past studies

Van Yken et al (2023) conducted a study on the economic feasibility of an integrated bio and hydrometallurgical process for extracting and recovering base and precious metals from PCBs. The benefits of using bio-hydrometallurgical process are the low costs of generating reagents indicated in the low raw material costs and the profitability even at 20% reduced process efficiency and 20% reduced commodity prices (Van Yken et al., 2023). However, this process is sensitive to labour and annualised

capital costs. The study recommended further investigation on how to reduce labour costs, how to recycle wastewater from the biogenetic H₂S generation process and the potential impact of this process on the environment Van Yken et al., 2023).

D'Almeida et al (2022) commissioned a study on the economic analysis of recycling PCBs by designing a conceptual treatment route based on the integration of different technologies. The mass and energy balances in ideal conditions were calculated to assess the feasibility of this conceptual process. Two scenarios were tested, 1) case a using PCBs from any type of e-waste and case b using PCBs from mobile phones. The results showed that the feasibility of this proposed process route. Both cases achieved positive net NPV of USD 44.4 billion and USD 3.2 billion, for case a and case b respectively (D'Almeida et al., 2022). Case a is sensitive to the price of gold, e-waste purchase price and processing value. Both cases produced an IRR of more than zero indicating the feasibility of this process. Further research on the logistics of transporting e-waste from the recycling points to the industrial plant and possibility of having own collection points were recommended (D'Almeida et al., 2022).

2.5 Economic Evaluation Methods

Economic evaluation entails the comparison of costs and outcomes from alternative use of resources (Johannesson et al., 1996). Lau and Kuziemy (2017) defines economic evaluation (also known as economic appraisal) as analysis of multiple interventions based on their costs and outcomes. There are four major kinds of economic evaluation methods, namely, Cost Utility Analysis (CUA), Cost Minimisation Analysis (CMA), Cost Effective Analysis (CEA) and Cost Benefit Analysis (CBA). All the stated economic evaluation methods entail systematic identification and measurement of costs and benefits of the interventions (Kobelt, 2013). The different types of economic evaluation methods are discussed below.

2.5.1 Cost utility analysis

CUA is a type of economic analysis that is used to compare the costs and outcomes of alternatives (Turner et al., 2021). This method is used when the goal has more than one dimension and when both quality and quantity aspects are of greater importance (Kobelt, 2013). CUA can be used in mining to measure the Life of Mine (LOM) of a mining project when used on process such as dump harvesting, which happens after decommissioning of primary production areas (Muzhizhizhi, 2021). The outcome of this economic evaluation method is in non-monetary form.

2.5.2 Cost minimisation analysis

Slothuus (2000) defines CMA as an economic evaluation method which is used when two interventions are expected to have the same outcome. The costs of each intervention are determined and compared, and the intervention with the lowest costs is considered if the goal is to minimize cost. The CMA economic evaluation method is generally used in health economic evaluation to compare the costs of medical interventions (Gellman and Turner, 2013). The CMA method is rarely used and only appropriate in rare circumstances (Turner et al., 2021).

2.5.3 Cost effective analysis

CEA is an economic evaluation method that is used to compare the costs and effectiveness of two or more alternatives with similar objectives (Fermanich, 2021). It measures the effectiveness of intervention in a single natural unit, and it is used to determine an alternative with the lowest cost per unit measured (Slothuus, 2000; Turner et al., 2021). CEA is used where it is difficult to monetize the benefits (Johnson, 2014). CEA produces cost effectiveness ratios for each alternative intervention and the ratio shows the cost per unit of improvement. The most desirable alternative intervention is the one with the lowest cost effectiveness ratio (Fermanich, 2021). The main challenge of CEA is the difficulty to find and compare alternative interventions with similar outcomes (Johnson, 2014).

2.5.4 Cost benefit analysis

Whenever a decision needs to be made, positive and negative feelings are used as well as the weighing of pros and cons to arrive at a particular choice option. Cost-benefit analysis (CBA) is therefore a method utilised to help make a choice following a systemic and consistent approach based on economic theory (Koopmans and Mouter, 2020). Stenis and Hogland (2014) defines cost-benefit analysis as method used to plan and assess social cost and determine the benefits associated with development projects to assist in deciding whether to invest in a project. CBA differs from other ordinary investment appraisal techniques used to evaluate projects by putting emphasis on the benefits and associated costs.

The plan is to “identify and measure the losses and gains in economic welfare which are incurred by society as a whole if the particular project in question is undertaken” (Stenis and Hogland, 2014; Stenis et al., 2011). This method is utilised to evaluate the costs and benefits of an investment for two reasons, namely, to determine the viability of the project and to compare investments of two or multiple projects (The Pan American Health Organisation). One of the advantages of using CBA is its adaptability and flexibility to indicate effects of income distributions (Department of Environmental Affairs and Tourism, 2004).

On the other hand, one key disadvantage of CBA is noted as prone to oversimplify, lessen complicated cause and effect connection to an individual value like the Net Present Value (NPV). However, sensitivity analysis can be conducted to solve this potential problem (Department of Environmental Affairs and Tourism, 2004).

2.5.5 Discounted cash flow (DCF)

A DCF is an old traditional method employed to assess the viability of projects (D’Adamo et al., 2019). Mirakovski et al (2009) defines DCF as “an evaluation method used to estimate the attractiveness of an investment

opportunity through future free cash flow projections and discounts them (most often using the weighted average cost of capital) to arrive at a present value, which is used to evaluate the potential for investment". It assumes that an investment in mining projects can go ahead provided a positive value is obtained when Net Present Value (NPV) of all its future cash flow is discounted to the present (Gardner, 2015). If the present value obtained by DCF analysis is higher than the investment cost, the investment is deemed profitable.

There are other several methods that are commonly used for valuation of mining projects, namely, Decision Trees (DT) and Monte Carlo Simulation (MCS) (Mirakovski et al., 2009). The DCF valuation method is a preferred valuation method because of its simplicity (Ardian and Kumral, 2018; Pivorienė, 2017). It can be performed using excel spreadsheet, can be utilised to determine IRR of projects and allows for sensitivity analysis to assess the change in parameters used to develop the valuation model (Marker, 2021). Most importantly it uses real cash flow generated by the investment. The following are the advantages and disadvantages of using DCF (Miraskovski et al., 2009). The following are advantages of using DCF.

- Clear, consistent decision criteria for all projects
- Same results regardless of the risk preference of investors
- Quantitative, decent level of precision, and economically rational
- Not as vulnerable to accounting conventions (depreciation, inventory valuation)
- Factors in the time value of money and basic risk structures
- Relatively simple, widely taught, and widely accepted and
- Simple to explain to management.

The disadvantages of using DCF include:

- It ignores randomness in cash flow variables
- Its analysis may use sensitivity analysis that varies a single variable at a time by a set percentage to gain insight into how NPV changes with random outcomes for that variable
- It ignores the effect of contingent cash flows and flexibility
- Its risk adjustments do not recognise the dynamic variation of cash flow risk through time and
- Its use of a single discount rate implies that project cash flow uncertainty increases through time in a regular manner.

The preferred valuation methods of projects are those that include cash flow projections and time value of money, especially NPV and Internal Rate of Return (IRR) instead of simple cost and revenue ratios or payback periods (Smith, 2002). The two most common methods used for evaluating mining projects in a DCF are discussed below.

2.5.6 Net present value (NPV)

NPV is a unit of measure used to evaluate the profitability of a project after having repaid all the debt, invested capital and interest of the project (Nicholas et al, 2018). It shows the distinction between the present value of money flowing into the business and the present value of going out of the business (Miraskovski et al, 2009). Equation 1 is used to calculate the NPV of the project (Saluga, 2019):

$$NPV = \sum_{t=0}^T \frac{CF_t}{(1+R)^t} \quad (1)$$

CF_t – cash flow (including capital, operating and closure cost)

R – discount rate or capital cost

2.5.7 Internal rate of return (IRR)

IRR is sometimes referred to as ‘economic rate of return’ and used to determine an investment’s rate of return (Miraskovski et al, 2009). It is the discount rate that brings NPV to zero (Brealey et al., 2011, Saluga, 2019). A project with a higher IRR would be considered the best and would be the first to be undertaken provided that all other factors are the same among different projects (Miraskovski et al, 2009). IRR can be calculated using the NPV formula, which is changed to the following formula (Saluga, 2019):

$$\sum_{t=0}^T \frac{CF_t}{(1+IRR)^t} = 0 \quad (2)$$

2.5.8 Discount rate

A discount rate is utilised to derive the present value or NPV of the expected future cash flow (Crosby and Weidner, 2023). The discount rate can be regarded in two ways, namely, the capital cost which is the rate of return in percentage the company must produce to give back the shareholder or financier and the opportunity cost which refers to the rate of return the business could make when using its money. Each project will have its own discount rate and own degree of risk (Park and Matunhire, 2011).

2.6 Chapter Summary

The chapter presented a summary on the history of UM. Previous studies on the comparison between UM and primary mining, and global e-waste and local e-waste industry have also been reviewed. The review indicates that a clear legal framework is needed to drive and promote proper management of e-waste.

Economic evaluation is an important process for mining investment and decision making. Different valuation methods were discussed, with DCF selected as the valuation methods for this research.

The current review indicates that advancement in the technology and infrastructure has a potential to unlock the value locked in e-waste. South Africa has potential to unlock between R438 million to R548 million per annum that is sent to landfill sites.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The chapter describes the methodology adopted for this research. The research used both the quantitative and qualitative techniques. The approach started with data collection, followed by analysis and interpretation of data to generate inputs for financial forecasting determinations. A DCF technique was used for valuation.

3.2 Research Approach

There are three main techniques to research, namely quantitative research approach, qualitative research approach and mixed method approach. Quantitative research approach involves as analysis, collecting, examination of data to produce dependable and measurable results (Ashley and Boyd, 2006). Yin (2003) defined qualitative research as an approach taken employed to understand the components and characteristics of a concept and trying to hypothesise around it. The mixed-method approach is defined as an approach for gathering, examining and interpreting data involving both qualitative and quantitative research methods (Creswell, 2012). The two techniques supplement and allow for a more complete analysis (Ivankova et al., 2006).

The research adopted mixed method approach and consisted of several well-structured questionnaires and interviews with key participants from identified organizations. The mixed method helped to gather information from a range of participants on the recovery of metals and the management e-waste thereof.

3.3 Ethical Clearance

The ethics clearance certificate was received from the school's ethics committee (non-medical) to comply with the University's ethics clearance. The ethical clearance protocol number is EMINN/2021/05. A copy of the ethical clearance certificate is found in appendix A.

The aim of the research was explained to the participants, and they were given a consent form (attached in appendix B) and participation information form (attached in appendix C). Amongst the ethical requirements that were discussed with the participants was that they were allowed to withdraw from the interview at any stage or reserve their input where it was deemed uncomfortable. The data collected from the participants was kept confidential for report writing and was used anonymously in the report.

3.4 Quantitative and Qualitative Data Source

This research used a combination of qualitative and quantitative methods to collect primary data and desktop study to gather secondary data. The two methods were utilised to validate the results. The primary data was compared with what is in the literature.

3.4.1 Primary data

Expert and knowledgeable individuals were contacted with a questionnaire consisting of open-ended questions and through interviews (as shown in Appendix D). These interviews were conducted face-to-face, telephonically and by electronic e-mails. The participants included chief operating officers, managers, researchers and government employees involved in the e-waste industry. A representative sample of participants is required for data collection and there are two primary sampling techniques, namely probability sampling and non-probability sampling (Showkat and Parveen, 2017). Adwok (2015) defines probability sampling technique as technique

where every individual has equal chance to be chosen as part of the sample. On the contrary, the non-probability sampling assumes that the population has the same characteristics making the sampler to believe the population to be selected is representative and the outcomes drawn would be accurate. The probability sampling is expensive and consumes a lot of time. The non-probability sampling technique was therefore adopted for this research.

A sample of four participants was interviewed during the data collection process. Four major recyclers were invited to take part in the study, and they showed no interest in the research with only one taking part in the research, hence the low number of participants. However, this was deemed not to impact the research, as it was complemented by secondary data. Also, the recycler interviewed has over 10 years recycling e-waste and selling PCBs in the export market. Research institutions such as Mintek also participated in the research. The participants' experience essential in shaping the quality of data collected.

3.4.2 Secondary data

Desktop review of past work was also done specifically on the recycling and management of e-waste. Secondary data was collected from reputable books, journals, reports, articles and websites on the handling, processing and management of e-waste.

3.5 Data Analysis

This research used mixed method to analyse the data. The collected quantitative data was populated into excel worksheet for examination. The data was captured and categorized into the input parameters for financial forecasting calculations. The qualitative data was also collected and populated into excel for analysis. An analysis of patterns from individual interviews and questionnaire was done and the patterns were captured.

A DCF technique was used to assess the economic feasibility of recycling PCBs using two scenarios namely, export and local refinery. The NPV together with the IRR were used as economic performance index. In each scenario, three cases were considered based on the grade of the PCBs. A DCF was done on gold and copper as the metal of interest. Sensitivity analysis was then applied to complement DCF to capture uncertainty and flexibility. Figure 3.1 shows the summary of approaches adopted in this research.

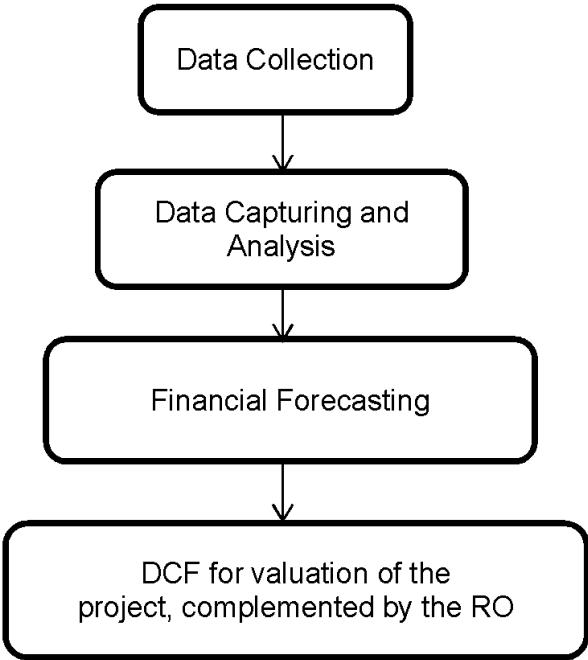


Figure 3.1: Methodology Adopted (Author’s own, 2024)

3.6 Research limitations and challenges

The research limitations and challenges include a smaller community of recyclers of e-waste particularly PCBs. With a limited number of recyclers being available, it was a challenge to have recyclers participates in the research. The other challenge was the limited number of published literatures on e-waste with limited access to data which the participants

deemed confidential. Secondary data was then used to supplement the primary data.

3.7 Discounted Cash Flow Input Parameters and Assumptions

The DCF requires several inputs including project life, production and/or processing rate, grade, mining and processing recoveries, commodity price, capital and operating costs, royalties, corporate tax and discount rate. Inputs such as the capital and operating costs presented by participants and previous studies were used to evaluate the feasibility of establishing such a plant. The capital investment represents the initial capital required to establish the plant, while operating costs includes labour, plant overheads, buying of waste PCBs, disposal costs, utilities, insurance, taxes, compliance costs and maintenance.

Some of the inputs can be estimated including inflation or as constant numbers. The use of constant numbers is referred to as the bare bone approach. A 'bare bone' approach can be used for valuation of mineral properties. The approach is defined as a cash flow technique based on constant metal prices, constant operating costs, constant money, no inflation, no debt, no interest, on a project basis and after tax (Smith, 2002). However, such a case never exists in valuation of mineral properties, but it gives a good reference point making it easier to compare different investments or projects. For this research, inflation was accounted for in the costs and prices.

According to Smith et al. (2007) cited in Birch (2016), real discount rates for South African mining projects range between 9-12% which is equivalent to nominal discount rates ranging between 14.5-17.6 % (assuming a 5% annual inflation rate). Based on these ranges, the DCF model assumes a maximum nominal discount rate of 17.6% and is based on a 10 year project life. Grades of PCBs used in this model as baseline are those that were

reported by Umicore. For this research, the plant feed tonnages and capacities were kept the same for the three DCF models.

3.7.1 Project Life

Figures 1.1 and 1.2 show that projection of e-waste volume is typically done for about 10 years. Therefore, a project life of 10 years was utilised for this research for both, export and local refining scenarios. The project life can be increased as the accurate tonnages of PCBs generated per year become available.

3.7.2 Production rate

A study commissioned by Mintek in 2017 indicated that the amount of PCBs produced in South Africa were between 5 500 tonnes and 7 500 tonnes during that year. However, the information collected from the interviews suggests that South Africa produces conservatively about 3 500 tonnes per year which was used for the DCF.

3.7.3 Capital cost

In the export scenario, capital cost was assumed to be zero. A financial model was developed to assess the viability of establishing a PCBs treatment plant in South Africa. Mintek in 2015 reported that a PCB recycling plant with a capacity of 2 tonnes per day to recover gold together with silver can cost between R20 million and R40 million. The demand for these two metals has increased rapidly because of their uses in the manufacturing of EEE. It is reported that about 267.3 million tonnes of gold and 727.5 million tonnes of silver are consumed annually for manufacturing of EEE, with only 15% being recycled (Vats and Sigh, 2015). This means that e-waste contains significant amount of these metals and therefore it is important evaluate the economic benefits of recovering these metals from e-waste. The worst-case scenario of R40 million was then used as the capital

investment for the local refining scenario which is the initial capital needed to set up the processing plant.

3.7.4 Operating cost

The participants did not disclose their operating costs as this information is treated as confidential. However, one respondent indicated that they spend around 25% of their total revenue on operating costs. A corporate tax of 27% was used as per the South African Revenue Services (SARS).

3.7.5 PCB grades

In South Africa, as in other places around the world, waste PCBs are generally graded into three main categories which show their precious metal content. The grades are only reported in terms of the gold content. Gold was only used as the metal of interest in this research. The grades of other precious metals in the three main categories are not reported. The three main categories are (Lydall et al., 2017):

- High grade PCBs – this fraction is made up of connected circuits containing gold, gold pin boards, palladium pin boards, discrete components, semi-conductors and opto-electronic devices. The high grade PCBs are obtained from computers, hard drives, laptops and display screens producing higher quantities of precious metals than medium and low grade PCBs. PCBs containing large number of semi-conductor chips are classified as high grade because of the chips being made up of large quantities of precious metals. High grade PCBs has a gold concentration of between 200 g/t and 400 g/t of gold.

- Medium grade PCBs – this fraction is comprised of precious metals from pin, edge connectors and aluminium capacitors. They are obtained from computers, set top boxes, display screen equipment and small mixed e-waste. Medium grade PCBs contains about 100 g/t of gold.
- Low grade PCBs – low grade PCBs are recovered from small mixed e-waste, CRT TVs and large household appliances. Low grade PCBs contains approximately 50 g/t of gold.

3.7.6 Waste PCBs prices

Formal recyclers operating in the dismantling and pre-processing stages sell the different grades of PCBs to the export market at around R40 000 per tonne for high grade PCBs, R30 000 per tonne for medium grade PCBs and R15 000 per tonne for low grade PCBs respectively. The prices were obtained from the interviews. Previous studies indicates that the Umicore which is a PCBs processor in Belgium was buying the waste PCBs at a price between R48 000 and R80 000 per tonne in 2016. The participants indicated that South Africa exports between 95% and 98% of the PCBs because the country does not have a commercially feasible plant to treat the waste PCBs. While Umicore has reported higher PCBs prices, the prices from the interviews were used in the DCF because the participants may not be selling to the Belgian market.

3.7.7 Recovery

Umicore Smelter and Refinery Group based in Belgium operates an integrated smelter and refinery plant which treats various materials ranging from energy, materials and performance materials and catalysts from automotives, oil refining, petrochemicals industries, mobile handset,

connectors, e-waste materials such as PCBs (Hagelucken, 2010; World Bank, 2012). It is one of the largest precious metals recovery plants with the capacity of recovering about 100 tonnes of Au, 50 tonnes of Platinum Group Metals (PGMs), 2 400 tonnes Ag (Hagelucken, 2010). Their plant recovers precious metals such as Au, Pt, Pd, Ag, Ir, Ru and Rh at a recovery rate of over 95% (McCarthy et al., 2021). The recovery is expected to be fluctuating because as equipment gets old the efficiency tends to drop, and the experience of operators has an impact on the efficiency of operation. A recovery of 90% was therefore used to offset the fluctuations.

3.7.8 Commodity Prices

For the export scenario, PCBs are sold, as such, prices of PCBs according to quality were used in the cashflows for exports. According to Huang et al., (2022), PCBs contain. According to Goldprice (2024), the price of gold ranged from about R410.49/g to R1 478.47/g over the past 10 years as shown in Figure 3.2. An average gold grade of R944.48/g was used as the base and then adjusted year-on-year using the average South African inflation rate noting that the gold price is traded on international markets. Over the past 10 years, the price of copper ranged from about R74 510 per metric tonne to R178 650 per metric tonne. Like gold, an average price for copper of R126 580 was used in the cash flows for local refinery. The risks of over or underestimating the NPV by using South African inflation rate is covered by the sensitivity analysis.



Figure 3.2: Price of Gold for the past 10 years (Goldprice, 2024)

3.7.9 Royalties

The literature and the respondents did not make any reference to royalties. For the DCF, it was assumed that they do not pay royalties.

3.7.10 Inflation

South Africa's inflation rate has remained within 5% to 6% in 2024 (Statistics South Africa, 2024). Therefore, an average inflation rate of 5.2% for the past 10 years was used (Focus Economics, 2024).

3.8 Chapter Summary

This chapter discussed the methodology of collecting data from different participants. A mixed approach was utilised to gather primary data and secondary was used to supplement and justify the primary data. The collected economic data and assumptions required to conduct a DCF analysis were further discussed. The DCF results are presented and interpreted in Chapter 4.

CHAPTER 4: RESULTS AND ANALYSIS

4.1 Introduction

This chapter discusses the results gathered from the research. The chapter starts by outlining the e-waste value chain and the current state of recycling. This is followed by the discussion on the material flow of PCBs in South Africa. The chapter closes by presenting and discussing the costs and benefits of building a recycling plant in South Africa to extract metals from waste PCBs.

4.2 Current State of Recycling in South Africa

The e-waste value chain consists of four stages. The value chain is consistent with what it has been reported in the literature. The four stages of e-waste value chain are discussed below.

4.2.1 Collection

From the interviews, it was reported that the country has seen a rise in the number informal companies involved in the collection of e-waste in the past few years. The informal e-waste collectors are not properly regulated and lack proper channels for collection and disregard safety measures. South Africa has few dedicated collection points for people to drop off their obsolete EEE and those that are available are located far away from people, like in the malls and pick-it up collection points being located only in metropolis, namely, Johannesburg, Pretoria, Cape Town and Durban.

The respondent reported that, South Africa has challenges of the availability and quality data on the production of e-waste, the flows, and the final market especially for specialised e-waste fractions such as PCBs. There is no accurate database on the installed capacity of EEE in household, business,

government offices; and amount of e-waste generated, collected, processed, sent to landfill and sold to the export market.

The critical challenges impacting on the collection of e-waste in South Africa includes storage of obsolete EEE and under-developed collection systems. Reasons reported for the storage of EEE includes difficulty in writing off assets from their asset's registers by business and government departments for fear of releasing confidential data into the hands of criminals (data security), the conviction that waste EEEs will have some value in future and the general attachment issues of South Africans always keeping their old EEEs at home. The other reasons are free riders, few collection points and those collection points are far away from waste generators and generally the lack of records.

Lydall et al (2017) reported that the major generators of PCBs in South Africa are the government department, business and households accounting for 40%, 35% and 25%, respectively. It was further reported in that study that South Africa produced between 5 500 tonnes and 7 500 tonnes of PCBs in that year. Additionally, no law compels recycling companies to report the volume of e-waste collected, recycled and the market where they sell their products. In 2012 the EU Commission introduced the European Directive 2012/19/EU as the only legislation that is clear and specific on e-waste recycling globally (Balde et al., 2017; Cocchiara et al., 2019). Its purpose is to lessen the production of large volumes of e-waste, to encourage re-use, recycling and reduction of waste disposal thus contributing to the better use of materials and recovery of metals (Cocchiara et al., 2019).

4.2.2 Dismantling

This stage involves breaking down of e-waste into components or fractions such as ferrous, non-ferrous, PCBs and hard drives that are re-used or sold for further processing. Hazardous substances such as batteries, condensers and capacitors are removed for safety reasons and may be taken out for re-use. The respondents indicated that many companies engaged in dismantling of e-waste still use manual dismantling methods. The companies prefer this method because it produces higher quality and uncontaminated fractions than mechanical dismantling. Tools such as screw drivers, grinder, hammers and chisels are used to dismantling process. Some of the companies involved in the dismantling stage includes Desco Electronic Recyclers (Desco), Sindawonye Granulators and Processors (Sindawonye), Africa E-Waste, AST Recyclers, SA Metals Group, Tshwane Electronic Waste, New Reclamation Group (Reclam), Bolunga Electronic Waste, Cape E-Waste, Computer Scrap Recycling, Sibanye Recycling, Effortless Computer Recycling, Electronic Cemetery, Sims Recycling, E-Waste Technologies, Inca Metals, Indalo Resources, Just PC, Metrex, Sims Recycling and Virgin Earth.

The respondents indicated that the main challenges in the dismantling of e-waste are access to funding, the exposure of employees to hazardous substances such as batteries, capacitors, condensers and cathode ray tubes which pose health hazards to employees. Additionally, the manual dismantling technique is labour intensive and expensive to small and medium sized businesses involved in the recycling of e-waste. Therefore, access to funding will help recyclers invest into mechanical technologies required to dismantle waste EEE safely and scale up their operations.

4.2.3 Pre-processing

In this stage mechanical processes such as shredding and granulation are used to separate and liberate e-waste components such as PCBs and plastics received from the dismantling stage and prepare the fractions into homogenous stream as inputs in the downstream processing stage. The fractions are crushed, shredded or cut into smaller parts to be separated and classified into homogenous streams such as ferrous and non-ferrous metals, precious and base metals, plastics and glass cullet. From separation, the different fractions are then sent to downstream for further processing, where the precious and base metals stream containing PCBs are treated for the recovery of metals such as gold, platinum/palladium and silver. The complexity of these fractions is easy to handle because the other components that make up a PCB board are removed. On the other hand, plastics are classified into different fractions based on density, colour and size after shredding.

In this stage, techniques like those used in mineral processing are used. The pre-processing stage is a two-stage process comprised of liberation and separation. The liberation stage reduces the size of the material and separation stage separates the metals from non-metals. The equipment used during liberation includes hammers, crusher and grinding mills. While dry separating equipment such as sorters, vibrating screens, magnetic separators, eddy current separators, electrostatic separators, and wet separating equipment such as jigs, sink-float separators, hydro cyclones and shaking tables are used during separation stage.

Pre-processing of e-waste is done by a few companies, with only about 9 out of 27 companies being interviewed by Mintek in a study in 2017. However, the kind of used technology at this stage is like that of well-developed e-waste markets. Pre-processors in South Africa include, Desco, Universal Recycling Limited (URC), E-Waste Africa, Reclam, Reclite, SA Metal Group, Sims Recycling Solutions and Sindawonye.

The main challenges faced by companies in pre-processing of e-waste are the capital required to buy mechanical equipment and the low levels of e-waste which makes it challenging to achieve economies of scale.

One respondent pointed out that it is challenging to estimate the costs of setting up a dismantling and pre-processing plants because the costs depend on factors such as the type of e-waste material to be treated, plant capacity and product specifications. The respondent did not disclose how much it cost them to build their dismantling and pre-processing plant. However, they have indicated that they pay about R4 million for operating license and compliance, which is payable every two years. Mintek reported in 2017 that a large, mechanised pre-processing plant to treat mixed e-waste needs a capital investment of between R5 million and R8 million. For example, a new shredder imported from Europe and China costs around R3 million and R1.5 million respectively. In South Africa, a second-hand shredder costs around R250 000. From literature, the processing plant needs between R20 million and 40 million, a capital cost of R40 million was assumed from this range, as such, this R40 million is further assumed to include a shredder.

4.2.4 Processing

This is the final stage in the e-waste value chain. Hydrometallurgical and pyrometallurgical techniques are used to treat outputs from the pre-processing stage through smelting and refining. There is not a single treatment process that can be used to extract metals comprised in complex e-waste. The recycling of PCBs is considered challenging because of the complex structure and complicated blend of materials. An example of a PCB taken at one of the recyclers is presented in Figure 4.1, showing the gold lines and connectors of a high grade PCB.

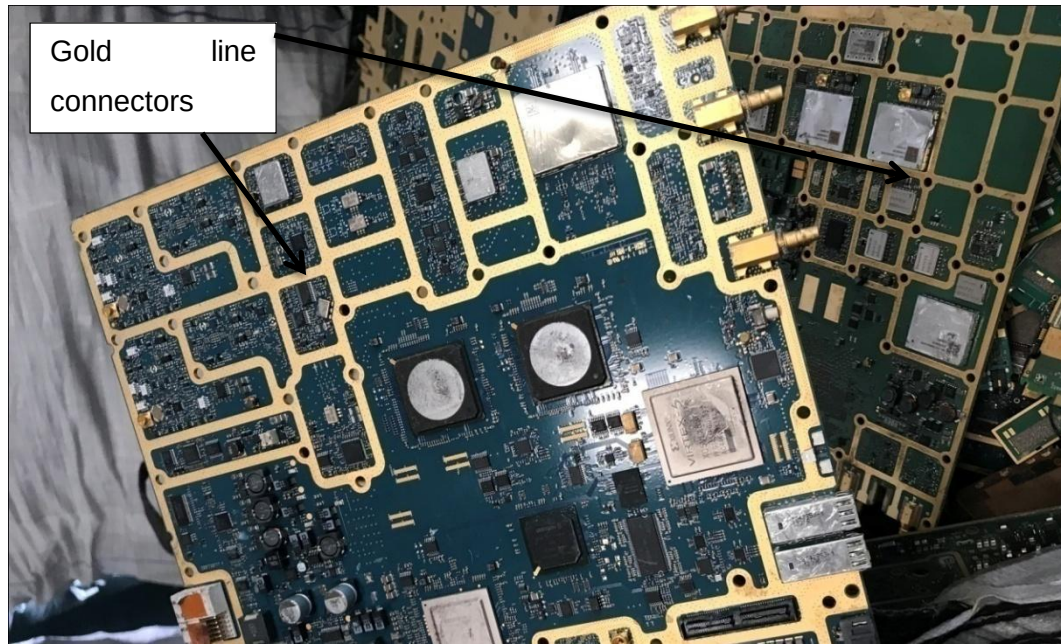


Figure 4.1: PCB showing gold lines connectors taken from one of the recyclers visited (Source: Author's own, 2023)

It is reported that up to 60 valuable and some hazardous elements are contained in PCBs. The different elements are categorized as metals (40%), organics (30%) and ceramics (30%) (Lydall et al., 2017). The composition of these different elements in PCBs depends on the type of PCB (electric or electronic), type of equipment and year of manufacture. The PCBs contain non-conducting substrate or laminate; components attached on the substrate and printed conducting lines. Other major elements of PCBs are polymers and industrial plastics which contains polyethylene, polypropylene, epoxies and polyesters (Abdelbasir et al., 2018).

Huang et al (2022) reported the lack of detailed information on the content of precious metals in PCBs, with manufacturers reluctant to share this information to protect the interests of their businesses. The metal content in PCBs was reported to be ranging from 19% to 40%, and an average of 34% by mass (Mori de Oliveira et al., 2022). The literature indicates that the percentage mass of gold, silver and palladium accounts for about 0.03%, 0.05% and 0.01% respectively (Huang et al., 2022; Mori de Oliveira et al.,

2022). Waste PCBs proves to be an essential supply of metals required for the new production of EEE.

The research indicated that large capital investments and sophisticated metallurgical treatment technologies are necessary to build metal recovery plants that yield high quality metals and low environmental impacts. South Africa does not have an integrated smelting and refining facilities to handle waste PCBs for the extraction of metals. The PCBs are currently sold in the export market, particularly in Europe. However, the participants indicated that two companies in South Africa were engaged in the recovery of metals from waste PCBs. One of the companies in partnership with one of South Africa's government research institutions (Mintek), collaborated on a study to recover metals from PCBs by feeding the waste PCBs into their existing process flow. However, the project was stopped because of the low volumes of waste PCBs required to operate the metal recovery plant.

The other company that was also recovering of metals from waste PCBs, developed a plant to treat about 2 tonnes per day of PCBs with the opportunity of scaling up to 16 tonnes per day provided economies of scale were achieved. However, the company was contacted for the interviews, and it was established that the plant has been shut down also because of low levels volumes of waste PCBs. Previous work done by Mintek reported that a pilot plant used for the recovery of gold and silver is estimated to cost between R 20 million to R 40 million.

The research conducted unearthed the following challenges as hindrance to the building of integrated metallurgical processing facilities to treat complex e-waste fractions in South Africa:

- Large capital investment;
- Low volumes of waste PCBs to achieve economies of scale;

- Lack of data in the volumes of waste PCBs the country is producing annually and
- The amount of money paid by the export market.

4.3 Discounted Cash Flow Model for Direct Export without Processing

4.3.1 High grade PCBs DCF model

A DCF analysis was done on the high grade PCBs to determine the current NPV on just selling the PCBs to the export market without any processing. Table 4.1 shows the DCF of this scenario which yielded a positive NPV of R436.89 million. Figure 4.2 shows the NPV against the discount rate

Table 4.1: Predicted Discounted Cash Flow Model for High Grade PCBs

	Project Year		Year									
		0	1	2	3	4	5	6	7	8	9	10
	Units	Base Year										
Production	Thousand tonnes		3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
PCB Price	Thousand R/t	40.00	42.08	44.27	46.57	48.99	51.54	54.22	57.04	60.00	63.13	66.41
Gross Sales Revenue	R million		147.28	154.94	163.00	171.47	180.39	189.77	199.64	210.02	220.94	232.43
Total Operating Costs (at 25% of gross revenue)	R million	25%	36.82	38.73	40.75	42.87	45.10	47.44	49.91	52.50	55.23	58.11
Operating Profit before Tax	R million		110.46	116.20	122.25	128.60	135.29	142.33	149.73	157.51	165.70	174.32
Corporate Tax Paid	R million	27%	29.82	31.38	33.01	34.72	36.53	38.43	40.43	42.53	44.74	47.07
Actual Cash Flow after Tax	R million		80.64	84.83	89.24	93.88	98.76	103.90	109.30	114.98	120.96	127.25
Discounted Cash Flow	R million	17.6%	68.57	61.34	54.87	49.08	43.91	39.28	35.14	31.43	28.12	25.15
NPV	R million	436.89										

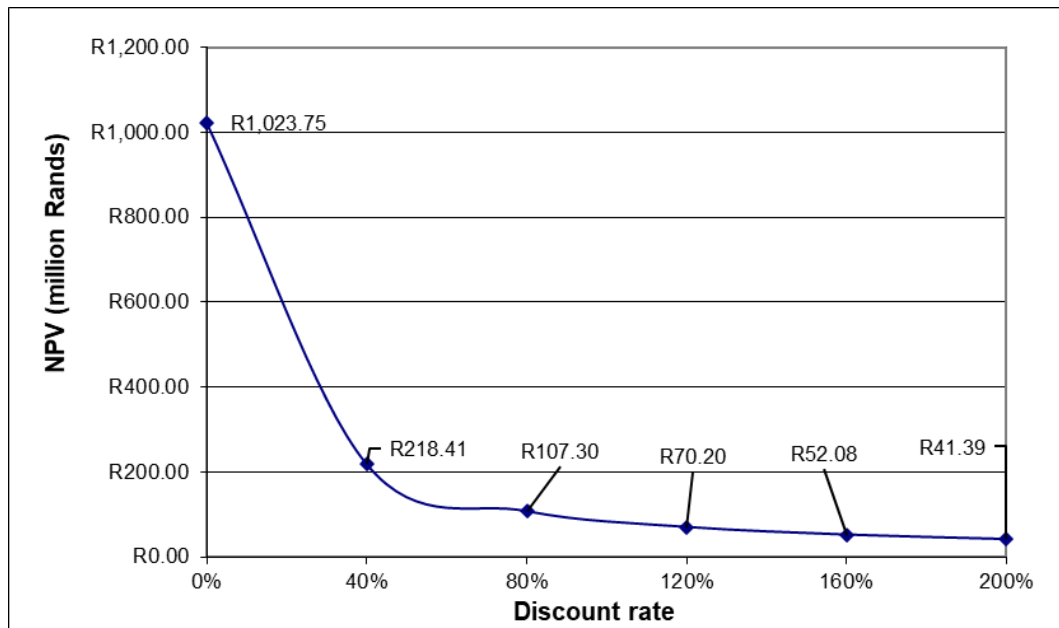


Figure 4.2: NPV versus Discount Rate

It can be noted from Figure 4.2 that up to a discount rate of 200%, an NPV of zero was not obtained. This means for this scenario; the IRR is greater than 200% and also larger than the discount rate (17.6%). A combination of a positive NPV and an IRR greater than the discount rate makes this scenario economically feasible.

4.3.2 Sensitivity analysis – High grade PCBs

The sensitivity analysis on the high grade PCBs is shown in Figure 4.3. Detailed input table is found in Appendix E (Export). The maximum value of NPV achieved in this model is R567.98 million at PCBs price +30% and the minimum NPV achieved is R305.82 at PCBs price -30% below of the base case. The NPV is most sensitive to the PCBs prices. This is the risk that must be managed, and management must always have an understanding of the market.



Figure 4.3: Change in NPV with change in economic parameters

4.3.3 Medium grade PCBs DCF model

The principle followed that of the high grade DCF model, by keeping the feed tonnages and recovery rates the same. The discount rate was also kept the same with the price of PCBs changing the total revenue generated by the project. Table 4.2 shows the DCF of this scenario which yielded a positive NPV of R319.10 million. Figure 4.4 shows the NPV against the discount rate.

Table 4.2: Predicted Discounted Cash Flow Model for Medium Grade PCBs

	Project Year		Year									
		0	1	2	3	4	5	6	7	8	9	10
	Units	Base Year										
Production	Thousand tonnes		3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
PCB Price	Thousand R/t	30.00	31.56	33.20	34.93	36.74	38.65	40.66	42.78	45.00	47.34	49.81
Gross Sales Revenue	R million		105.00	116.20	122.25	128.60	135.29	142.33	149.73	157.51	165.70	174.32
Total Operating Costs (at 25% of gross revenue)	R million	25%	26.25	29.05	30.56	32.15	33.82	35.58	37.43	39.38	41.43	43.58
Operating Profit before Tax	R million		78.75	87.15	91.68	96.45	101.47	106.74	112.30	118.13	124.28	130.74
Corporate Tax	%	27%	28.35	23.53	24.75	26.04	27.40	28.82	30.32	31.90	33.55	35.30
Actual Cash Flow after Tax	R million		50.40	63.62	66.93	70.41	74.07	77.92	81.98	86.24	90.72	95.44
Discounted Cash Flow	R million	17.6%	42.86	46.00	41.15	36.81	32.93	29.46	26.35	23.57	21.09	18.87
NPV	R million	319.10										

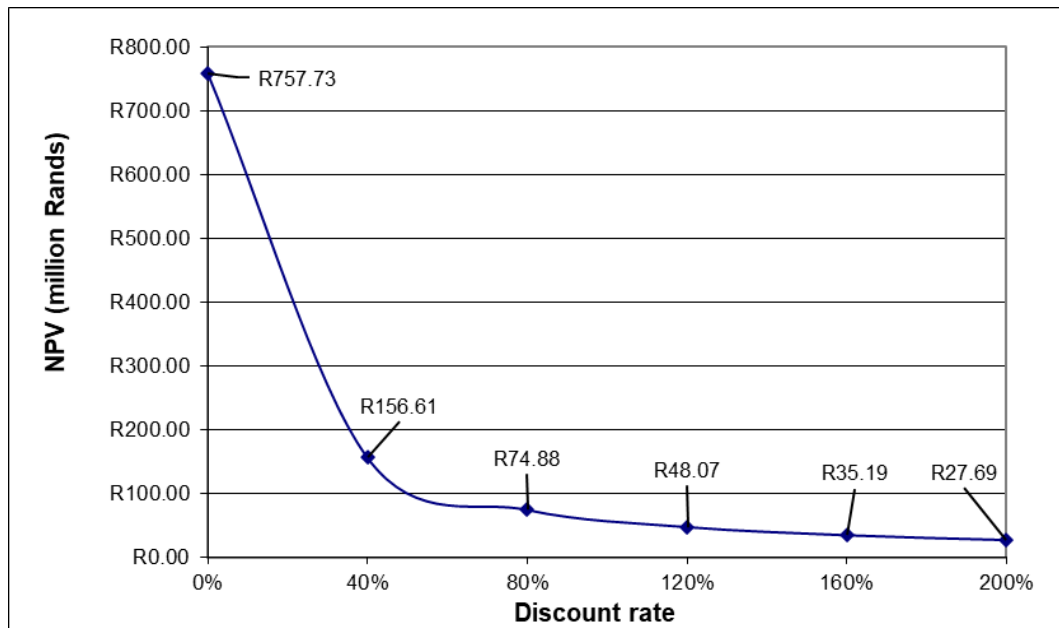


Figure 4.4: NPV versus Discount Rate

It can be noted from Figure 4.4 that up to a discount rate of 200%, an NPV of zero was not obtained. This means for this scenario; the IRR is greater than 200% and also larger than the discount rate (17.6%). A combination of a positive NPV and an IRR greater than the discount rate makes this scenario economically feasible.

4.3.4 Sensitivity analysis – Medium grade PCB

The sensitivity analysis on the medium grade PCBs is shown in Figure 4.5. Appendix E (Export). The maximum value of NPV achieved in this model is R382.92 million at PCBs price +30% and the minimum NPV achieved is R223.37 at PCBs price -30% below of the base case. The NPV is most sensitive to the PCBs prices. This is the risk that must be managed, and management must always have an understanding of the market.

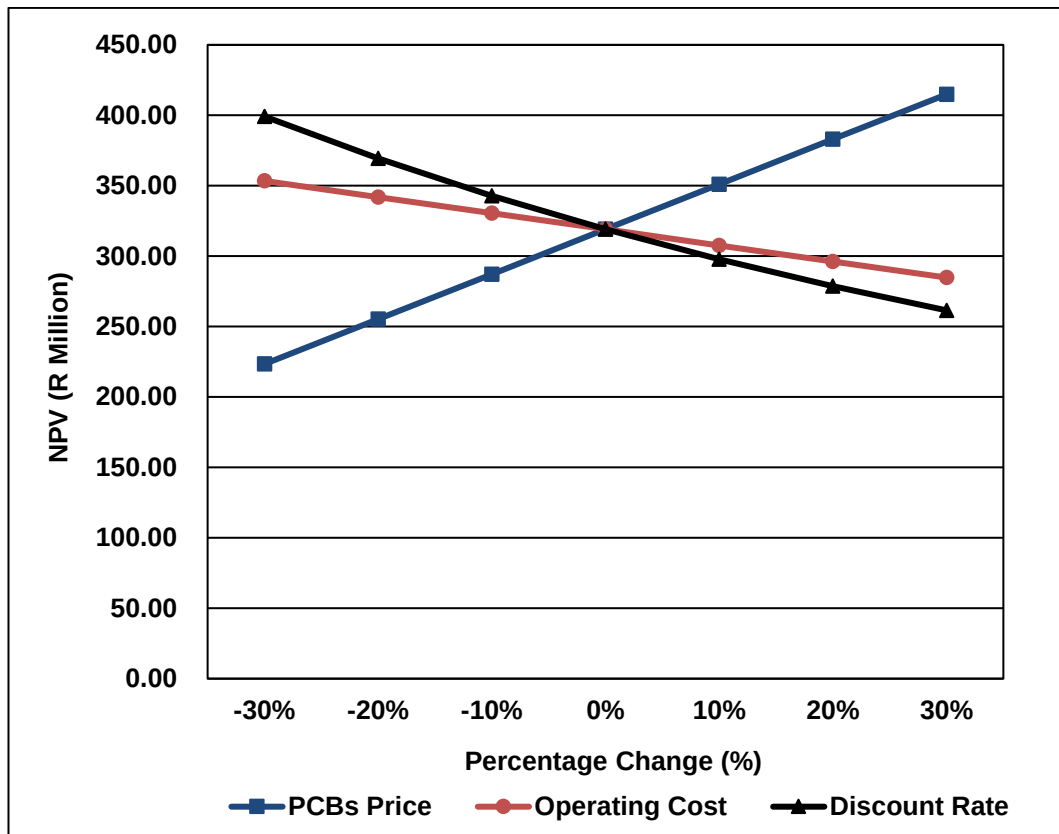


Figure 4.5: Change in NPV with change in economic parameters

4.3.5 Low grade PCBs DCF model

The DCF model for the low grade is shown in Table 4.3 from which an NPV of R163.83 million can be seen. The model indicated that low grade PCBs generate lower margin as compared to both high grade and medium grade PCBs. Low grade PCBs yielded a positive NPV due to various factors including aggregation of operating costs to 25% of the revenue. While this value was obtained from the respondents, it would be more accurate to obtain actual operating cost breakdown in future research. Figure 4.6 shows the NPV against the discount rate for the low grade PCBs.

Table 4.3: Predicted Discounted Cash Flow Model for Low Grade PCBs

	Project Year		Year									
		0	1	2	3	4	5	6	7	8	9	10
	Units	Base Year										
Production	Thousand tonnes		3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
PCB Price	Thousand R/t	15.00	15.78	16.60	17.46	18.37	19.33	20.33	21.39	22.50	23.67	24.90
Gross Sales Revenue	R million		55.23	58.10	61.12	64.30	67.65	71.16	74.86	78.76	82.85	87.16
Total Operating Costs (at 25% of gross revenue)	R million	25%	13.81	14.53	15.28	16.08	16.91	17.79	18.72	19.69	20.71	21.79
Operating Profit before Tax			41.42	43.58	45.84	48.23	50.73	53.37	56.15	59.07	62.14	65.37
Corporate Tax	%	27%	11.18	11.77	12.38	13.02	13.70	14.41	15.16	15.95	16.78	17.65
Actual Cash Flow after Tax	R million		30.24	31.81	33.46	35.21	37.04	38.96	40.99	43.12	45.36	47.72
Discounted Cash Flow	R million	17.6%	25.71	23.00	20.58	18.41	16.47	14.73	13.18	11.79	10.54	9.43
NPV	R million	163.83										

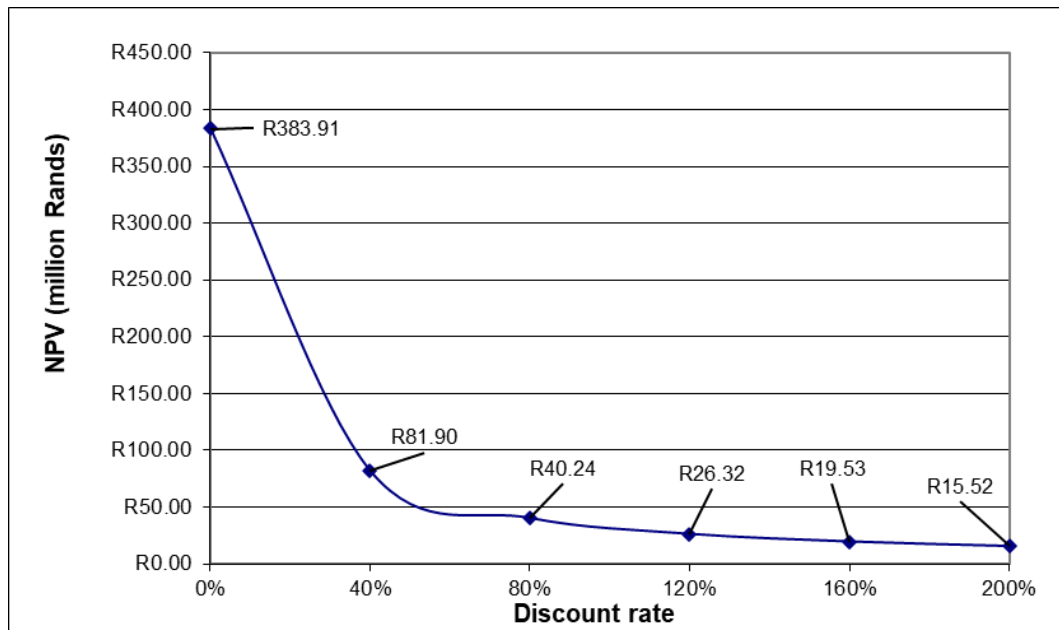


Figure 4.6: NPV versus Discount Rate

It can be noted from Figure 4.6 that up to a discount rate of 200%, an NPV of zero was not obtained. This means for this scenario; the IRR is greater than 200% and also larger than the discount rate (17.6%). A combination of a positive NPV and an IRR greater than the discount rate makes this scenario economically feasible.

Even though a higher IRR shows the feasibility of a project, it has risks. The shortfalls include interpretation of internal rate of return as the annual equivalent return on a given investment and also an IRR which is higher than the true investment rate for interim cash flow, it often over estimates (Keller and MacCormack, 2005).

4.3.6 Sensitivity analysis – Low grade PCBs

The sensitivity analysis on the medium grade PCBs is shown in Figure 4.5. Appendix E (Export). The maximum value of NPV achieved in this model is R212.98 million at PCBs price +30% and the minimum NPV achieved is R114.68 at PCBs price -30% below of the base case. The NPV is most

sensitive to the PCBs prices. This is the risk that must be managed, and management must always have an understanding of the market.

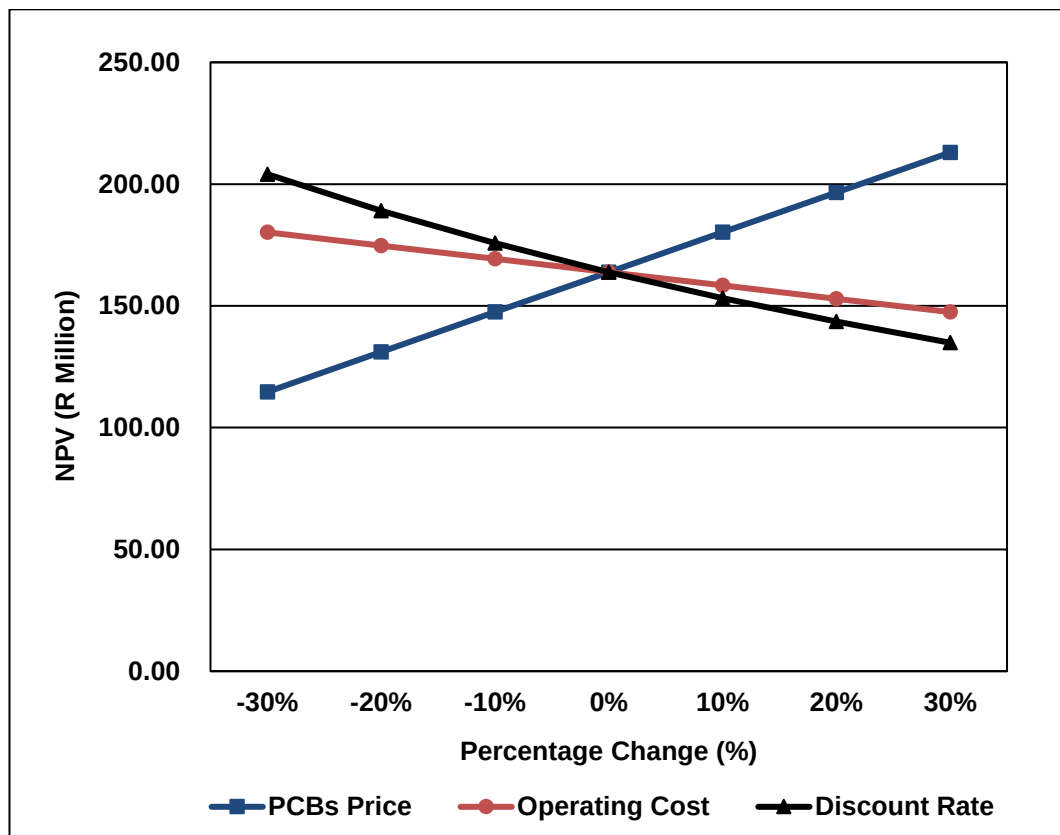


Figure 4.7: Change in NPV with change in economic parameters

4.4 DCF of Setting up a Recovery Plant on South Africa

A DCF was conducted to establish the costs and assess the viability of setting up a refining plant to recover valuable metals. Sensitivity analysis was performed to establish the risks affecting the profitability of this project by applying the change in economic parameters in a DCF model.

If the NPV of a project is sensitive to a small change of an economic parameter, the risk associated with that economic parameter is high. The sensitivity analysis was also performed on three different grades of PCBs to understand the effects of uncertainty. The economic parameters applied

were PCB price, operating costs, capital costs, discount rate and production.

4.4.1 High grade PCBs DCF model

The DCF model achieved an NPV of R3 446.85 million and an IRR of more than 200%. The IRR was calculated to be more than the discount rate of 17.6%. The NPV and IRR show the profitability of the project. The DCF model results on the high grade PCBs are shown in Table 4.4.

Table 4.4: Predicted Discounted Cash Flow Model for High Grade PCBs

	Project Year	0	Year									
			1	2	3	4	5	6	7	8	9	10
	Units	Base Year										
Tonnes of PCBs	Tonnes		3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500
Copper Content (at 55.87% by weight)	Metric tonnes		1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45
Gold Content	kilograms	300	1,050	1,050	1,050	1,050	1,050	1,050	1,050	1,050	1,050	1,050
Recovery		0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Copper Produced	Tonnes		1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91
Gold Produced	kilograms		945	945	945	945	945	945	945	945	945	945
Gold price (nominal)	R/g	944.48	993.59	1,045.26	1,099.61	1,156.79	1,216.95	1,280.23	1,346.80	1,416.83	1,490.51	1,568.01
Copper price (nominal)	R/t	126,580.00	133,162.16	140,086.59	147,371.10	155,034.39	163,096.18	171,577.18	180,499.20	189,885.15	199,759.18	210,146.66
Gross Sales Revenue	R million		1,173.30	1,234.31	1,298.49	1,366.02	1,437.05	1,511.77	1,590.39	1,673.09	1,760.09	1,851.61
Operating Costs	R million	25%	293.32	308.58	324.62	341.50	359.26	377.94	397.60	418.27	440.02	462.90
License cost	R million	4.00	4.21		4.66		5.15		5.70		6.31	
Net Sales Revenue (operating profit) before Capex	R million		875.77	925.73	969.21	1,024.51	1,072.63	1,133.83	1,187.09	1,254.82	1,313.75	1,388.71
Capital expenditure (nominal)	R mil	- 40.00										
Unredeemed Capex (nominal)	R mil	- 40.00										
Operating Profit before Tax	R million		835.77	925.73	969.21	1,024.51	1,072.63	1,133.83	1,187.09	1,254.82	1,313.75	1,388.71
Corporate Tax	R million	27.00%	225.66	249.95	261.69	276.62	289.61	306.13	320.51	338.80	354.71	374.95
Actual Cash Flow after Tax	R million		610.11	675.78	707.53	747.89	783.02	827.70	866.57	916.02	959.04	1,013.76
Discounted Cash Flow	R million	17.60%	518.80	488.65	435.03	391.03	348.13	312.92	278.58	250.41	222.93	200.38
NPV	R million	3,446.85										

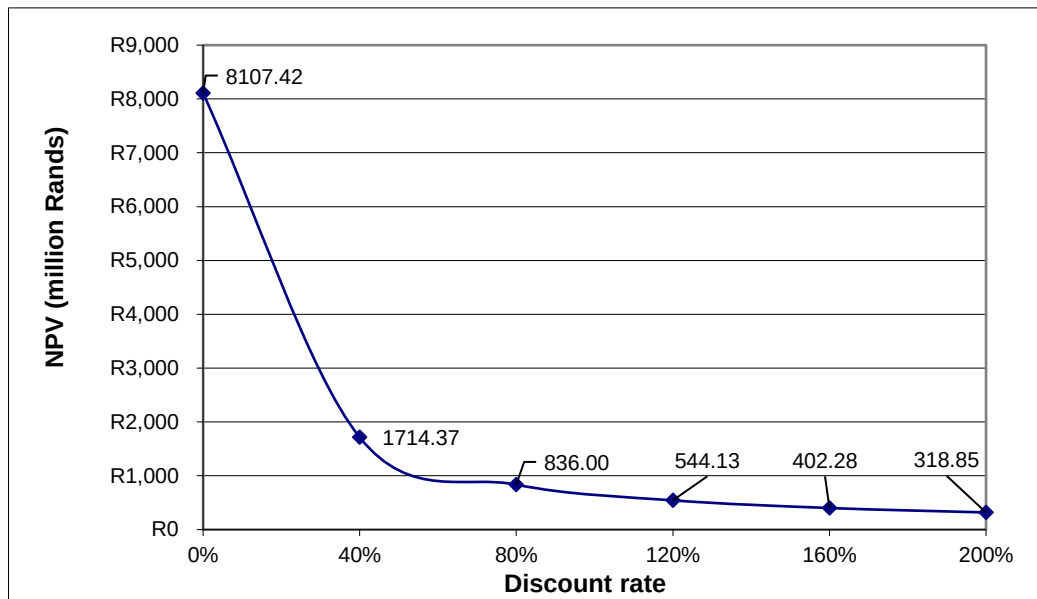


Figure 4.8: NPV versus Discount Rate

4.4.2 Sensitivity analysis – High grade PCBs

The sensitivity analysis on high grade PCBs is shown in Figure 4.9. Detailed input table is found in Appendix E (Refining). The graph indicates that the NPV is affected by the change in economic parameters. The maximum value of NPV is R4 298.46 million at discount rate -30% and the minimum NPV achieved is R2 833.71 at production +30% below the baseline. The NPV is most sensitive to the discount rate. This is the risk that could be managed by managing the source(s) of capital.

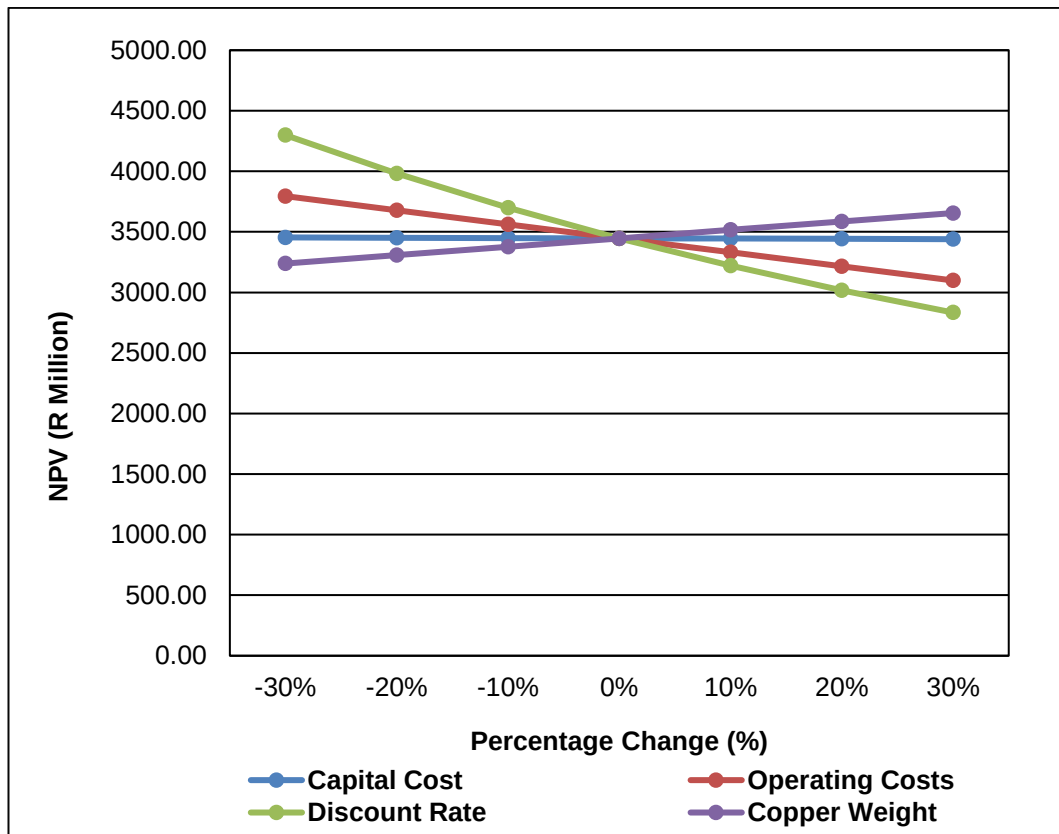


Figure 4.9 Change in NPV with change in economic parameters

4.4.3 Medium grade PCBs DCF model

The DCF model results on medium grade are shown in Table 4.5. The model achieved an NPV of R1 590 million and an IRR of more than 200%. The results show the profitability of the project on the medium grade PCBs.

Table 4.5: Predicted Discounted Cash Flow Model for Medium Grade PCBs

	Project Year	0	Year									
			1	2	3	4	5	6	7	8	9	10
	Units	Base Year										
Production												
Tonnes of PCBs	Tonnes		3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500
Copper Content (at 55.87% by weight)	Metric tonnes	55.87%	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45	1,955.45
Gold Content	kilograms	100	350	350	350	350	350	350	350	350	350	350
Recovery		0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Copper Produced	Tonnes		1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91	1,759.91
Gold Produced	kilograms		315	315	315	315	315	315	315	315	315	315
Gold price (nominal)	R/g	944.48	993.59	1,045.26	1,099.61	1,156.79	1,216.95	1,280.23	1,346.80	1,416.83	1,490.51	1,568.01
Copper price (nominal)	R/t	126,580.00	133,162.16	140,086.59	147,371.10	155,034.39	163,096.18	171,577.18	180,499.20	189,885.15	199,759.18	210,146.66
Gross Sales Revenue	R million		547.33	575.80	605.74	637.24	670.37	705.23	741.90	780.48	821.07	863.76
Operating Costs (at 25% of gross revenue)	R million	25%	136.83	143.95	151.43	159.31	167.59	176.31	185.48	195.12	205.27	215.94
License cost	R million	4.00	4.21		4.66		5.15		5.70		6.31	
Net Sales Revenue (operating profit) before Capex	R million		406.29	431.85	449.65	477.93	497.63	528.92	550.72	585.36	609.49	647.82
Capital expenditure (nominal)	R million	- 40.00										
Unredeemed Capex (nominal)	R million	- 40.00										
Operating Profit before Tax	R million		366.29	431.85	449.65	477.93	497.63	528.92	550.72	585.36	609.49	647.82
Corporate Tax	R million	27.00%	98.90	116.60	121.40	129.04	134.36	142.81	148.70	158.05	164.56	174.91
Actual Cash Flow after Tax	R million		267.39	315.25	328.24	348.89	363.27	386.11	402.03	427.31	444.93	472.91
Discounted Cash Flow	R million	17.60%	227.38	227.95	201.82	182.41	161.51	145.97	129.24	116.81	103.42	93.48
NPV	R million	1,590.00										

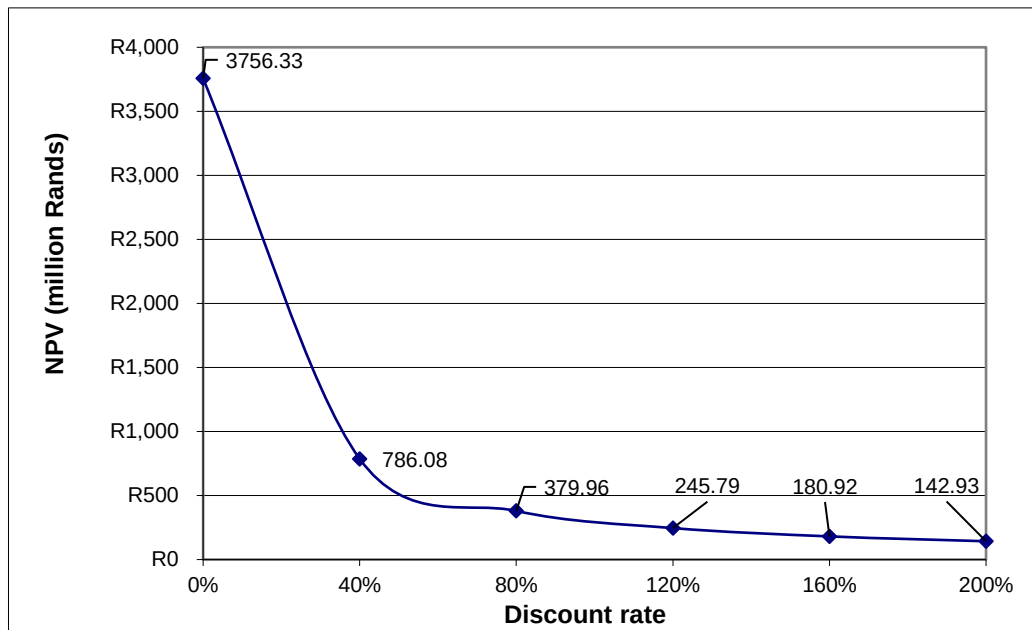


Figure 4.10: NPV versus Discount Rate

It can be noted from Figure 4.10 that up to a discount rate of 200%, an NPV of zero was not obtained. This means for this scenario; the IRR is greater than 200% and also larger than the discount rate (17.6%). A combination of a positive NPV and an IRR greater than the discount rate makes this scenario economically feasible.

4.4.4 Sensitivity analysis – Medium grade PCBs

The sensitivity analysis on the medium grade PCBs is shown in Figure 4.11. Detailed input table is found in Appendix E (Refining). The maximum value of NPV achieved in this model is R1 985.62 million at discount rate -30% and the minimum NPV achieved is R1 390.48 at discount rate +30% below of the base case. The NPV is most sensitive to the discount rate. This is the risk that could be managed by managing the source of capital.

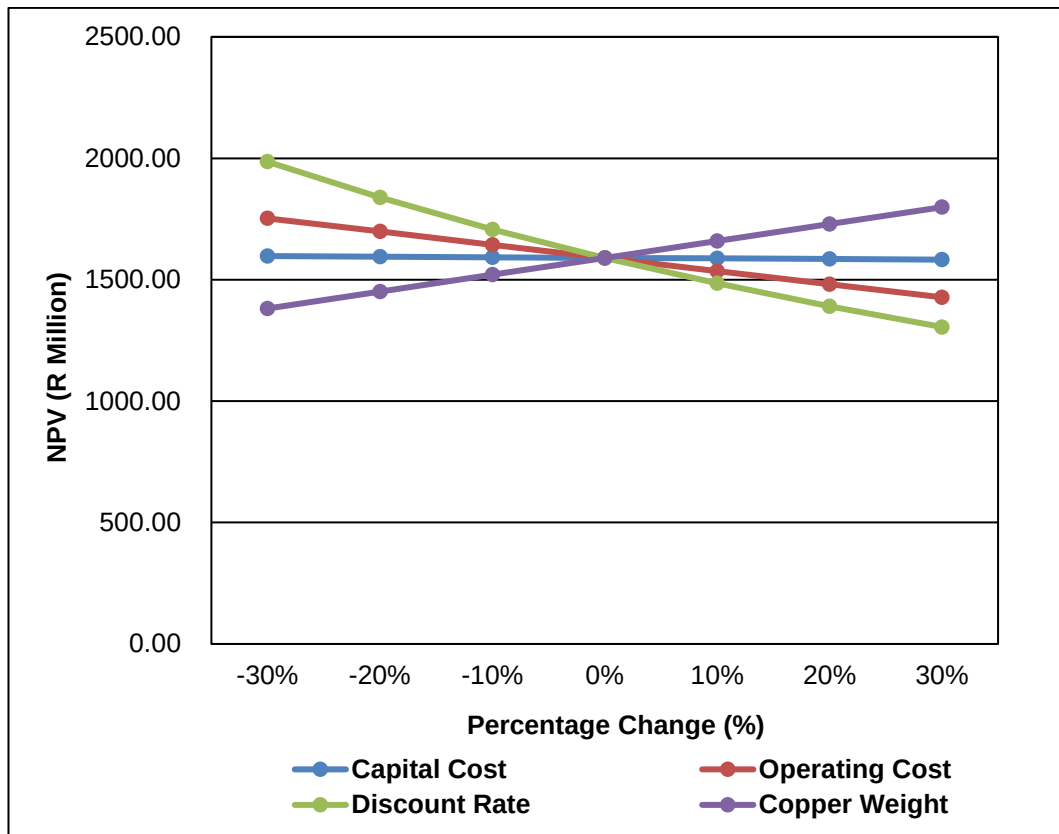


Figure 4.11: Change in NPV with change in economic parameters

4.4.5 Low grade PCBs DCF model

The DCF model results on the low grade PCBs are shown in Table 4.6. The model achieved an NPV of R1 125.78 million and an IRR of more than 200%. The low grade PCBs achieved an NPV that is more than three times lower than that of high grade PCBs. The low grade PCBs show profitability however, large volumes will be required to realise maximum profits. This is because the low grade PCBs generates low value as they yield about 50 g/t. Even in the export market the exporters breakeven because of high shipping costs associated with moving large quantities of low grade PCBs required to generate a profit. Blending of low grade PCBs with either high grade or medium grade PCBs would help offset the costs.

Table 4.6: Predicted Discounted Cash Flow Model for Low Grade PCBs

	Project Year	0	Year									
			1	2	3	4	5	6	7	8	9	10
	Units	Base Year										
Production												
Tonnes of PCBs	Tonnes		3 500.00	3 500.00	3 500.00	3 500.00	3 500.00	3 500.00	3 500.00	3 500.00	3 500.00	3 500.00
Copper Content (at 55.87% by weight)	Metric tonnes	55.87%	1 955.45	1 955.45	1 955.45	1 955.45	1 955.45	1 955.45	1 955.45	1 955.45	1 955.45	1 955.45
Gold Content	kilograms		175.00	175.00	175.00	175.00	175.00	175.00	175.00	175.00	175.00	175.00
Recovery		0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Copper Produced	Tonnes		1 759.91	1 759.91	1 759.91	1 759.91	1 759.91	1 759.91	1 759.91	1 759.91	1 759.91	1 759.91
Gold Produced	kilograms		157.50	157.50	157.50	157.50	157.50	157.50	157.50	157.50	157.50	157.50
Gold price (nominal)	R/g	944.48	993.59	1 045.26	1 099.61	1 156.79	1 216.95	1 280.23	1 346.80	1 416.83	1 490.51	1 568.01
Copper price (nominal)	R/t	126 580.00	133 162.16	140 086.59	147 371.10	155 034.39	163 096.18	171 577.18	180 499.20	189 885.15	199 759.18	210 146.66
Gross Sales Revenue	R million		390.84	411.17	432.55	455.04	478.70	503.60	529.78	557.33	586.31	616.80
Total Operating Costs (at 25% of gross revenue)	R million	25%	97.71	102.79	108.14	113.76	119.68	125.90	132.45	139.33	146.58	154.20
License cost	R million	4.00	4.21		4.66		5.15		5.70		6.31	
Net Sales Revenue (operating profit) before Capex	R million		288.92	308.38	319.75	341.28	353.87	377.70	391.63	418.00	433.42	462.60
Capital expenditure (nominal)	R million	- 40.00										
Unredeemed Capex (nominal)	R million	- 40.00										
Operating Profit before Tax	R million		248.92	308.38	319.75	341.28	353.87	377.70	391.63	418.00	433.42	462.60
Corporate Tax	R million	27.00%	67.21	83.26	86.33	92.15	95.55	101.98	105.74	112.86	117.02	124.90
Actual Cash Flow after Tax	R million		181.72	225.11	233.42	249.13	258.33	275.72	285.89	305.14	316.40	337.70
Discounted Cash Flow	R million	17.60%	154.52	162.78	143.52	130.26	114.85	104.24	91.91	83.41	73.55	66.75
NPV	R million	1 125.78										

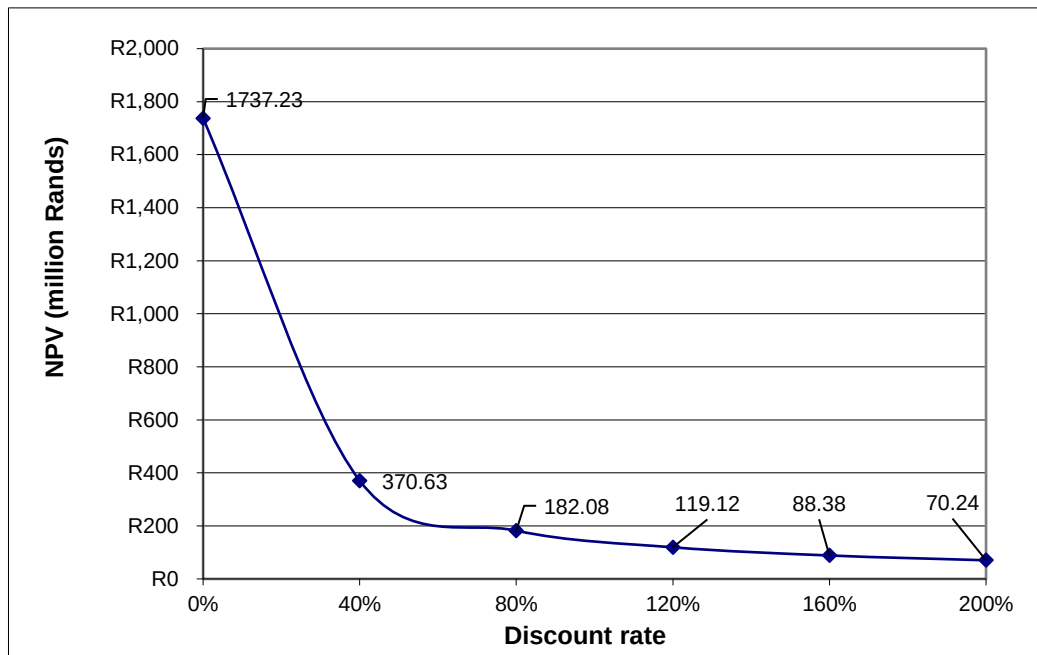


Figure 4.12: NPV versus Discount Rate

It can be noted from Figure 4.12 that up to a discount rate of 200%, an NPV of zero was not obtained. This means for this scenario; the IRR is greater than 200% and also larger than the discount rate (17.6%). A combination of a positive NPV and an IRR greater than the discount rate makes this scenario economically feasible.

4.4.6 Sensitivity analysis – Low grade PCBs

The sensitivity analysis on the low grade PCBs is shown in Figure 4.13. Detailed input table is found in Appendix E (Refining). The maximum and minimum value of NPV in this model is R1 407.41 million and R923.18 million at discount rate - 30% and +30%, respectively. The NPV is most sensitive to the discount rate and copper weight. These are the risks that must be managed by managing the source of capital and grade of the feed material.

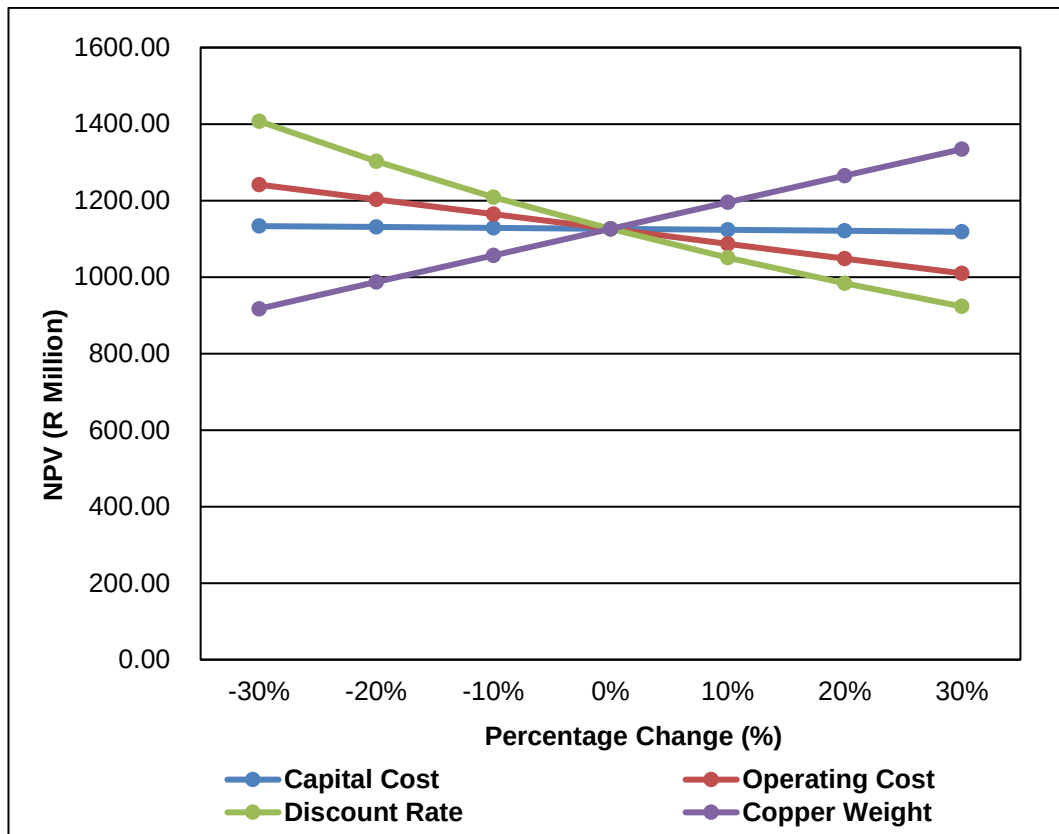


Figure 4.13: Change in NPV with change in economic parameters

4.5 Chapter Summary

This chapter evaluated different DCF scenarios on the high grade PCBs, medium grade PCBs and low grade PCBs. Firstly, the DCF analysis was conducted on the PCBs sent to the export market as a base case. A DCF analysis was also conducted to determine the NPV by incurring additional costs to set up a refining plant to recover metals such as gold metal. Inputs such as PCB prices, operating costs, capital costs, discount rate and production were used in the DCF to determine the NPV and IRR. The NPV and IRR were then used to assess the viability of setting up a refining plant in South Africa. Both high grade and medium grade PCBs had better NPV than the low grade PCBs. This indicated that it is feasible to invest into setting up a refining plant to recover valuable metals from PCBs. However, the low grade PCBs showed a lower NPV that three times lower than that on high grade PCBs. This suggests the blending of low grade PCBs with

higher grade PCBs to achieve maximum returns. The summary and conclusion of the research are presented in Chapter 5, with recommendations for further studies.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The analysis of results was done to provide an overview of the present state of recycling of e-waste in South Africa, particularly the PCBs. A DCF analysis was conducted to calculate the NPV which was then used to evaluate the suitability of setting up a refining plant for the recovery of metals in South Africa. This chapter concludes by listing recommendations together with suggestions for further research.

5.2 Summary

The literature review indicated the benefits of recycling e-waste for the recovery of metals. E-waste stream can help meet the rising demand for valuable and critical metals for the production of EEE. The recycling of this waste stream comes with the benefits of generating revenue, creating job opportunities and reducing the flow of waste into landfill sites polluting the environment.

A cost and benefit analysis using a DCF technique was conducted to first understand the NPV generated by selling the dismantled PCBs into the export market. The NPV was used as a base case to assess the economic viability of setting up a refining plant in South Africa to treat the waste PCBs. Three different grades of PCBs, namely, high grade, medium grade and low grade were used in calculating the NPV. Gold was used as a metal of interest in calculating the NPV.

The DCF results indicated that it is profitable to set up such a plant in South Africa especially for the high grade and medium grade PCBs, even by incurring additional costs of building the plant. However, the low grade PCBs can be supplemented by blending with higher grade PCBs and or by

increasing the throughput to the refining plant. This is because the low grade PCBs have lower metal content of about 50 g/t of gold. The IRR for the project on all the NPV calculations for the high grade PCBs, medium grade PCBs and low grade PCBs indicated that the investment can be made in building a waste PCB refining plant.

5.3 Research Findings

The DCF results on the exporting of PCBs showed a positive NPV on all three different grades of PCBs. The NPV for the high grade PCBs, medium grade PCBs and low grade PCBs are R436.89 million, R319.10 million and R163.83 million, respectively. The results indicate a net positive NPV thus showing the economic feasibility of the project. However, the drop in the grade of gold in the PCB has a huge impact on the net NPV especially on the low grade PCBs. Large volumes of low grade PCBs are therefore required to make up for the low grade of gold in the PCB, which has a direct effect on the total revenue generated.

The DCF results on the option of evaluating the viability of building a refining plant also had a net positive NPV. However, there is a significant drop in the low grade PCBs. The NPV for the high grade, medium grade and low grade are R3 446.85 million, R1 590 million and R1 125.78 million, respectively. By incurring the cost of building a refining plant that can treat about 3 500 tonnes per year, both the high grade and medium grade PCBs still indicate significant present value. The low grade as indicated in the base case shows a net positive NPV, however again large volumes will be needed to achieve maximum returns. The IRR for all the export and refining were all found to more than 200%. This indicates the economic viability of setting up a refining plant in South Africa.

A sensitivity analysis results indicates that the change in economic parameters can negatively impact the profitability of the project. The NPV shows sensitivity to PCBs price and discount rate for export and local refining, respectively. For export, the price of PCBs must be managed, and the management must always have an understanding of the market. The risk on local refining must be managed by managing the source of capital. The results showed a maximum and minimum value of NPV at +30% and -30% PCBs price for the high grade PCBs for export to be R567.98 million and R305.82 million respectively.

The medium grade PCBs for export achieved a maximum and minimum NPV of R382.92 million and R223.37 million. The NPV for the low grade PCBs for export were achieved a maximum and minimum NPV of R212.98 million and R114.68 million at +30% and -30% PCB price respectively. On the other hand, the maximum and minimum NPV's for local refining for high grade PCBs were calculated to be R4 298.46 million at discount rate -30% and R2 833.71 million at discounted rate +30%. The medium grade PCBs achieved a maximum and minimum NPV of R1 985.62 million at -30% discount rate and R1 390.48 million at +30% discount rate. The low grade PCBs achieved a maximum and minimum NPV of R1 407.41 million at -30% discount rate and R923.18 million at +30% discount rate.

5.4 Conclusion

The growing demand for precious and critical metals has provided an opportunity to search for other sources of metals to meet the growing demand. The secondary resource proves to be the much needed source of metals to add to the current metal production from primary resources. An outline of South Africa's e-waste value chain together with the current state of recycling was reviewed in the research. The production volumes were also estimated for the DCF analysis to evaluate the profitability of recovering valuable metals from waste PCBs. A well-structured questionnaire with

open ended questions and interviews were conducted to gather the primary data, supplemented by secondary data.

The NPV of the base case for the three different grades of PCBs shows the profitability of the project. The export PCBs had net positive NPV of R436.89 million, R319.10 million and R163.83 million for the high grade, medium grade and low grade PCBs respectively. The NPV for the option of setting up a refining plant are R3 446.85 million, R1 590 million and R1 125.78 million all achieving an IRR of more than 200% for the high grade PCBs, medium grade PCBs and low grade PCBs respectively. Both the export PCBs and the option of building a refining plant show the profitability of the project. The project is more sensitive to change in price of PCBs and discount rate. The low grade PCBs shows the highest sensitivity because of the low metal content of gold. Blending of low grade PCBs with higher grade PCBs can help achieve maximum returns and offset the sensitivity to price and production change.

5.5 Research Limitations

The recyclers were reluctant to share some of the information like the volume of PCB they produce and sell to the export market, their clients and the revenue they generate as the information was deemed confidential. The other limitation was the limited and lack of quality data on e-waste recycling particularly in South Africa. The grading of different PCBs as in the world, the metal content of different PCBs is only reported in terms of gold content. This was a challenge to estimate other precious metals because with the limited research done on PCBs, different researchers used different types and models of PCB materials which are not comparable and do not present the metal content of other contained metals in different categories of PCBs. Production rate and recovery were assumed to be constant in all the scenarios which might not be a true reflection of what would happen across the years. However, it allowed for easy of comparison. The cash flows and

subsequently NPV and IRR are based on deterministic input assumptions which are subjected to change with time.

5.6 Recommendations

From the study, it is recommended that further study in the amount of PCBs South Africa produce to generate certainty and quality data in the production rates and also study the three different grades of PCBs from different sources of e-waste to determine the grades of other valuable metals contained in PCBs such as silver and palladium. It is further recommended that research is conducted to look into sourcing e-waste from other Southern African Development Community markets (SADC) to improve the economies of scale. There is a need to improve the reliability of input parameters, as such, further research is recommended on accurate volumes of PCBs generated and operating cost estimates. Further cash flow analysis should be conducted using stochastic input parameters.

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APPENDIX A: ETHICS CLEARANCE



SCHOOL OF MINING ETHICS COMMITTEE
CONSTITUTED UNDER THE UNIVERSITY HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)

CLEARANCE CERTIFICATE

PROTOCOL NUMBER: EMINN/2021/05

PROJECT TITLE

Cost-benefit analysis of recovering valuable metals from e-waste in South Africa: An assessment of waste Printed Circuit Board.

INVESTIGATOR

Mr Diketane Mogodiri Clifford

SCHOOL/DEPARTMENT OF INVESTIGATOR

School of Mining

DATE CONSIDERED

21 May 2021

DECISION OF THE COMMITTEE

Approved unconditionally

RISK LEVEL

MINIMAL RISK

EXPIRY DATE

20 May 2024

ISSUE DATE OF CERTIFICATE 26 May 2021

CHAIRPERSON
(Mr H Thomas)

cc: Supervisor: Ms P Neingo & Ms P Twala

DECLARATION OF INVESTIGATOR

To be completed in duplicate and **ONE COPY** returned to the Chairperson of the School/Department ethics committee.

I fully understand the conditions under which I am authorized to carry out the abovementioned research and I guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee.


Signature

Date

12/08/2021

PLEASE QUOTE THE PROTOCOL NUMBER ON ALL ENQUIRIES

APPENDIX B: CONSENT FORM

Consent Form - Interview

Title of project: Financial valuation of recovering valuable metals from e-waste in South Africa: An assessment of waste Printed Circuit Board

Name of researcher: Diketane Mogodiri Clifford

I.....agree to participate in this research project. The research has been explained to me and I understand what my participation will involve. I agree to the following:

(Please circle the relevant options below).

I agree that the interview may be YES NO
audio recorded

I agree that the researcher may use YES NO
anonymous quotes in his / her
research report

I do not wish to be quoted by name,
but only under a generic description
that will keep my identity confidential.

YES NO

I agree that the information I provide YES NO
may be used anonymously after this
project has ended, for academic

purposes by other researchers,
subject to their own ethics clearance
being obtained.

I was provided the opportunity to ask YES NO
questions, and all my questions were
answered.

Name of participant:

Date:

Signature:

Researcher:

Date:

Signature:

APPENDIX C: PARTICIPATION INFORMATION SHEET



Participant Information Sheet - Interview

Dear Sir/Madam,

My name is Diketane Mogodiri Clifford, and I am a Masters student in School of Mining Engineering at the University of the Witwatersrand, Johannesburg. As part of my studies, I have to undertake a research project, which is titled: Financial valuation of recovering valuable metals from e-waste in South Africa: An assessment of waste printed circuit boards (PCB). The research is under the co-supervision of Ms. Paskalia Neingo and Mrs. Pontsho Twala.

As part of this project, I would like to invite you to take part in an interview. The interview will involve answering questions and will take between 30 and 40 minutes of your time. With your permission, I would like to record the interview using a digital audio device.

Kindly note that there will be no personal costs to you if you participate in this research. You will not receive any direct benefits from your participation and there are no disadvantages and/or penalties if you choose to not participate or if you want to withdraw from the research. Kindly note that you

may withdraw from the research at any time, or you may not answer any question(s) if you are not comfortable. The interview will be kept confidential. I will not be asking for your name or any identifying information. The information you give to me will be held securely and not disclosed to anyone. The responses from the interviews will be aggregated to maintain individual confidentiality. If given permission, I will use generic description to represent your participation in my final research report. The request is included in the consent form. If you experience any distress and/or discomfort at any point during the interview, the interview will be stopped and rescheduled for another time when you are available.

If you have any questions during or afterwards about this research, feel free to contact me on the details provided below. This research will be written up as a research report which will be available online through the University's library website. If you wish to receive a summary of this report, I will be happy to send it to you. With your permission, the data collected from this research project may be used by other researchers. This is included in the consent form. If you have any concerns or complaints regarding the ethical procedures of this study, you are welcome to contact the University Human Research Ethics Committee (Non-Medical), telephone +27(0)11 717 1408, email hrecnon-medical@wits.ac.za

Yours sincerely,

Diketane Mogodiri Clifford

Researcher:

Diketane Mogodiri Clifford, 375698@student.wits.ac.za

Supervisors:

PaskaliaNeingo, paskalia.neingo@wits.ac.za, 011 717 7445

PontshoTwala, pontsho.ledwaba@wits.ac.za, 011 717 7429

APPENDIX D: QUESTIONNAIRE

QUESTIONNAIRE

Date of the interview						
Designation						
Name of the organisation						
Years in operation						
Participation in the e-waste value chain (tick)	Collection	Dismantling	Pre-processing	Processing	Export market	Domestic market
QUANTITATIVE DATA INPUTS						
What are the volumes of PCBs generated annually?						
What are the feed and product grades?						
How do companies involved in the recovery of PBCs estimate different grades of PBCs.						
What are the production volumes/trends?						
What are the exports volumes?						
What are the processing costs?						
What are the volumes of e-waste send to landfills?						

How much do companies involved in the recovery of PBCs fetch in the export market?	
What are the companies currently involved in re-cycling of e-waste and stages of value chain involved in?	
QUALITATIVE DATA INPUTS	
What are the challenges in the estimation and collection of e-waste?	
What are the challenges in the dismantling stage of the value chain?	
What are the challenges in the pre-processing stage of the value chain?	
What are the challenges in the processing stage of the value chain?	
What should be done to improve production from e-waste?	
What opportunities exist in the e-waste industry in South Africa?	
What is the current legislation governing e-waste in South Africa?	
Does the legislation support the expansion of e-waste recycling in South Africa?	
What programmes have been implemented to support e-waste recycling in South Africa?	

What government interventions are required to unlock potential business opportunities and support organizations involved in the recycling of e-waste in South Africa?	
Reasons for the export of PCB fractions to the export market?	

APPENDIX E: SENSITIVITY ANALYSIS

Export

Sensitivity Area	High Grade			Medium			Low		
	Percentage Change		NPV Million (R)	Percentage Change	Cost (R)	NPV Million (R)	Percentage Change	Cost (R)	NPV Million (R)
PCBs Price (R)	-30%	R 28 000.00	R 305.82	-30%	R 21 000.00	R 223.37	-30%	R 10 500.00	R 114.68
	-20%	R 32 000.00	R 349.51	-20%	R 24 000.00	R 255.26	-20%	R 12 000.00	R 131.07
	-10%	R 36 000.00	R 393.20	-10%	R 27 000.00	R 287.19	-10%	R 13 500.00	R 147.45
	0%	R 40 000.00	R 436.89	0%	R 30 000.00	R 319.10	0%	R 15 000.00	R 163.83
	+10%	R 44 000.00	R 480.58	+10%	R 33 000.00	R 351.01	+10%	R 16 500.00	R 180.22
	+20%	R 48 000.00	R 524.27	+20%	R 36 000.00	R 382.92	+20%	R 18 000.00	R 196.60
	+30%	R 52 000.00	R 567.96	+30%	R 39 000.00	R 414.83	+30%	R 19 500.00	R 212.98
Operating Cost/ Year	-30%	17.50%	R 480.58	-30%	17.50%	R 353.42	-30%	R 9 187 500.00	R 180.22
	-20%	20.00%	R 466.02	-20%	20.00%	R 341.98	-20%	R 10 500 000.00	R 174.76
	-10%	22.50%	R 451.45	-10%	22.50%	R 330.54	-10%	R 11 812 500.00	R 169.30
	0%	25.00%	R 436.89	0%	25.00%	R 319.10	0%	R 13 125 000.00	R 163.83
	+10%	27.50%	R 422.33	+10%	27.50%	R 307.66	+10%	R 14 437 500.00	R 158.37
	+20%	30.00%	R 407.76	+20%	30.00%	R 296.22	+20%	R 15 750 000.00	R 152.91
	+30%	32.50%	R 393.20	+30%	32.50%	R 284.78	+30%	R 17 062 500.00	R 147.45
Discount Rate (%)	-30%	12.32%	R 544.18	-30%	12.32%	R 399.16	-30%	12.32%	R 204.07
	-20%	14.08%	R 504.25	-20%	14.08%	R 369.35	-20%	14.08%	R 189.09
	-10%	15.84%	R 468.68	-10%	15.84%	R 342.81	-10%	15.84%	R 175.76
	0%	17.60%	R 436.89	0%	17.60%	R 319.10	0%	17.60%	R 163.83
	+10%	19.36%	R 408.38	+10%	19.36%	R 297.85	+10%	19.36%	R 153.14
	+20%	21.12%	R 382.75	+20%	21.12%	R 278.74	+20%	21.12%	R 143.53
	+30%	22.88%	R 359.62	+30%	22.88%	R 261.51	+30%	22.88%	R 134.86

Refining

Sensitivity Area	High Grade			Medium			Low		
	Percentage Change		NPV Million (R)	Percentage Change	Cost (R)	NPV Million (R)	Percentage Change	Cost (R)	NPV Million (R)
Capital Cost	-30%	R 28 000.00	R 3 454.30	-30%	R 21 000.00	R 1 597.44	-30%	R 10 500.00	R 1 133.23
	-20%	R 32 000.00	R 3 451.82	-20%	R 24 000.00	R 1 594.96	-20%	R 12 000.00	R 1 130.75
	-10%	R 36 000.00	R 3 449.33	-10%	R 27 000.00	R 1 592.48	-10%	R 13 500.00	R 1 128.26
	0%	R 40 000.00	R 3 446.85	0%	R 30 000.00	R 1 590.00	0%	R 15 000.00	R 1 125.78
	+10%	R 44 000.00	R 3 444.37	+10%	R 33 000.00	R 1 587.51	+10%	R 16 500.00	R 1 123.30
	+20%	R 48 000.00	R 3 441.89	+20%	R 36 000.00	R 1 585.03	+20%	R 18 000.00	R 1 120.82
	+30%	R 52 000.00	R 3 439.40	+30%	R 39 000.00	R 1 582.55	+30%	R 19 500.00	R 1 118.33
Operating Cost/ Year	-30%	17.50%	R 3 794.90	-30%	17.50%	R 1 752.36	-30%	17.50%	R 1 241.72
	-20%	20.00%	R 3 678.88	-20%	20.00%	R 1 698.24	-20%	20.00%	R 1 203.08
	-10%	22.50%	R 3 562.87	-10%	22.50%	R 1 644.12	-10%	22.50%	R 1 164.43
	0%	25.00%	R 3 446.85	0%	25.00%	R 1 590.00	0%	25.00%	R 1 125.78
	+10%	27.50%	R 3 330.84	+10%	27.50%	R 1 535.88	+10%	27.50%	R 1 087.14
	+20%	30.00%	R 3 214.82	+20%	30.00%	R 1 481.76	+20%	30.00%	R 1 048.49
	+30%	32.50%	R 3 098.80	+30%	32.50%	R 1 427.63	+30%	32.50%	R 1 009.84
Discount Rate (%)	-30%	17.50%	R 4 298.46	-30%	17.50%	R 1 985.62	-30%	17.50%	R 1 407.41
	-20%	20.00%	R 3 981.46	-20%	20.00%	R 1 838.35	-20%	20.00%	R 1 302.56
	-10%	22.50%	R 3 699.17	-10%	22.50%	R 1 707.19	-10%	22.50%	R 1 209.20
	0%	17.60%	R 3 446.85	0%	17.60%	R 1 590.00	0%	17.60%	R 1 125.78
	+10%	27.50%	R 3 220.64	+10%	27.50%	R 1 484.94	+10%	27.50%	R 1 051.02
	+20%	30.00%	R 3 017.21	+20%	30.00%	R 1 390.48	+20%	30.00%	R 983.80
	+30%	32.50%	R 2 833.71	+30%	32.50%	R 1 305.29	+30%	32.50%	R 923.18
Copper Weight	-30%	39.11%	R 3 238.31	-30%	39.11%	R 1 381.45	-30%	39.11%	R 917.24
	-20%	44.70%	R 3 307.86	-20%	44.70%	R 1 451.01	-20%	44.70%	R 986.80
	-10%	50.28%	R 3 377.30	-10%	50.28%	R 1 520.44	-10%	50.28%	R 1 056.23
	0%	55.87%	R 3 446.85	0%	55.87%	R 1 590.00	0%	12.00%	R 1 125.78
	+10%	61.46%	R 3 516.41	+10%	61.46%	R 1 659.55	+10%	61.46%	R 1 195.34
	+20%	67.04%	R 3 585.84	+20%	67.04%	R 1 728.98	+20%	67.04%	R 1 264.77
	+30%	72.63%	R 3 655.39	+30%	72.63%	R 1 798.54	+30%	72.63%	R 1 334.32