

Major Project – Exploring the Viability and Effectiveness of the Royal Mint's E- waste Diversification Strategy in Response to the Decline of Circulation Coinage (ACFA7003)

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I. Executive Summary

In recent years, The Royal Mint (TRM) has made strides towards becoming more environmentally conscious, including developing an e-waste plant aimed at recovering gold from electronic waste. The project involved building a facility that would utilize cutting-edge technology to extract precious metals from discarded electronic devices. The goal was to not only generate revenue for the Royal Mint but also reduce the amount of electronic waste that ends up in landfills.

The project was initiated several years ago when The Royal Mint realised the potential for gold recovery from electronic waste. With the increasing prevalence of technology, discarded electronics were quickly becoming a significant source of environmental waste. TRM saw an opportunity to not only reduce this waste but also extract valuable resources that could be used in the production of new products.

The e-waste plant is to be designed using a proprietary solution developed by TRM and their technology partner Excir. The technology is intended to be more efficient, more environmentally friendly, safer to use and more effective than traditional methods of gold recovery from electronic waste.

The initial lab scale results show that technologically, the concept is promising, with the solution (lixiviant) successfully extracting gold from electronic waste quickly, selectively and efficiently when compared to other known methods.

A number of risks to the project have been highlighted, the most concerning is the development of printed circuit board (PCB) technology. Manufacturers are intending on moving away from precious metals due to the unpredictable market and high associated costs. Other risks including environmental permits, scaling and feedstock still exist.

From this report, it has become apparent that the project may not become profitable. This can be attributed to the high resource costs, raw materials and processing costs associated with the plant's operation. The recovery of additional base metals and precious metals in phase two of the project will help to increase profitability, this phase should commence as soon as economically and technologically viable.

Despite the uncertainty highlighted, TRM is committed to the project. There is a belief internally that being first to market will attract custom, allowing further development and improvement of the process to take place, hopefully reducing the cost and making the project profitable.

II. [Statement regarding copyright](#)

Declaration Statement: Alex Collier

I certify that this is all my own work and that all other sources of information, data, images etc. have been acknowledged and referenced. This work has not been previously accepted in substance for any other degree and is not being concurrently submitted in candidature for any other degree.

Signed: 

Date: 28th of February 2023

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VI. [List of Abbreviations](#)

WEEE – Waste Electrical and Electronic Equipment

TRM – The Royal Mint

EEE – Electrical and Electronic Equipment

PCB – Printed Circuit Board

Ag – Silver

Au – Gold

PM – Precious Metals

TV – Television

RAMM - Random Access Memory Modules

BML – Base Metal Leach

PML – Precious Metal Leach

AATF - Authorised Approved Treatment Facility

LCD – Liquid Crystal Display

UNEP – The United Nations Environment Programme's

CSR – Corporate Social Responsibility

GM – General Motors

CA – Competent Authority

COMAH – Control of Major Accident Hazards

NRW – Natural Resources Wales

BATRRT - Best Available Treatment, Recovery and Recycling Techniques

R&D – Research and Development

CPs – Conductive Polymers

SHE – Safety, Health and Environment

RME – Royal Mint Experience

Kg - Kilogram

1.0 Context of study

This research focusses on a major innovation in the precious metals (PM) and the waste electrical and electronic equipment (WEEE) recycling industry. The research will include how The Royal Mint (TRM) are attempting to secure their future by disrupting the PM market, using a novel metal recovery technology. In doing so, TRM are making a significant impact on one of the world's greatest environmental challenges today and in the future. The author will evaluate the whole of the new value stream, from WEEE, through to final product and potential application.

1.1 Problem

For over 1100 years, The Royal Mint has created circulation coinage for the United Kingdom and many other countries around the world. In developed nations around the globe, cash transactions are decreasing. In 2021, just 15% of all payments in the UK were cash transactions, this is forecast to continue declining (UK Finance, 2022). To ensure continuous operations at TRM, the organisation is diversifying the products and services that it provides, including jewellery and luxury collectibles (886), historic coins and financial services.

For production, The Royal Mint requires raw materials including gold, platinum, palladium, silver and base metals such as copper and nickel. As, over the long term, the availability of these materials from virgin sources will reduce and prices are likely to increase. TRM is seeking to invest in the recovery of these materials from waste resources.

For the first phase of this project, TRM are only looking to recover gold. To assist TRM with this, the organisation is working with a third party, named Excir.

1.2 Aim

The aim of this report is to look at TRM's suggested route for e-waste recycling in order to collect precious metals, although, phase one (1) of the project is primarily focussed on gold. This new process aims to extract gold from discarded electronics in a more efficient and eco-friendly manner. However, before we can assess the feasibility of this proposed solution, it's important to understand the current state of e-waste recycling and the competition in the industry.

The existing process for e-waste recycling involves crushing and burning the discarded electronics to extract the metals. This method is not only inefficient, but it also releases harmful chemicals into the environment, posing a risk to both human health and the ecosystem.

Several competitors already exist in the e-waste recycling industry. These companies use various methods to extract PM from e-waste, such as pyrometallurgy, hydrometallurgy, and biometallurgy.

TRM's proposed route for e-waste recycling involves a combination of chemistry and electrolysis to extract gold. This process is expected to be more efficient, eco-friendly, and cost-effective than the existing methods. However, there are still potential risks involved.

This report aims to determine whether this novel process is technologically, economically, financially and commercially viable.

1.3 Objectives

- To evaluate the technological feasibility of the novel e-waste recycling process and assess whether it can be implemented on a large scale.
- To analyse the financial viability of the new process, including the cost of materials, labour, and equipment required, as well as the potential revenue from extracted gold.
- To assess the efficiency of the new process compared to existing e-waste recycling methods and evaluate whether it can provide a competitive advantage in the industry.
- To identify potential risks and challenges with the new process.
- To explore potential market demand and consumer preferences for eco-friendly and sustainable e-waste recycling processes.

1.4 Justification

With the decline of circulation coinage globally, TRM has had to seek new opportunities in new markets wherever a gap is identified.

As a consumer and retailer of precious metals TRM have decided to commence with a project to recover gold from WEEE sustainably. In 2022, TRM manufactured 3000 kilograms (kg) of gold products. In addition, there is continued environmental, corporate, social responsibility of being a government owned business, TRM must ensure that they are working to the highest standards to achieve targets set out by the owners.

The PM market, as per any other market is subject to fluctuations and can be unstable for a variety of reasons, such as:

- Market conditions - inflation/ interest rates
- Political and Geopolitical events - Political tensions/ geopolitical risks
- Supply and demand – Consumer behaviour/ mining production increase or decrease
- Currency movements – Exchange rates/ currency value

By recovering PM sustainably, TRM are hoping to secure supply at a more fixed price, whilst creating a market for dealing with WEEE in a responsible way.

2.0 Introduction

2.1 History of The Royal Mint

The Royal Mint (TRM) is a Limited Company, wholly owned by His Majesty's Treasury. It holds the exclusive contract to supply the UK's coinage. The Royal Mint also exports to an average of 60 countries a year, making up 70% of its total sales. Formed over 1,100 years ago, TRM was historically part of a series of mints producing coinage (Clancy, 2016). These became centralised in 1968 at the new plant in Llantrisant, Wales. As well as minting coins for domestic and international use, TRM also produces blanks (planchets), commemorative coins, medals and precious metal bullion.

Since 2009, when TRM ceased being an executive government agency and became a limited company, the business has expanded its business interests by reviving its bullion trade and developing a £9 million visitor centre. This is in part, driven by a forecast reduction in global coin usage. TRM has been looking for new business opportunities aligned to its core skills in metallurgy, bullion, jewellery and currency production.

The organisation have been presented with an opportunity by Excir, a Canadian organisation that have developed a patented technology that is capable of recovering gold from e-waste quickly and efficiently. The Royal Mint (2023) has partnered with this innovative company to further develop this process, providing brand new facilities and resources to recover PM at the site in Llantrisant.

2.2 Driver for innovation

It has been recognised that virgin materials required to continue operations are becoming both scarce and ever more expensive. With the decline of circulation coinage, TRM have been working with academic institutions and organisations, to diversify, using knowledge, equipment and resources already available. TRM have identified a process to recover these materials from waste resources.

These materials will be recovered, then re-manufactured to create a new product at TRM, mostly for the 886 luxury goods range, thus, ensuring continued operations for the organisation.

TRM had an opportunity presented to them by a Canadian organisation called Excir. Excir have been developing a similar process for the recycling of e-waste, to remove all valuable materials and deal with remaining waste responsibly.

The development work that has been completed by Excir to date is a significant starting point for TRM to continue maturing this technology. Once the process is finalized, there may be further opportunities to licence the advanced process to other organisations.

2.3 Introduction to WEEE

WEEE stands for Waste Electrical and Electronic Equipment and can also be referred to as e-waste. WEEE refers to any electrical or electronic equipment that has reached the end of its life and is being discarded. Examples of WEEE include computers, televisions, cell phones, refrigerators, and other household appliances, basically, anything with a battery or a plug. In the United Kingdom, the WEEE regulations are a set of rules aimed at reducing the environmental impact of electronic waste by encouraging the collection, treatment, and recycling of discarded electronic equipment.

According to Dalrymple et al (2007) e-waste is the fastest growing waste stream on the planet. The United Nations (2019) claim that as much as fifty (50) million tonnes of e-waste is generated annually, with recycling rates as low as 20%. This is the total waste, not the mass of valuable circuit boards.

WEEE is considered hazardous, as it contains toxic heavy metals and brominated flame retardants (BFR), this poses a risk to human health and the environment (Song and Li, 2014).

According to the House of Commons environmental audit committee (2020), The UK creates the second highest amount of e-waste in the world, sending 40% of this overseas. In the countries that receive our electronic waste, it is often dumped, with toxic chemicals leaching into the environment and harming people. This is illegal.

2.4 Printed circuit board (PCB)

The printed circuit board (PCB) is a crucial component in electronic devices, serving as the main connecting and supporting element for other electronic parts such as resistors, capacitors, and integrated circuits. It can be found in almost every type of electronic product (Duan et al, 2011). The basic structure of a PCB is a copper-clad laminate made up of a mixture of glass-reinforced epoxy resin and various metallic materials, including base metals and precious metal (Ghosh et al, 2015). The typical make-up of a medium grade PCB can be seen in Table 1.

Element	PCB Content Range		Medium Grade Board –
	From		Typical Content To
Copper	10%	28%	23%
Tin	2%	6%	4%
Iron	1%	25%	4%
Aluminium	2%	10%	3%
Zinc	0%	2%	0.5%
Lead	0%	3%	0%
Nickel	0%	0.3%	0.1%
Chromium	0%	0.3%	0%
Cadmium	0%	0.1%	0%
Antimony	0%	0.05%	0.01%
Silver	100ppm	5000ppm	800ppm
Gold	5ppm	1000ppm	150ppm
Palladium	1ppm	50ppm	25ppm
Platinum	<1ppm	3ppm	1ppm
Co, Ge, In, Ir, Nb, Nd, Rh, Ru, Sb, Se, Ta, W, Y			traces
Total Metals			~35%
BALANCE			
Epoxy Resin			~35%
Glass Fibre			~24%
BFR*			~6%

*BFR – Brominated Fire Retardant, usually Tetra-bromine-bis-phenol-A

Table 1 - Typical medium grade printed circuit board make up

PM are used to prevent surface corrosion in circuit board componentry due to their inert nature; they will not oxidise under normal environmental conditions. Gold (Au) is seen as the more noble metal, however, Silver (Ag) is the best conductor, is cheaper, but more reactive. According to HSE (2023), cooling appliances and large household appliances account for more than 40% of the weight of electrical and electronic equipment (EEE) placed on the market, however the circuit boards in them tend to contain very little gold. A higher concentration of gold is found in equipment designed for high reliability and use in rugged environments. Computer equipment is an obvious example where gold plating tends to be used on contact surfaces such as board edge connectors and connector pins & sockets. Mobile phones are designed to function in what most electronics would find to be hostile

operating conditions; continually bumped and banged about. For this reason, their circuit boards are generally heavily gold plated.

Due to the variation in PM content, PCBs are graded accordingly.

2.4.1 Low grade PCB



Figure 1 - Low grade PCB (5g - 80g Au per tonne (Au/t))

The category of low-grade boards is fairly broad combining post Pentium III technology, switch mode power supplies from more modern equipment, component-through-board power circuits from old small appliances and cathode ray tube television (TV) PCBs. Typical, one would expect to see between 5g to 80g Au/t and 20 to 30% copper.

2.4.2 Medium grade PCB



Figure 2 - Medium grade PCB (150g - 400g Au per tonne (Au/t))

Medium-grade pin-connector boards, often found in networking equipment. Each may have one or two connector modules each with a set of gold-plated pins inside a plastic enclosure. Tracked boards are also considered medium grade, with a maximum gold content of 400 g Au/t.

2.4.3 High grade PCB



Figure 3 - High grade PCB (700g - 7000g Au per tonne (Au/t))

Gold edged Random Access Memory Modules (RAMM) typically contain between 700g and 1500g of Au/t, with significant amounts of palladium (Pd) also present. Very high grade gold CPUs, early Pentium range and equivalents are extremely rare, but can yield 7000g Au/t.

2.4.4 Typical market pricing

Circuit boards are generally sold on a tel quel basis, or 'as is/ as seen' .When selling circuit board material, it is accepted good practice to roughly separate value ranges from each other and sell as individual lots. This allows tel quel sellers and buyers to have a better idea of the transaction metal contents.

Completing a market search of various operators, it was found that the average tel quel pricing is as in Table 2. The results of the search are displayed as a comparison against expected smelter returns for twenty (20) tonnes lot sizes.

	Tel quel pricing	Assay	Expected Smelter Return
High grade memory	£15-22 per Kg	800g Au/t	£32 per Kg
High medium grade	£4.50 to £6.00 per Kg	200g Au/t	£8.90 per Kg
Low medium grade	£1.80 to £3.25 per Kg	100g Au/t	£4.46 per Kg
Low grade	£300 per tonne	30g Au/t	£993 per tonne

Table 2 - Comparison of pricing against smelter return

From the table, it can be seen that buyers (smelters) are currently looking to make a margin of 50 to 100% of their cost price for high grade material and around 200% for very low-grade material.

Broken down further, the value of the PM contained within PCBs can be seen in Table 3.

Circuit Board Example	Low grade	Med Grade	Med-high grade	High grade
Value of Au, Ag, & Pd contained in 1kg of PCB's	£2.00	£7.00	£10.00	£24.00
Return as % of total value	42%	73%	80%	89%

Table 3 - E-waste grade and PMs contained within

2.5 Gold and precious metals

Gold along with silver and the platinum group metals (platinum, palladium, osmium, rhodium, ruthenium and iridium) are a group of elements that are known as 'precious metals' due to their rarity, unique properties, and high economic value.

Historically, utilisation of these materials beyond jewellery, coins, and bullion, has been limited (Corti, 2021). More recently, new applications have been found which make use of their chemical and physical properties. Electronics is just one industry that has capitalised on the use of PM. Gold is widely used throughout the industry for excellent conductivity for both electricity and heat, without being tarnished when exposed to air and/or moisture (Chen et al, 2013). Due to the recyclability, this creates what is known as secondary sources, rather than only natural source availability.

Gold has further unique properties, including ductility and malleability making it easy to form into foil sheets and wires. Gold is also highly resistant to oxidation and corrosion, this is attributed to gold having the lowest electrochemical potential among all metals in the periodic table.

In the year 2022, gold mining production reached 3611 tonnes increasing 1% from the previous year. Whilst from secondary sources such as jewellery and electronic scraps, a further 1144 tonnes was recovered (World Gold Council, 2023).

3.0 Gold extraction

3.1 Industry methods used for gold extraction

Gold extraction from ore has been a critical and economically significant process for thousands of years. With the increasing demand for gold and its widespread use in various

industries, the extraction and recovery of gold from ores has become increasingly important. There are several processes used for gold extraction from ore, including cyanide leaching, gravity separation, flotation, roasting, and smelting. In addition, the increasing issue of waste electronic and electrical equipment (WEEE) has led to the development of chemical leaching methods for the recovery of gold from WEEE.

Gold occurs mainly as native metal, alloyed with silver and/or other metals, and as tellurides.

3.1.1 Cyanidation

Cyanidation or cyanide leaching, is the most commonly used process for gold extraction from ores state Konyratbekova et al (2014). This hydrometallurgical method is used as a result of availability, economics and effectiveness (Bio intelligence service, 2010). In this process, metallic gold is oxidised and dissolved in an alkaline sodium cyanide solution. When gold dissolution is complete, the gold-bearing solution is separated from the solids.

Flemming (1992) claims that high grade ores (greater than 20 grams of gold per tonne of ore), the process is completed by vat leaching or agitation leaching, which involves holding a slurry of ore and solvent in large tanks equipped with agitators for anywhere between twenty-four (24) to seventy-two (72) hours.

The cyanidation method is also used in gold recovery from WEEE. The method involves using a cyanide solution to dissolve the gold from the e-waste, which can then be recovered by various means such as precipitation or electrowinning.

When extracting from lower grade ores, heap leaching is practiced. Large heaps are sprayed with a dilute solution of sodium cyanide, and this percolates down through the piled ore, dissolving the gold (World Gold Council, 2023). This process is inexpensive to complete. Although, complete extraction of the gold may be missed, this is attributed to the leach liquor not contacting the precious metal.

Rules for the safe and responsible use of cyanides are well documented in the international Cyanide Code (2016). Sodium cyanide is a rapidly acting poisonous compound to humans and aquatic life if ingested. Exposure to high levels of cyanide for a short time harms the brain and heart, and can even cause coma and death. A number of environmental accidents and incidents have occurred around the world from the gold recovery processes (Syed, 2012). Some of these can be seen in Table 4. (Bio intelligence service, 2010), (Anane, 2001) (Mazzeo, 2015).

Mine	Date	Impact
Veladero, Argentina	2015	1,072 cubic meters of cyanide solution reached the Potrerillos River due to a valve failure
Mount Polley, Canada	2014	10 million cubic meters of water and 4.5 million cubic meters of toxic slurry being spilled
Ahafo, Ghana	2009	Overflow of process solution containing sodium cyanide occurred. This resulted in water contamination and fish mortality.
Baia Borsa, Romania	2000	22,000 tonnes of tailings contaminated by heavy metals released
Baia Mare, Romania	2000	100,000 m ³ cyanide contaminated water with some tailings released
Los Frailes, Spain	1998	4-5 million cubic meters of toxic tailings slurries released
Stava, Italy	1985	269 deaths, tailing flowed up to 8km

Table 4 - Serious accidents worldwide from gold processing industry

3.1.2 Cyanide alternatives

A number of alternatives to cyanidation are available, although commercially, only the two following lixivants are established and considered realistic (Cui and Zhang, 2008). This is attributed to chemistry complexity and level of research completed.

3.1.2.1 Thiosulfate leaching

Thiosulfate is a chemical widely used in the pharmaceutical industry and has been proposed by a number of authors as a substitute for cyanide (Huang et al, 2022) (O'Reilly, 2002).

O'Reilly (2002) completed successful experiments using this method, resulting in a stable gold complexes being formed. Huang et al (2022) compared the thiosulfate method to the Aqua regia digestion method. They found that the thiosulfate leaching could be commercialised for removing gold from e-waste from a financial stand point. However, the authors also remark that the process is difficult and slow acting, among other concerns such as risk to health.

Cui and Zhang (2008) disagree and state that the thiosulfate process is neither simple nor affordable despite the environmental benefit. It is claimed that the largest issue with the process is that it consumes huge quantities of reagents to ensure the leaching reaction continues.

3.1.2.2 Thiourea leaching

Ghosh et al (2005) claim that thiourea, just as thiosulfate leaching is a reasonably slow process and requires further development before becoming commercially available.

Thiourea is expensive and like the thiosulfate process, consumes reagent quickly, leading to cost increases to ensure maximum yield.

Behnamfard et al (2013) completed experiments using this process, achieving just 86% extraction of gold following a three (3) hour leach period of PCBs. Unfortunately, also complexed within the solution was large amounts of base metals. Further processing is required to remove these impurities.

Huang et al (2022) compared the thiourea leaching to both thiosulfate leaching and aqua regia digestion methods. It was found that the thiourea process was significantly less efficient than the previously mentioned processes. It was also found to contain high amounts of base metals, particularly copper.

3.1.3 Recovery of gold from secondary sources

The recovery of metals from WEEE can be achieved through a variety of treatments, including physical, chemical, and biological processes. According to Dimitrijevi et al (2013), WEEE and other secondary sources are significantly richer in gold than the sources of the primary ores today.

3.1.3.1 Aqua Regia

Aqua regia is a combination of nitric acid and hydrochloric acid. It is made by mixing one (1) volume of concentrated nitric acid with four (4) volumes of concentrated hydrochloric acid. Both acids, especially hydrochloric emit acrid fumes. No heat is evolved when mixing but the aqua-regia will emit chlorine gas, which evolves slowly for several days. Concentrated aqua regia is an extremely hazardous chemical and is considered an oxidiser, corrosive and a poison, as well as liberating toxic gas (Pertan Materials, 2010).

The aqua regia process typically takes three (3) steps.

- De-population of the circuit boards, must be completed. This can be achieved either chemically or mechanically.
- Dissolution of metals then occurs when aqua regia is added to the WEEE. The aqua regia is commonly heated to further facilitate dissolution of metals.
- Separation of metals can then occur using a number of techniques including precipitation or electrowinning.

In a study complete by Sheng and Etsell (2007), it was found that temperature is the greatest variable for this process. At 90°C, gold dissolution is complete in under thirty (30) minutes.

3.1.3.2 Smelting

Smelting is a process of extracting a metal from its ore or waste materials by heating it to a high temperature, so that the metal and its impurities can be separated. Smelting is a pyrometallurgical process and is the conventional method for recovering metals from PCBs, with up to 80% of PCBs being treated in this way. This method it is not suitable for selectively extracting individual metals in one process (Ghosh et al, 2015).

Sum (1991) describes how the smelting operation is often completed in the presence of selective gases, which have characteristics to allow for the recovery of non-ferrous metals.

The recovery of PM typically involves multiple steps (Marra, et al, 2018):

- Collection and sorting: The first step involves collecting electronic waste and sorting it into different types of materials. This helps to separate the different metals and make it easier to process each type of material.
- Pre-treatment: The next step involves pre-treating the waste materials, which can involve shredding, grinding, or breaking down the materials into smaller pieces.
- Leaching: In this step, a chemical solution is applied to the waste materials to dissolve the metals. The solution is then filtered to remove any impurities and the metal-rich solution is collected.
- Smelting: The metal-rich solution is then subjected to smelting, in which the metals are separated from the solution through heating (approximately 1200°C). The impurities are burned off and the metal is left in an alloyed form.
- Refining: The final step involves refining the metal to remove any remaining impurities. This can involve several processes such as electrorefining, precipitation, or distillation.

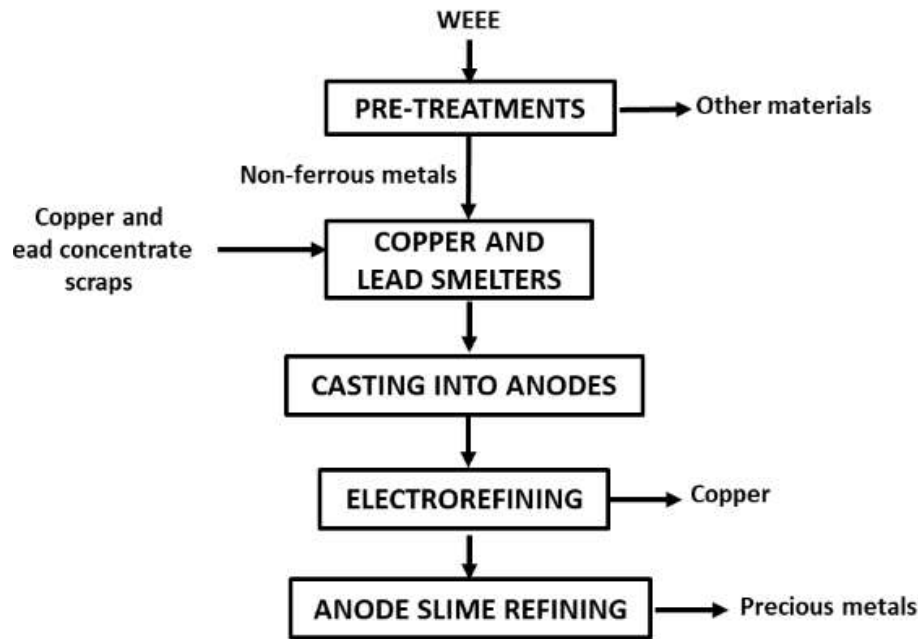


Figure 4 - Flowchart of WEEE smelting operation to recover gold (Marra et al, 2018)

This pyrometallurgical method has the disadvantage of producing pollution and using a lot of energy during the process. To address this, e-waste recycling facilities often have extensive emission control systems in place to protect the environment. With vacuum pyrometallurgy, metals with different boiling points can be separated through distillation or sublimation, and then recovered by condensation under specific conditions (Zhan and Xu, 2009). This method, known as vacuum metallurgy separation (VMS), has been used to recover heavy metals such as bismuth, antimony, lead, and others with high vapour pressures (Zhan and Xu, 2011).

3.1.3.3 Other novel technologies (main competitors)

Following extensive research, and are the most likely competitors for TRM using novel technologies.

Novel Refiner	Development stage	Full PM recovery	Hydro or Pyro	Risks/Concerns
EnviroLeach	Commercial	No	Hydro	Costly Iodine based electro-chemical process. Only 87% recovery, with questions on chemical stability
Ronin-8	Scale up	No	Hydro	Very expensive sonic chamber for separation. End product still shipped to smelter for recovery
Advanced Chemical Company	Commercial	No	Hydro	Uses toxic cyanidation process. Old inefficient technology

UWin Nanotech Co	Small Commercial	No	Hydro	The chemistry is not selective. Probably only economical for high grade PCBs
Mint Innovations	Commercial	Yes	Hydro	The use of concentrated chemistries and handling of live microbes. Risk of gas liberation
Excir (TRM partner)	Scale up	Yes	Hydro	Chemistry is extremely flammable at low (40°C) temperatures. Any loss of pregnated solution will be costly

Table 5 summarises the findings.

Ronin 8 – This organisations current system is designed and optimized to process printed circuit boards as their main feed stocks. First, the PCBs are shredded to a specific particle size which then the suspended material is circulated in recycled water through a specific sonic chamber, this liberates metals from non-metals. Upon completion of this, metals and non-metals are separated into different streams of concentrates. The unseparated material is recirculated in the sonic liberation circuit until separation becomes possible. The separated metal and non-metal concentrates are de-watered and dried to prepare for downstream processing (Ronin8 Technologies, 2018).

This is a very efficient process for removing metals and polymers from PCBs. Although, the core technology is a very expensive sonic chamber. Another limitation to this technology is the final product (metal concentrate) would require shipment to a smelter in order to extract the main value from processed e-waste.

EnviroLeach – The process used at EnviroLeach uses an established, but historic method in a new and innovative way to recycle gold from e-waste. This technique is well documented in literature (Jha et al, 2018) (Demirkol and Pala, 2020). In a patent published by the founders of the organisation, the solution is prepared, agitated and passed through an electrochemical cell to activate. The pulverized e-waste is mixed with the leaching solution at room temperature for around one hundred and twenty (120) minutes. Gold and other dissolved metals in solution are then recovered by raising the pH with the addition of a hydroxide, such as sodium or potassium hydroxide (Nelson et al, 2017).

The iodine chemistry is very costly, and the applied diamond-based electrochemical cells to activate the chemistry makes the whole process extremely expensive. The gold recovery rate from WEEE using the EnviroLeach chemistry is low (87%) even after two (2) hours.

Advanced Chemical Company – The process used here implements the cyanidation process at a high temperature (120°C). The process is only suitable for materials which are plated with a single layer of gold such as printed circuit boards and gold-plated jewellery. They also offer the acid digestion method using an aqua regia solution which is known to be successful. (avdchem.com, 2023)

The use of toxic cyanides is generally declining worldwide. The recovery of gold from cyanide solution is a tedious process resulting in an impure product which requires additional steps to get to bullion grade. Also, as mentioned previously, the aqua regia digestion process also has potential safety, health and environmental (SHE) concerns.

UWin Nanotech Co – This company has recently had a patent accepted for a technology that claims to be more environmentally friendly and uses less toxic gold stripping chemicals when compared to cyanide chemistry for gold recovery from e-waste. From the patent, the chemistry used is nitric acid based, with a number of additives included (probably sulphide based). The dissolved gold is precipitated from the pregnant solution using zinc powder and therefore requires further purification. (Hsu, 2012).

Mint Innovations – This organisation has developed a very novel method, both biological and chemical for gold extraction. In this process, WEEE is first ground, then mixed in a concentrated sulphuric acid solution, microbes are then added to this solution to digest PM. To recover the gold, the laden microbes are removed through a filter press, then heated in a centrifuge to remove the gold from the 'bug paste' (Mint.bio, 2023).

There are a number of risks that need to be considered using this method, including, the handling of concentrated chemistries and live microbes. It is unknown what process is used to grow the microbes, and what conditions are required to sustain them. From a process description, it is believed that there is potential to create both hydrogen and chlorine gas.

Excir - The Excir solution provides a novel method of quickly extracting gold from a wide feedstock (surface and powder). The chemical solution contains mostly glacial acetic acid, a small quantity of hydrochloric acid, and a small quantity of solid calcium hypochlorite. The process runs at ambient temperature and there is a low probability of fume liberation. This lixiviant has a high affinity for gold, removing it from the WEEE in just a few minutes.

Glacial acetic acid is hazardous and presents a fire risk due to its flammability (flash point is 40°C) and toxicity. As the process is so selective, single batches of solution contain high quantities of gold (reportedly up to two hundred (200) grams per litre (g/L)), any spillage or loss of this lixiviant would be extremely expensive.

Novel Refiner	Development stage	Full PM recovery	Hydro or Pyro	Risks/Concerns
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Ronin-8	Scale up	No	Hydro	Very expensive sonic chamber for separation. End product still shipped to smelter for recovery
Advanced Chemical Company	Commercial Small	No	Hydro	Uses toxic cyanidation process. Old inefficient technology
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Table 5 - TRM competitors using novel processes

3.2 Changing of business model

Since 2009, TRM have been looking for opportunities in divergent markets where it has the expertise, facilities, equipment and knowledge to disrupt. Some of these ventures include:

- Collector Services – In 2018, TRM created a historic coin division of the business. The idea is that TRM will purchase historic coins from individuals or organisations, authenticate them, re-package them in TRM branded packaging (depending on denomination, some are turned into sets), then sell these at coin collector auctions. This has been a valuable business venture for TRM making an increased profit year on year since it has been established, reaching an operating profit of £3.3m in 2021 – 2022. With this business, there is also a service, TRM will authenticate, source, and advise on historic British coins and works of numismatic art to help customers build a collection or invest (The Royal Mint, 2022).
- The Royal Mint Experience – In 2017, TRM opened a visitor centre at its site in Llantrisant. The Royal Mint Experience (RME) gives customers the opportunity to visit TRM and see how coins are manufactured first hand. It also provides a space for activities to take place for the public, with large galleries available for hire. RME made a £0.1m profit in the year 2021 – 2022 (The Royal Mint, 2022).
- Precious Metals – Over the last three (3) years, TRM Precious Metals division has grown and now accounts for almost half of the businesses total profit for year 2021 - 2022 with an operating profit of £20.3m. It has quickly become a very important business within TRM portfolio offering the sale of a variety of PM products, including

bullion coins, bars, and one-off commemorative items. This is popular with investors who want to hold physical PM as part of their investment portfolio (The Royal Mint, 2022).

- 886 jewellery – 886 by TRM is a new business that currently employs fourteen (14) people from within the business to create unique jewellery products made from sustainably sourced precious metals. In 2022, 886 by TRM opened a store in London's Burlington Arcade.
- Covid visors – During the coronavirus pandemic, TRM developed and manufactured medical visors to support NHS staff. In addition, TRM also supplied its project managers to support the NHS and supplied other essential PPE that it was holding in its stores. This ensured that TRM did not need to furlough many of their staff, utilising personnel from all business areas (The Royal Mint, n. d).

Businesses need to adapt to a number of changing conditions, including markets, consumer trends and competition. Recently most businesses needed to adapt to the worldwide SARS-CoV-2 Coronavirus Covid-19 pandemic.

Manufacturing companies have faced several challenges, including supply chain disruptions, labour shortages, and reduced demand for their products. However, some manufacturing businesses have been successful in adapting to the changing circumstances, while others have not pivoted so well. Some examples of manufacturing businesses that have changed their business models have been studied.

3.2.1 General Motors

General Motors (GM) is a manufacturing company that produces vehicles and automotive parts. During the pandemic, the company faced supply chain disruptions and labour shortages. However, GM was able to adapt to the changing circumstances by pivoting to produce medical equipment. In March 2020, the company partnered with Ventec Life Systems to produce ventilators for hospitals (General Motors, 2020). GM retooled its manufacturing plants to produce the necessary parts and components, and the company was able to produce and ship the first ventilators within a month.

3.2.2 LVMH

Similarly, during the pandemic, LVMH, a luxury goods manufacturer that produces products under various high-end brands, including Louis Vuitton and Dior faced supply chain disruptions and a decline in demand for luxury goods. However, the company was able to adapt to the changing circumstances by pivoting to produce hand sanitizer. LVMH retooled its perfume factories to produce hand sanitizer, which was in high demand. According to the Financial Times (2020) claims the project was conceptualised, and brought to life within just

seventy two (72) hours. In March 2020, LVMH produced twelve (12) tonnes of hand sanitizer.

3.2.3 Rolls Royce

Rolls-Royce is a British multinational engineering company that is centred on the automotive, defence and aerospace industries. More recently, the company that has been involved in the design and manufacture of nuclear reactors. More specifically, the company has been developing small modular reactors (SMRs) that can be deployed in various settings, including remote communities, industrial facilities, and power grids. In January 2021, Rolls-Royce signed an agreement with the UK government to pursue the construction of up to 16 SMRs in the UK over the next few years. The company is working with a consortium of partners, including the National Nuclear Laboratory, the Nuclear Advanced Manufacturing Research Centre (Rolls Royce, 2023).

3.2.4 Tesla

Tesla is an electric vehicle manufacturer that, like all businesses has been impacted by the pandemic. However, unlike the organisations aforementioned, Tesla as an organisation initially resisted closing its factories, although eventually did cease to operate, closing down production for a number of weeks. When the company eventually resumed production, they did so without the understanding of the changing circumstances. Tesla continued to produce high-end electric vehicles, despite reduced demand, and did not pivot to produce medical equipment or other products in high demand. As a result, the company's stock price fell, and its production levels declined. (Financial Times, 2020).

Eventually, Tesla did start the manufacture of ventilators, however, health officials claimed that they were not suitable critical patients of the virus (Robertson, 2020)

4.0 Sustainable Precious Metals (SPM)

4.1 Introduction

The Royal Mint, working with academic organisations and Excir have developed a novel method of quickly extracting gold from a selective feedstock from the surface of WEEE. The project internally is known as SPM.

4.2 Process

The author has completed some laboratory scale trials to determine whether the process chosen is technologically achievable.

4.2.1 Disassembly line

To begin the process, de-soldering and de-population of boards is required. This is complete using a tumbling drum with a flow of hot air, this encourages the surface mounted

components to detach from the printed circuit boards (PCBs). The melting temperature of the tin based solder is approximately 220°C.

(For the trial completed, all components have been removed mechanically using a hammer and chisel.)

The remaining products from de-soldering must next be sorted. A number of options were considered for this, including: Hand sorting, optical sorting and screening.

Hand sorting on a large scale was considered too difficult and possibly unachievable. Optical sorting is expensive, and may not be effective for surface mount capacitors and resistors under 3mm. This leaves screening, which also has a number of limitations but is the most effective mechanism investigated to date.

4.2.2 Surface Extraction

Using an industrial shredder, the boards are cut to reduce the size of the boards. The leaching solution developed by TRM has been tested to determine its effectiveness at the removal of PM from pre-plated test samples and e-waste. This novel lixiviant operates at room temperature (22°C) and removes gold at a rapid rate, stripping de-populated e-waste (RAMM boards) in two (2) to four (4) minutes. For comparison, the Aqua Regia process requires an elevated temperature of 90°C for approximately ten (10) to fifteen (15) minutes.

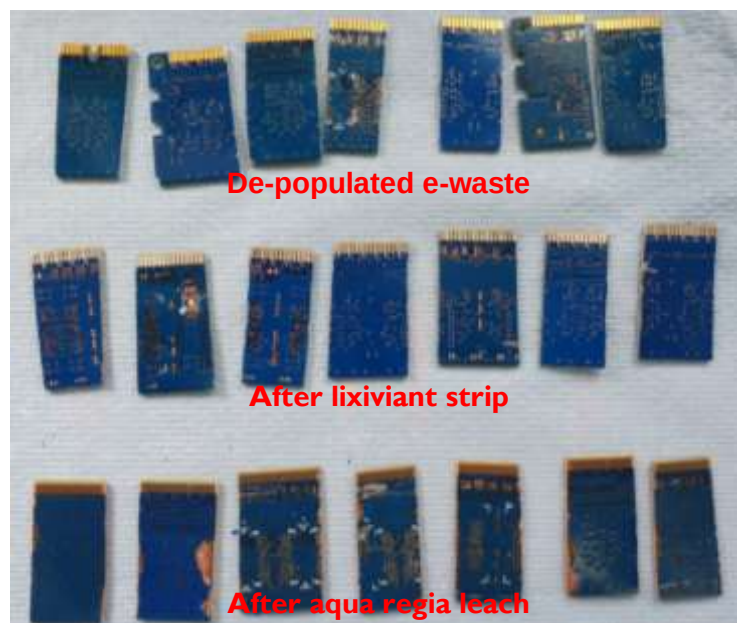


Figure 5 - 99% exposed gold leach extraction from surface e-waste

This was tested using pre-plated test strips. It was found that greater than 99% of the exposed surface gold was leached from the strips. This test was performed in duplicate.

The same test was completed using de-populated RAMM boards and duplicated. Greater than 99% of the exposed surface gold was leached from the de-populated e-waste.

Using a leachate and iron chloride precipitation, the gold can then be recovered. In all tests completed, greater than 99% precipitation of gold from solution was observed.

4.2.3 Powder Preparation

Following surface gold extraction, the boards are dried and the size reduced to approximately one millimetre (1mm) using a hammer crusher. This allows the pulverised boards to be loaded into a grinding machine. The grinding machine reduces the size further, to approximately four hundred microns (400µm) before being milled reducing to 200µm.

This material are then sorted using an electrostatic separator. The purpose of this is to minimise overall chemical consumption by taking out the base metals through a physical separation.



Figure 6 - Image of powdered e-waste for leaching

4.2.4 Powder Extraction

The powder extraction process is more complicated than the surface chemistry. It requires two base metal leach (BML) stages to remove copper, silver, tin, iron, aluminium and other base metals. The powder must then be dried and subjected to the precious metal leach (PML) using Excir's patented leach solution. The BML requires approximately two (2) hours to complete at 50°C, with the PML taking approximately one hundred and fifty (150) minutes (3x 50 minute leaches on separate batches of powder from the BML at room temperature (22°C)).

Powder which is made from ground up e-waste and was created by TRM for testing (as in Figure 6). The powder was split into six (6) batches for testing following the patented process. The gold leach extraction from the powder was determined from a baseline analysis of the powder, using hot aqua regia solution. The TRM process could then be compared to hot aqua regia of the recovered powder after the PML stage.

Test	Recovery Au (%)
TRM 1	92.85
TRM 2	97.14
TRM 3	100.00*
TRM 4	84.28
TRM 5	95.30
TRM 6	99.32

*No recovery calculated from leftover powder, calculated from BML or PML leach vs starting material.

Table 6 - Results of precious metal leaching of powder

4.3 Implementation

TRM are currently starting the implementation of the new plant and equipment for the project. In order to achieve this, a number of considerations and alterations to the current site are required. Figure 7 shows an aerial view of TRM site. Areal A (circled) shows the area that is going to be utilised for de-soldering and de-population (dry end). Area B (circled) has been chosen as the building to complete the gold recovery using the chosen lixiviant process (wet end).

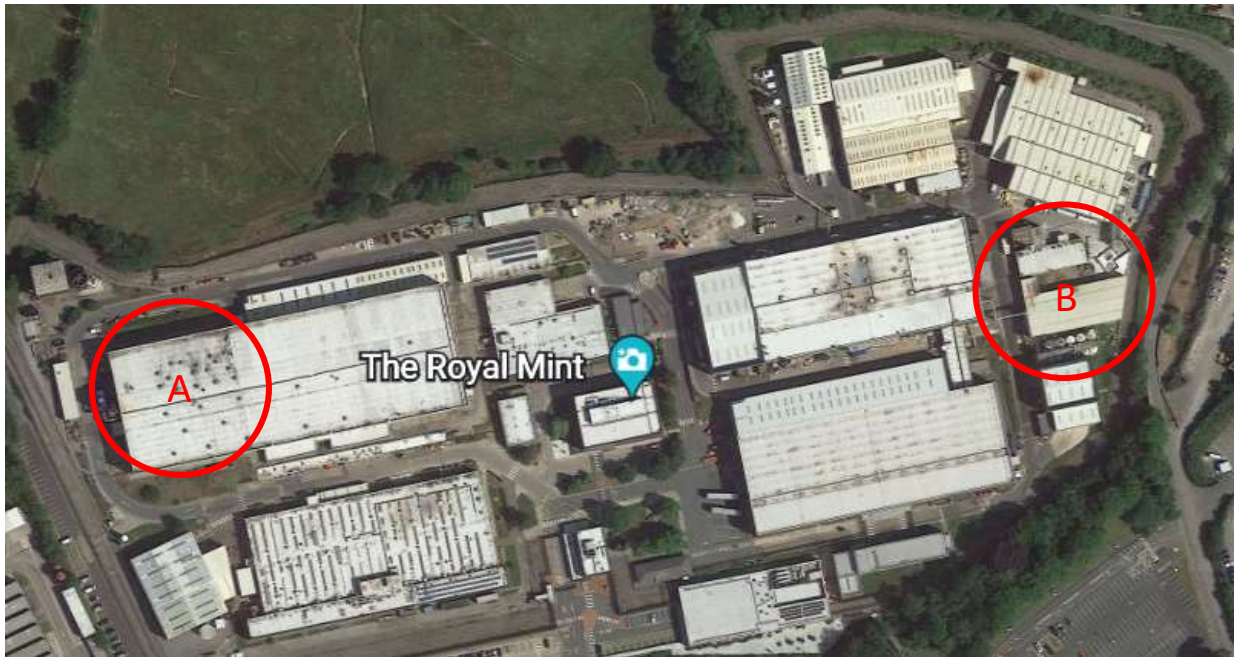


Figure 7 - Aerial view of The Royal Mint site, Llantrisant (Google Maps, 2023)

4.3.1 Removal of assets and upgrading

In order to create space for the new equipment in area A. Two melting furnaces required removal from the area. This space then needed upgrading to ensure it that it was suitable to receive the new equipment.

The removal of these assets reveals TRM's intentions for the future, as well as the confidence the company has in this project becoming a success.

The furnaces that were removed had almost reached operational end of life and required capital investment to improve their condition. The closing of these furnaces now restricts TRM operations to cast non-ferrous strip for use in their circulating coin business. In 2022, TRM processed 2880 tonnes of non-ferrous material for circulation coinage. This material was procured through a third party, as there is no longer capability internally to produce this.

The estimated cost for the removal of these melting furnaces, upgrading of building and making suitable of area A can be seen below. The relatively low cost of removing these assets is attributed to the sale of a number of assets associated with the melting process. The melting furnaces, when removed, were sold as scrap, this also offsets the cost of the work that was carried out.

CAPITAL INVESTMENT - AREA A		
1	Area A - Making suitable (Removal of existing equipment, floor repairs, removal of pipework etc.)	£1,113,000
2	Civil Work (bunds, containment, plinths, internal and external works for scrubbers etc.)	£125,882
3	Mechanical / Electrical Services	£112,000
TOTAL		£1,350,882

Table 7 - Breakdown of expected costs to make area A suitable

Area B was previously a nickel electroplating plant. The building had fallen into a state of disrepair, with severe corrosion visible on the corrugated wall panels and roof. The floor of the building was previously a bunded area (to contain chemistry in event of spill) for the nickel electroplating plant. As a consequence of many years of chemical attack, and damage from the removal of the plant, the concrete floor would require replacing.

CAPITAL INVESTMENT - AREA B		
1	Area B - Making suitable (replacement of corroded sheets, removal of historic pipework, new roof etc.)	£500,000
2	Civil Work (bunds, containment, plinths, internal and external works for scrubbers etc.)	£230,000
3	Mechanical / Electrical Services	£170,000
TOTAL		£900,000

Table 8 - Breakdown of expected costs to make area B suitable

In total, to even start the scaling of this project, TRM have committed approximately £2,250,882 to prepare the areas for the arrival of new equipment.

4.3.2 Resource plan

The effective implementation of a resource plan is crucial to ensuring the acquisition of all necessary knowledge, the successful operation and management of the plant, the development of the process, the completion of engineering works, and the provision of project managers for the facilitation of implementation.

4.3.2.1 Knowledge expansion

To ensure the project has every chance of success, TRM decided that it would require further knowledge and expertise. TRM have done this by hiring personnel from other industries (e-waste, chemical etc.) and internally. Some of the roles are for a fixed term, whilst others are permanent.

Role	New/ Replace	Internal/ External	Salary
SPM Graduate	New	External	£25,000
SPM Graduate	New	External	£25,000
Head of Development	New	External	£74,500
Head of BDM	New	External	£74,500
Engineering Project Manager	Replacement	External	£42,100
Business Development Manager			
SPM	New	External	£42,000
Head of Business Development -			
SPM	New	External	£70,000
Chemical Analyst	New	External	£55,130*
Chemical Analyst	New	External	£55,130*
Contract Chemist	New	External	£55,000
SPM Team Leader	New	Internal	£55,160*
SPM SHE Support	New	Internal	£42,000
SPM Teamworker	New	Internal	£43,105*
SPM Teamworker	New	Internal	£43,105*
SPM Teamworker	New	Internal	£43,105*
SPM Teamworker	New	Internal	£43,105*
SPM Teamworker	New	Internal	£43,105*
SPM Teamworker	New	Internal	£43,105*
SPM Teamworker	New	Internal	£43,105*
SPM Teamworker	New	Internal	£43,105*
SPM Teamworker	New	Internal	£43,105*
SPM Project Engineer	Replacement	Internal	£42,100
TOTAL			£1,002,460

*Inclusive of shift allowance

Table 9 - New and replacement roles associated with the project

Further recruitment is expected to continue this project. Table 9 shows the new and replacement roles for the project to date, with an estimated salary. The table does not take seconded personnel into account. There are currently nine (9) TRM personnel from different parts of the organisation seconded to the project on top of these new and replacement roles.

Excluding the replacement roles and staff that are seconded to the project, there is an overall increase of the wages bill to the business £918,260.

4.3.2.2 Operating resource

The operating resource plan below is based on the amount of staff that are expected to be required to run the plant based on different volume breaks. The assumptions are based on one (1) person operating the surface plant per shift and three (3) to operate the disassembly and other processes including powder and base metal leaching. The plant is expected to operate approximately three hundred and sixty (360) days per year, seven (7) days a week, as per the rest of TRM operations. A four-crew shift pattern is currently employed around the business to cover manufacturing areas, ensuring coverage for twenty four seven (24/7) operations.

Plant Volume	Salary	250t		1,000t		2,000t		3,000t	
Plant operating	£43,105	1	£43,105	2	£86,210	3	£129,315	3	£129,315
Plant Sampling and Mechanical	£43,105	3	£129,315	6	£258,630	9	£387,945	9	£387,945
Supervisor	£55,160	1	£55,160	2	£110,320	3	£165,480	3	£165,480
Total Labour		5	£227,580	10	£455,160	15	£682,740	15	£682,740

Table 10 - Expected operating resource plan and costs

All salaries included in Table 10 are inclusive of shift allowances but do not include contributions to pensions. As previously mentioned, the figures are based on a four-crew working pattern. This means, when the operation is at 100% capacity, resource alone will cost £2,730,960 per year.

4.3.3 Purchasing and installation of new equipment

In order to complete the project, a huge amount of new equipment is required. Table 11 shows an estimated cost breakdown for the installation of this new equipment. Please note that this does not include project managers/ SHE personnel salaries.

New plant equipment and resource list		
1	Initial Plant Costs	£1,881,861
2	Ancillary Equipment / Extraction etc.	£420,000
3	Engineering / Process Compliance / safety and environmental assessments	£200,000
4	Installation & Commissioning	£225,000
5	Contingency 20% (based on the fact that the proposal is very much concept phase for end-to-end process)	£545,372
	TOTAL	£3,272,233

Table 11 - Breakdown of expected costs for installation of new equipment

Once installed, it is likely that the only ongoing cost will be for periodic maintenance, breakdowns and any parts that are expendable. The cost of the plant and extraction can also be spread over a long period of time. This is attributed to the expected life of the new assets.

4.3.4 Chemistry and processing costs

Annually, there will be an ongoing cost of processing and leaching of all e-waste. This includes the de-population, surface treatment, and all powder processing. Estimations of these costs have been completed in Table 12.

						Tonnes to process	3000
Equipment	Base Cost /t	Yield	Re-use	Processing Cost / t	Percentage Processed	Tonnes processed	Processing Cost
Sampling Plant	£12.59	100%	1	£12.59	100%	3,000	£37,770.00
Process Mechanical Plant	£116.76	100%	1	£116.76	100%	3,000	£350,280.00
Gold Surface Plant	£1,599.39	80%	5	£399.85	85%	2,550	£1,019,609.07
Mixed Metal Refining	£750.00	100%	1	£750.00	30%	900	£675,000.00
Base Metal Leach	£1,344.36	100%	1	£1,344.36	15%	450	£604,962.43
Gold Powder Plant	£1,599.39	60%	2	£1,332.82	15%	450	£599,770.04
TOTAL							£3,287,391.54

Table 12 - Approximated chemistry and processing costs per year

The total cost for the full treatment of WEEE totals over £3.2million annually, when targeting 3000 tonnes of feedstock throughput. The figures are based on chemistry prices, electricity prices, yield and total e-waste that will be treated in this way.

4.4 PESTLE

	EXTERNAL FACTORS TO CONSIDER	FACTORS AFFECTED WITHIN THE INDUSTRY	IMPORTANCE TO ORGANISATION
POLITICAL	- Government Policy	The decision by the government to announce a 'digital' pound creates uncertainty about TRM future role (HM Treasury, 2023).	Medium
	- Industry Regulation	WEEE industry regulation is ever	

		changing, this has potential to affect feedstock	High
	- Global trade agreements & restrictions	Government imposed lockdowns forced more of the public to shop online using digital transactions	Medium
	- Inflation	War in Ukraine is currently making gold a 'safe haven'	Low
		Rising inflation has a direct affect on the commodities market	High
ECONOMIC	- Economic growth/ decline	Uncertainty continues in the UK business markets and investors due to the UK leaving the EU.	Low
	- Labour costs	Rising labour costs of all employees making process less profitable	Low
		Gold is not always a safe investment	Medium
SOCIAL	- Consumer buying habits	TRM 886 jewellery does not cater for all ages. Aimed at demographic with disposable income	Medium: Market research to be complete further
	- Population demographics	In some regions local demographic labour markets do not want to work in manufacturing	Low
	- Disruptive Technologies	Is our technology fit for purpose now and for the future?	High: Continuous research required to monitor market
TECHNOLOGY	- Security	Rise in cybercrime risk to data protection and operational stability.	High
	- Innovation and Automation	Greater employee expertise required	Medium
LEGAL	- H & S regulations	TRM operate a top tier COMAH site 365 days a year	High
	- WEEE regulations	Currently favourable for TRM, but could change	Medium
ENVIRONMENTAL	- CSR (Corporate social responsibility)	There is a rise in ethically and environmentally conscious customer base	Medium

- Transportation	The process is mainly completed on TRM site	Low: Determine most efficient transportation of feedstock to TRM
- Environmental restrictions	Environmental permits required to commence operations	High: Ongoing with issuing authority

5.0 [Opportunity assessment](#)

5.1 [Life cycle of a laptop](#)

The subject of electronic waste is as broad as its applications. TRM are specifically interested with the part of electronic waste that yields PM, which is a subset of all electronic waste. Given the sheer volume, TRM are looking to focus on this by way of example being the life cycle of a laptop.

5.1.1 [The laptop](#)

- Probably manufactured in the Far East with raw materials sourced from the Far East.
- Shipped to the UK for distribution.
- Used in both business and domestic environments.

5.1.2 [Options at the end of 'first life'](#)

- Reuse.
- Leasing /Retailer /Distributor collection through a Waste Electrical & Electronic Equipment (WEEE) take-back scheme & subsequent treatment by Authorised Approved Treatment Facility (AATF).
- Disposal via collection service offered by an Asset Management Company – may or may not be an Authorised Approved Treatment Facility.
- Drop off by end user at a Civic Amenity site for recycling by a WEEE Compliance Scheme.
- Disposal in general waste (in contravention of WEEE regulations)
- Other illegal disposal.

From the above and as illustrated in Figure 8, there are many legitimate, accredited routes from which electronic waste is supplied. Although, a report by the World Economic Forum (2019), supported by the United Nations claims that less than 20% is formally recycled.



Figure 8 - Simplified, the fate of WEEE

Given its sheer scale, the complexities with recycling, some of the more noxious components and the opportunities for short cutting more expensive accredited routes, e-waste is becoming, alongside plastic, one of the world's greatest environmental challenges for the future.

5.1.3 Approved processing

The processing of the laptop should be carried out in accordance with the requirements of Data Protection Act, the WEEE Directive, with specific, mandatory treatment for batteries, liquid crystal displays (LCDs) & printed circuit boards (PCBs) and the Classification of Wastes.

Initial processing will ensure the removal of data. The rechargeable battery will then be removed. At the next stage, the laptop will be dismantled to yield the LCD display module, CD/DVD removable drive, laptop motherboard, memory modules, as well as polymer and/or aluminium cases.

The process TRM is proposing is the recycling of PCB materials and the recovery of precious metals within.

PCB materials removed would usually be refined at a smelter. Laptop memory is high grade, approximately 700g - 800g of gold per tonne. The motherboard is likely high medium grade, around 200g - 225g of gold per tonne.

5.2 TRM disruptive opportunities

Currently, 80% of all e-waste is processed using the smelting method (Ghosh et al, 2005). Smelters are high throughput operations with typical throughputs of hundreds of thousands of tonnes per annum, of which circuit boards are only a fraction of the feedstock. The process requires a balanced mixture of secondary feed materials to operate efficiently. Without additional material to burn, the economics of the management of printed circuit boards would not be viable (Czajczynska et al, 2017). This considered, it is reasonable to assume that smelting operations prefer to receive large lot sizes (over ten (10) tonnes), as opposed to smaller lot sizes. Once an acceptable volume is achieved, the waste is then shipped to smelters, usually in the Far East or Eastern Europe (Bloomberg, 2007).

This allows TRM to potentially disrupt the market in two (2) different ways.

Firstly, as a batch process, it is ideally suited for lot sizes as low as 500kg. As previously mentioned, as smelters do not want to receive these small lots, circuit board producers often rely on mediators or middle-men according to the International Labour Organization (2014). These aggregators will take a margin to cover pricing fluctuations, the interest on purchase for the period outlay through settlement and his profit. The TRM process has the potential to circumvent the middleman and give the small producer the actual value for their product. TRM is also a trusted brand, which will give suppliers confidence to use its' services.

Secondly, the TRM process is going to be completed on its current site in Llantrisant. This means sourcing from local supplies, resulting in the reduction of shipping materials internationally, which is both a margin opportunity versus the current process, as well as reducing the carbon footprint of the treatment of e-waste.

With most PCBs recovered using pyrometallurgical techniques, strict emission control are required. There is often a significant amount of carbon dioxide generation among other noxious gases which are released into the local population and surrounding areas. This presents TRM with another opportunity for a paradigm shift in the market.

The process that TRM operates is carried out at ambient temperature, with low carbon footprint and no emissions of noxious gases (from what has been established through trials to date). According to Cooke (2023), the process will reduce carbon dioxide generation, nitrous oxide and acidification by 100%. The process will also consume just 0.5% of the fossil fuels required during the smelting route.

Using the pyrometallurgical route, the value of e-waste is determined after receipt of works. This can take up to four (4) weeks. Samples are analysed independently by both parties, assays are then exchanged subject to procedure. If the assays fall within splitting limits

defined within the contract terms, the results are split. If the splitting limit is not achieved, samples are sent to a neutral umpire for additional determination and settlement made according to an agreed procedure. Generally, the conclusion of purchase takes place approximately one hundred and twenty (120) days after arrival at the smelting site. The final payment is based on material market fixes from a date (chosen by the seller).

In addition, the sampling process has potential for inherent errors and margin swings can be the difference between significant profit and significant loss on a batch. Not only is this model unstable, it significantly increases the negative behaviours associated with scrapyard dealers, given the huge incentive to 'play games' with the sampling and payment process.

This opens up a new opportunity for TRM to disrupt. As a process, the hydrometallurgical route used is much faster than conventional smelting. Metal output is complete in just several days, a substantial improvement on the one hundred and twenty (120) days at the smelter. Furthermore, TRM is able to accurately (within a margin of <1% error) pay the correct amount based on analysis, allowing the provider of electronic waste to get paid for the value they provide, all at the market rate.

Principally, this is a significant advancement in the entire process, legitimising the supply chain as well as professionalising the operation. Cooke (2023) states that this is likely to be the single most influential part of gaining market share in the supply of electronic waste.

As part of the smelting process, any alloyed metal output is required to be de-alloyed and refined to enable these precious metals to be reused. For the smelter, this creates an additional cost, whilst having a greater environmental impact and an additional process. This creates another benefit for TRM process over conventional methods.

The process used is capable of producing a refined gold output of 99.99% purity with just one pass through the plant. This means there will be no need for further refining. However, there are current plans to bring back refining into TRM site for other purposes as the technology could be leveraged across many areas.

The United Nations Environment Programme's (UNEP) (UNEP, 2015) report states that approximately \$19 billion (£12 billion) worth of electronic waste is illegally disposed of, dumped or traded each year, which accounts for up to 90% of the global electronic waste. UNEP (2015) follow this by claiming thousands of tonnes of e-waste are falsely declared as second-hand goods and exported from developed to developing countries.

This significant ecological and social issue presents TRM with its final opportunity for disruption. Using current technology partners, it is believed that a process to repurpose the

by-products and waste generated during the metal removal operation to create new commercial opportunities is achievable. Through the use of the current laboratory chemistry, the waste can potentially be transformed into fire retardant drywall, which can be utilized in construction, or cement and aggregates for the building industry. This can either be sold or made available at cost, this can be incorporated as part of TRM's overall CSR strategy.

5.3 Environmental considerations

The Royal Mint (2021) state that they operate an upper-tier (tier 1) control of major accident hazard (COMAH) site, this is overseen by the Competent Authority (CA). The organisation also operates within an environmental permit, which is regulated by Natural Resources Wales (NRW).

When considering TRM PML chemistry that will be used, it is thought to be unlikely that the operating permit held by the organisation will need modification. This is as a result of the volumes expected. However, the process itself may require a variation to the operating permit, this would be dependent on if TRM introduces a new emission point to air (scrubber etc.) or a new waste discharge to sewer. It is believed that an amendment will be required, as the process will create effluent which will be treated on site, before being released to sewer.

In terms of receiving materials, TRM is not registered as a waste receiving site, registration will be required prior to receiving large quantities of WEEE. TRM should consider this a significant risk to the project, as amendments to licences and permits are often slow processes. The author could find no evidence of a permit variation proposal being submitted to NRW using the public register.

It is not believed that TRM facility will require to register as an AATF in order to accept WEEE for metal refining; it is an end process. However, AATFs have a responsibility to ensure that downstream processing of their material meets the standards of best available treatment, recovery and recycling techniques (BATRRRT). Currently, smelters meet this requirement. Energy created by the burning of circuit boards is used to drive the process; this is classed as energy recovery, but also replacement of fossil fuel that would otherwise be required for the process. The burning of boards also produces a slag material (from iron, aluminium and silica), this 'waste' can be cast into blocks and used as building materials and secondary aggregate. TRM will have to rigorously examine the environmental benefits of the proposed process to show that it conforms to BATRRRT.

5.4 Customer Acquisition

Aside from the clear adjacencies in providing recycled PM for use by TRM to improve current business margins and enable the use of these processes in jewellery production and reclamation, the primary opportunity may lie in collaborating with major electronic companies and jewellery retailers, which have this at the forefront of their CSR agendas. Below illustrate two company's agendas, but represents the global agenda for most electronics and other businesses where precious metals play a role (automotive, aerospace military etc.).

5.4.1 Apple

In a statement made by Lisa Jackson, Apple's vice president of Environment, Policy and Social Initiatives said "Advanced recycling must become an important part of the electronics supply chain, and Apple is pioneering a new path to help push our industry forward" (Apple, 2019).

Apple currently use 100% recycled tin for a main component of the logic board used in eleven (11) different products. The MacBook Air and MacBook mini have almost half the carbon footprint of previous models, this is attributed to the 100% recycled aluminium from the Apple Trade-In program being used in the aluminium alloy case.

5.4.2 Pandora

Pandora, a provider of jewellery, have pledged that they will become carbon neutral by the year 2025. To achieve this aspirational target, Pandora have pledged to use 100% recycled gold and silver. Mads Twomey-Madsen, head of sustainability at Pandora said regarding this, "With that, we then, of course, sit down and look at what are the main levers that we can pull to reach carbon neutrality and to reduce the footprint of the value chain connected with crafting our jewellery, delivering our jewellery, and then this comes in as one of those components" (Pandora, 2020).

5.5 Risks

Undertaking a project involves a certain degree of risk. This is because projects are typically complex, involve multiple stakeholders, and are often subject to uncertainties such as changing requirements, resource constraints, and unforeseen events. Risks can arise at any stage of the project, from planning and design to execution and delivery, and can have a significant impact on the project's success or failure. Some risks may be manageable through proactive planning and mitigation strategies, while others may be outside of the organisations control and require contingency plans.

5.5.1 Scaling

When scaling from laboratory tests to full scale, there are several risks that need to be taken into consideration. There may be differences in the equipment used in the laboratory and in the full-scale process, which can affect the accuracy and reproducibility of the results.

Another risk when scaling is that the dynamics of the process may change, which can lead to unexpected or uncontrolled reactions, equipment failure, or other safety hazards.

From the process view point, as it becomes more complex and involves more people, there is an increased risk of human error. This can lead to equipment failure, contamination, and other problems. All these risks require mitigation.

5.5.2 Legal

The treatment of WEEE is dictated by the Waste Electrical and Electronic Equipment Directive. Treating WEEE will require environmental site and integrated pollution & control permitting by Natural Resources Wales. TRM already possesses permits for current operations which will need modification and approval from the issuing authorities for the new processes.

Until recently, printed circuit boards have been classified as green list wastes for trans-frontier shipment. However, this guidance was revised in June 2020 to re-classify printed circuit boards as hazardous waste. This means that shipments of printed circuit boards destined for overseas recovery operations will require a financial bond to be placed with the appropriate Environment Agency, to cover the potential inability of the destination facility to process material. This will affect TRM if any of the treated materials require further treatment overseas.

5.5.3 Supplier source risk

In order to attract suppliers, TRM procurement terms must be competitive with existing trading routes. Valpak (2018) claim that just 42% of WEEE generated was treated within the regulatory system. 24% of all was lost to the residual waste stream and 34% likely to be treated or reused in some way but not reported to the agency.

The market currently is largely unregulated, and has a poor reputation for a lack of standards.

5.5.4 Reputational risk

If TRM process is heralded as the environmentally sound answer to PCB processing, it must be just that, or there is reputational risk. Questions relating to the disposal of spent solutions and residues must be resolved and open to inspection. TRM must also follow best industry/

environmental practice and all methods (sampling, assaying etc.) should follow international standard procedures.

TRM have stated their goal for their technology is to achieve 100% recycling of circuit board materials, although, at this phase of the project, that is not what is being practiced.

5.5.5 PCB technology

Gold is an expensive noble metal and the price is unpredictable, strongly affecting manufacturing profit margins and, in the end, component prices. In terms of precious metals in circuit boards, there will always be a movement towards reducing content. Research and development (R&D) facilities and academic institutions are continually investigating alternative materials.

5.5.5.1 Graphene

Graphene is a two-dimensional material made from carbon atoms, arranged in a honeycomb (orthohexagonal) lattice was developed in 2004. It has excellent electrical conductivity and mechanical strength, making it a promising alternative to precious metals in electronic applications. A study completed by Papamatthaiou et al (2021) found it was possible (under laboratory conditions) to print graphene, using inkjet printing technology directly onto a PCB for use in high specification applications. An older study conducted by Kwang et al (2013) determined that graphene can outperform gold in terms of electrical conductivity and resistance to oxidation.

This would make it an ideal replacement, but the high production cost and the technical challenges of using this material are slowing progress (Ball, 2019).

5.5.5.2 Conductive polymers

Conductive polymers (CPs) are organic materials that have electrical conductivity. Conductive polymers have the advantage of being lightweight, flexible, and inexpensive compared to precious metals. However, they have lower conductivity and stability than some metals, so researchers are working to improve their properties. Sharma et al (2021) completed a deep dive into recent trends and developments of CPs. They conclude that there is promise in these materials due to their manageable electrical characteristics, light colour, lower density, and overall convenience. Global Market Insights (2022) agree, and claim that the CP industry will have a valuation of \$8 billion by the year 2032.

However, there would be great challenges recycling these materials using current methods, this is attributed to a number of polymers (some toxic) and fillers (including nano-fillers) all existing within the same matrix.

5.5.5.3 Silver MaxPhase

MaxPhase materials are a type of composite material that consists of a ceramic phase and a metallic phase. The ceramic phase provides mechanical stability and high-temperature stability, while the metallic phase provides electrical conductivity. Silver MaxPhase is a MaxPhase material that contains silver as the metallic phase and has been patented by Impact Coatings (2014) to replace gold for electrical contacts in some applications. It drastically reduces manufacturing cost whilst maintaining high resistance to corrosion and wear. The contact coating is qualified for low voltage and low contact force connectors that were earlier gold plated, for example, battery and I/O connectors for mobile phones, making it suitable for some PCBs.

Silver MaxPhase is a promising material for use in a variety of applications, including as an electrode material in lithium-ion batteries. However, more research is needed to fully understand its properties and optimise its performance in different applications

5.6 Financial viability

To determine whether the project is economically feasible, further cost analysis should first be completed.

Based on Table 2, the below table has been created to give an approximation of gold recovered and the value of this at market value (gold.co.uk, 2023)

Tonnes to process		3000	Au value per kg (22.02.2023)	£48,830.83
Grade	Au in WEEE (g/ t)	Yield	Recovered Au (t)	Value (£)
Low	30	80%	0.072	£3,515,819.76
Low medium	100	80%	0.24	£11,719,399.20
High medium	200	80%	0.48	£23,438,798.40
High	800	80%	1.92	£93,755,193.60

Table 13 - Expected recovery and value of gold

From Table 13 it can be seen that the grade of PCB used in the process is critical to return. It is currently unknown what grade of WEEE will be used as the main feedstock in TRM process. It is unlikely that low or high grade will be utilised for the process, this is owing to the low value held in low grade PCBs and the scarcity and availability of high grade WEEE.

Also from Table 2, we can estimate the total cost of each type of feedstock at the volumes expected for processing. The cost for each grade used is the median value, so not to over or under estimate.

	Tonnes to process	3000
Grade	Pricing of WEEE (£/t)	Total WEEE cost
Low	£300.00	£900,000.00
Low medium	£2,525.00	£7,575,000.00
High medium	£5,250.00	£15,750,000.00
High	£18,500.00	£55,500,000.00

Table 14 - Cost of feedstock per grade

From Table 14, the huge amount of potential feedstock prices can be seen. As previously mentioned, it is unlikely that TRM will process low or high grade e-waste. For this reason, the table below only account for both medium grade boards. The cost of the upgrading works and plant equipment is not included, as this is part of the project cost and is one-off. Only operational costs are considered.

					Tonnes to process	3000
	Processing cost total	Feedstock cost total	Labour cost	TOTAL cost	Au value	TOTAL profit
Low						
Medium	£3,287,391.54	£7,575,000.00	£2,730,960	£13,593,351.54	£11,719,399.20	-£1,873,952.34
High						
Medium	£3,287,391.54	£15,750,000.00	£2,730,960	£21,768,351.54	£23,438,798.40	£1,670,446.86

Table 15 - Final cost analysis to determine financial viability

From Table 15 the low medium grade PCB process returns a loss when considering all processing that is required, this is based on processing 3000 tonnes of material a year. High medium grade returns a £1.67m profit.

From this analysis, the fine margins on making a profit or a loss can be appreciated. It is important to remember that no equipment, upgrading or waste treatment costs have been included in this analysis.

6.0 Further development

Further work is required to maximise the potential of this project.

6.1 Becoming circular

For TRM to truly make a difference environmentally, the process is going to need to become circular. Currently, in phase one (1) of this project, TRM are focussed on removing gold from WEEE.

In The Royal Mint annual statement 2021 – 2022 (2022), TRM claims that they aim to make the UK leaders in the circular economy of electronic goods and precious metals.

Unfortunately, at least at this stage of the project, this is not a circular process.

It is unknown currently what route the remaining (precious metal extracted) e-waste will take, as it still has a number of resources contained within it. The composition of the remaining waste will be heavily laden with copper, tin and other base metals. Also, the bromine based fire retardant (tetrabromophthalic anhydride (TBPA)) containing polymer/ ceramic and fibres, which makes up over 70% of the total material will require a sustainable disposal route. This is made more difficult, as this will be classified as 'hazardous'.

If these are broken down correctly, the bromine gas could be captured, concentrated and sold to another organisation for re-use. The polymer is generally low grade when the card is manufactured, it is so far undetermined whether this could be recycled into another lower grade plastic.

Glass fibres also have a value. If the glass fibres can be split from the composite board, recovered and cleaned (probably chemically), then these can also be re-used in a number of industries that manufacture composites.

The process is likely to produce some amount of hazardous effluent, which TRM can treat on site using the current effluent treatment facilities based on site. As much of this effluent should be recovered wherever possible and used within the process, this will reduce costs of treatment and disposal.

Spent lixiviants are going to need to be recovered using new technologies to split the chemistry back into its original components to be re-used. Not only does this make the process more environmentally friendly, but it may result in a decrease in processing costs.

6.2 Phase two

Phase two of the project needs to become operational as soon as economically and technologically possible. This should increase the profit margin significantly. Recovering just copper from the BML waste would create a huge amount of revenue for TRM. From Table 1,

it can be seen that a significant amount of copper with the PCBs. Copper prices are between five (£5) and six (£6) pounds per kilogram. If 100% of this copper could be recovered from the PCBs, based on a price of five pound fifty per kilogram (£5.50/kg), there is potential to introduce another £3.795m of revenue. Any extra processing costs would need to be subtracted from this.

It is unknown what will happen to this material throughout phase one of the project. It is expected that all BML waste will be collected and sent for treatment through pyrometallurgical techniques. TRM will be able to recover some value from this material following this route, however, this does not fit into the environmentally friendly, circular marketing that has been published (The Royal Mint, 2023).

7.0 Discussion

Internally, there is a belief within TRM that becoming the first to market within the United Kingdom (UK) to offer this kind of service will attract organisations that are willing to do business based on TRMs secure brand. Further work can then be continued on the process, focussing on reducing cost of processing and becoming more efficient.

If TRM could reduce the cost of the feedstock by offering a secure data destruction and disposal service, this will have a powerful effect on gross profit, potentially making all feedstock financially viable.

The TRM have partnered with Excir and together have successfully developed a process and solution for treating PCBs to recover gold. The method employed has been marketed as safer and more environmentally friendly and is the first plant of this type to be built within the UK. Although, in 2022, TRM also invested in another plant. This was a brass electroplating plant. Approximately £9m was invested into this plant. The purpose was to replace two ageing plants (copper electroplating and zinc electroplating) and streamline the process of creating a brass plated product.

The new brass plating plant uses a cyanide based chemistry to achieve a brass plated deposit on circulating coin products. This proves that TRM are comfortable dealing with cyanide based solutions and have no plans to cease using this chemical.

The copper plating plant that is now no longer required for operations, also used a cyanide based chemistry. The copper plating plant had all the safety features, cyanide destruction units and ancillary equipment required to develop a cyanide based gold leaching solution. As previously mentioned, cyanidation is the primary method used to remove gold from its ore. Cyanidation can also be used on e-waste, as proven by the Advanced Chemistry Company. They have made their sodium cyanide based chemistry commercially viable for this purpose.

Given the proven success of cyanidation in WEEE recycling, the facilities and expertise available, it is reasonable to question why TRM has not pursued this method.

The business model for this project is still undetermined. TRM manufactured and sold 3000kg of gold products in the year 2022. At full capacity using high medium grade PCBs, just 480kg, even if high grade boards were used, TRM could not fulfil its requirement.

Whether the true value will be to distribute this recovered material to collaborators, such as jewellery manufacturers and electronics companies for a fee above market value, due to its 'sustainable' nature, remains to be seen.

Until phase two of the project commences, TRM are going to generate BML waste containing a large amount of base metals. It is assumed that TRM will send this for pyrometallurgical recovery (smelting) to attempt to recover some value, although, there is a large reputational risk that comes with this. The project has been marketed as a solution to the WEEE problem that deals with the waste responsibly and in a circular manner. If this route is taken, TRM could face bad publicity and lose trust of customers.

8.0 Conclusion

In conclusion, TRM's development of an e-waste plant aimed at recovering gold from electronic waste has shown great potential for environmental sustainability and resource utilisation. However, the project's profitability has been hindered by several factors, including resource costs, feedstock prices, and processing costs.

Despite the challenges faced by the project, the technology developed by TRM and Excir to extract gold from electronic waste has proven to be efficient and effective. The plant successfully extracted gold from WEEE, and the technology used is more advanced than traditional methods of gold recovery. This represents a significant step towards sustainable resource utilisation, as electronic waste is the fastest growing waste stream worldwide.

The project's initial development was based on TRM's desire to reduce environmental waste and to find new ways to utilise resources to ensure its continued operation. This project is an important step towards this goal, it also represents TRM's commitment to environmental sustainability and their wider CSR agenda.

However, the profitability of the project has been impacted by several factors, primarily resource, feedstock prices and processing costs. The feedstock prices, which are the prices paid for the electronic waste used as raw materials, also fluctuate to changing market conditions, affecting the profitability of the project, which is essential for its long-term sustainability. For the purpose of this report, the median value of PCBs has been used.

To address these challenges, TRM may need to explore alternative business models or partnerships that could help to reduce costs and increase revenues. For example, the organisation could partner with companies that generate significant amounts of WEEE, such as electronics manufacturers, to secure a reliable supply of feedstock at a more predictable price. Alternatively, TRM must push ahead with the next phase of the project in order to monetize other valuable metals that are present in e-waste.

In addition to the profitability challenges, a number of risks still exist to the success of the project. Rapid PCB technology advancements could destroy the future market availability of e-waste for the purposes of removing precious metals. The recovery of these new materials will require new, advanced processes to ensure future circularity.

The scaling of this project from the current stage, to full production will require significant investment of approximately £5,523,115. This sum does not include any development work, the salaries of new employees, and no running costs. It is currently unknown whether scaling of the technology will compromise effectiveness.

Another risk is obtaining the necessary environmental permits to operate the e-waste plant. TRM must ensure that the plant complies with all relevant environmental regulations and that it operates to BATRRRT in a way that is environmentally responsible in the eyes of the regulatory bodies.

Finally, TRM as a leading, government owned and funded institution must ensure that the project does not cause reputational damage. To manage this risk, TRM must be transparent about the e-waste plant's operations and engage with wider stakeholders, to ensure that the project aligns with their expectations.

Overall, the process developed by TRM and Excir for extracting gold from WEEE is technologically viable. The process is faster, more effective and more efficient than traditional and alternative novel techniques, although, the operations relating to this are very expensive. There are still many unknowns within the project, this makes it difficult to conclude whether this business venture will be financially viable. Much depends on the feedstock price and grade used. Many other risks still exist, with mitigation required for each of the risks highlighted in the report. Creating a sustainable, environmentally friendly process for extracting gold from secondary sources is necessary, if TRM can make the process profitable, then the project economically and commercially is viable.

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