

CRUCIAL RECOVERY STRATEGIES OF RARE/PRECIOUS METALS FROM E-WASTE

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ABSTRACT

Electronic waste (e-waste) contains a variety of rare and precious metals, such as gold, silver, palladium, and copper, which can be recovered and reused. The recovery of these metals is crucial for both economic and environmental reasons. This paper reviews the current state of e-waste recycling, the challenges faced in the recovery of rare and precious metals, and the strategies that can be used to overcome these challenges. The strategies discussed include mechanical separation, hydrometallurgy, pyrometallurgy, and biometallurgy. The advantages and disadvantages of each strategy are also discussed. The paper concludes that the recovery of rare and precious metals from e-waste is not only necessary for the sustainable use of resources but also presents a significant economic opportunity.

Keywords: *Rare earths, precious metals, electronic waste, recycling*

INTRODUCTION

(Baldé, Wang, Kuehr, & Huisman, 2015; Dodson, Hunt, Parker, Yang, & Clark, 2012) The rapid evolution of electronic devices, which will eventually become electronic waste (e-waste), provides an important resource that could be leveraged to produce a sustainable supply chain for scarce and critical materials. This resource could be leveraged to produce a sustainable supply chain for scarce and critical materials. The wide variety of elements and the high concentrations of those elements, which are higher than what is found in mineral ores (Akcil et al., 2015), imply that there will be an economic gain derived from the recovery of various value streams. Not only because of the economic value of these elements, but also because of the need for a proper handling and disposal of e-waste that mitigates its potential environmental risks, extensive research efforts are currently being developed for the recovery of precious metals (Ag, Pd, and Au) and base metals (Cu, Sn, Pb, Ni, and Zn). These efforts are currently being developed for the recovery of precious metals (Ag, Pd, and Au) and base metals (Cu, Sn (Sun, Xiao, Sietsma, Agterhuis, & Yang, 2015).

According to Baldé et al. (2015), there are six distinct categories for the classification of electronic waste. These categories are as follows: temperature exchange equipment; screens; lighting; big equipment; tiny equipment; and small IT. Among them, tiny IT waste is exhibiting the most significant growth, which is driven by rapid changes in technology as well as fashion (Geyer & Doctori Blass, 2010). According to Baldé et al. (2015), the quantity of e-waste created by small IT, which includes mobile devices such as cell phones, personal computers, and tablets, accounted for close to 10% of the overall amount of e-waste generated in 2014. It has been estimated that the United States produced around 707 kt of minor amounts of electronic trash related to information technology.

In addition to precious and base metals, tiny IT trash also includes rare earth elements such as Nd, Pr, Dy, and Gd. These elements are among those that the United States Department of Energy identifies as being absolutely

necessary for the production of renewable energy technology (DOE, 2011). Even though they are only found in trace amounts in vibrators, hard disc drives, and speakers (Lister, Wang, & Anderko, 2014; Tukker, 2014), the volume of small IT waste that is generated presents a significant opportunity for the stabilisation of the REE markets, which are currently controlled by China (Tukker, 2014), through the use of recycling. This opportunity can be seen in the volume of small IT waste that is generated. Nevertheless, there are a number of technical obstacles that need to be overcome in order to establish a method that is both sustainable and effective in recovering essential materials from electronic trash. The compact nature of small IT waste makes it difficult to access and recover elements (Lister et al., 2014). Additionally, the low recycle rates of e-waste, which do not exceed 30% in the United States (Coalition, 2014), have an impact on the availability of feedstock as well as the price of feedstock.

Processes that are either pyrometallurgical or hydrometallurgical, or even mixes of the two, are used in today's technologies for extracting metals from electronic trash (Hagelken, 2006). Yet, there are a number of obstacles in the way of the efficient and cost-effective recovery of valuable and essential elements from electronic trash. These obstacles include a high demand for energy and chemicals, as well as the production of waste (Khaliq, Rhamdhani, Brooks, & Masood, 2014). On the other hand, based on the composition of the e-waste as well as the distribution of value within it, close to 80% of the total recovery value falls over the precious metals (Diaz, Lister, Parkman, & Clark, 2015). However, precious metals make up less than 1% of the total content of the e-waste. Therefore, over 90 percent of the total content, which is comprised of less noble metals, has a limited contribution to the total recoverable value in e-waste while consuming the majority of the chemicals necessary for the extraction in a hydrometallurgical process. This is because of the nature of the metals. We have presented an alternative method, which is a complete process for the recovery of valuable and crucial materials. Our method is based on an electrochemical-hydrometallurgical approach that is mediated by the method (Diaz et al., 2015; Lister et al., 2014). An electrochemical recovery procedure (ER) utilising a weak oxidant (Fe^{3+}) was then suggested. This oxidant may be produced at the anode of an electrochemical cell and then regenerated following the extraction of base metals. In the cathode of the electrochemical cell, the extracted metals are oxidised by the process of electrowinning. The entire process for the recovery of critical and valuable materials has been developed to run at normal temperatures (about 25 degrees Celsius), as was detailed in a previous study. This process has also been intended to be environmentally friendly (Diaz et al., 2015). Comminution and separation of the ferromagnetic fraction are required for the recovery of rare earth elements (REE), whereas the recovery of non-magnetic fraction comes after the sequential recovery of base metals. The full recovery of value metals comprises both processes. Figure 1 is a flowchart depicting the process being analysed.

This study presents a preliminary evaluation of the entire recovery process from a technological and economic standpoint (critical and value metals). In order to evaluate the processing of tiny amounts of IT trash, a base of ten tonnes of material from mobile phones each day, which is indicative of a regional processing plant, has been taken. In this section, an overview of the main phases of the process as well as an analysis of the impact the ER process has on operating expenses and the economic viability of the process are provided.

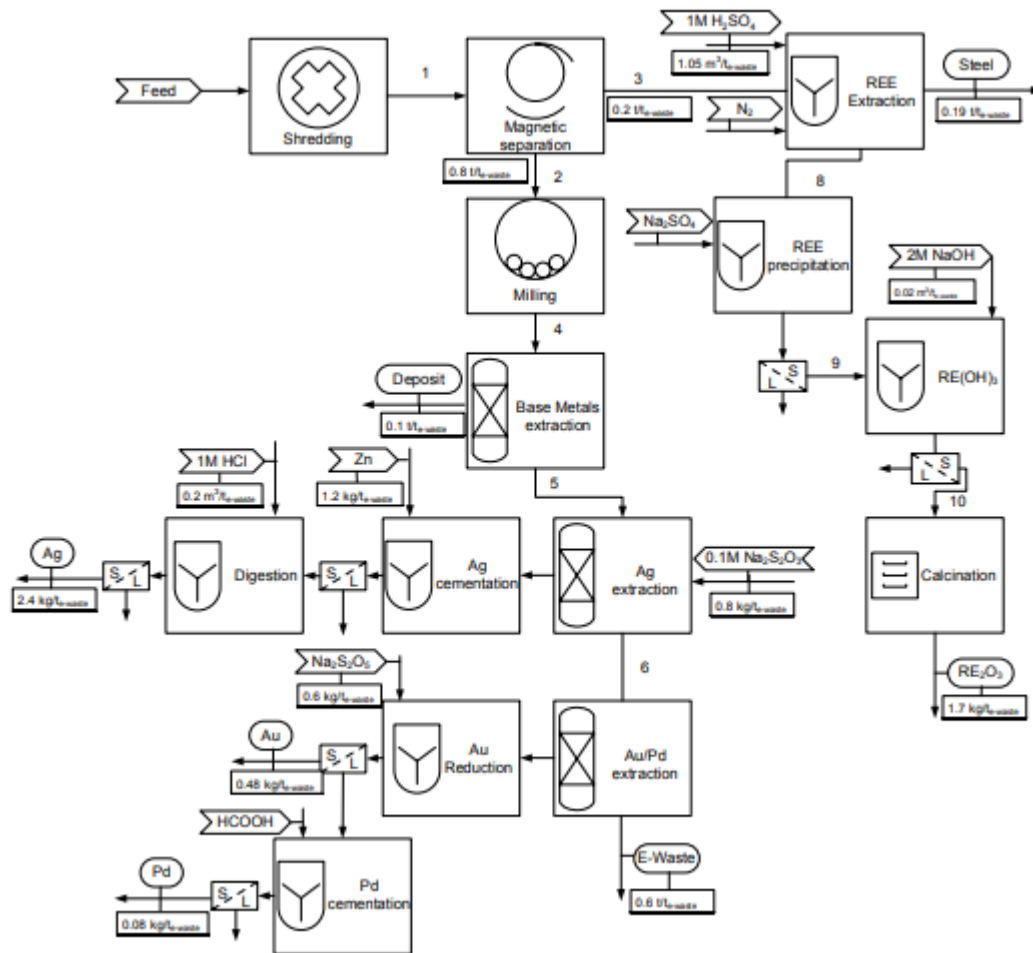


Figure 1 – Diagram of the process flow for the entire recovery process of crucial and valuable elements from discarded electronic equipment

BASE AND PRECIOUS METALS EXTRACTION

Electrochemical Recovery (ER) Process

The milled non-magnetic portion of tiny IT debris is packed in extraction columns during the ER process (Diaz et al., 2015; Lister et al., 2014) (Diaz et al., 2015; Lister et al., 2014). After coming into touch with the anode of the electrochemical cell where the oxidant (Fe^{3+}) is formed, the leaching solution, which is made up of $FeCl_2$ and HCl , exits an electrochemical reactor. The leaching solution, together with the oxidant, is introduced to the base of one of the packed columns in order to oxidise the base metals while protecting the gold and platinum from being harmed. Galvanic processes define the metal ions departing the column in such a way that the least noble metals are first to leave. This is despite the fact that the oxidant is capable of oxidising many metals. After passing through the columns, the metal-rich solution is taken to the cathode side of the electrochemical cell, where it is used to electrowin the material that has been removed. In order to achieve the goal of containing the mass transfer zone, also known as the reaction zone, inside the packed columns, a sequence of three columns has been tried (Figure 2).

This makes it possible to completely reduce the oxidant, which in turn boosts the effectiveness of the present process towards the deposition of the recovered metals. When the entire extraction of base metals has been accomplished in the first column, that column may be exchanged with a new column, which will then occupy

the position of the last column in the series, so enabling a semi-continuous operation. For the ER process, a parametric optimization of the flow rate, applied current density, and iron concentration was carried out in order to bring down the amount of energy that was required to produce the deposit to as little as 1.94 kWhr/kg (Diaz, Clark, & Lister, 2016).

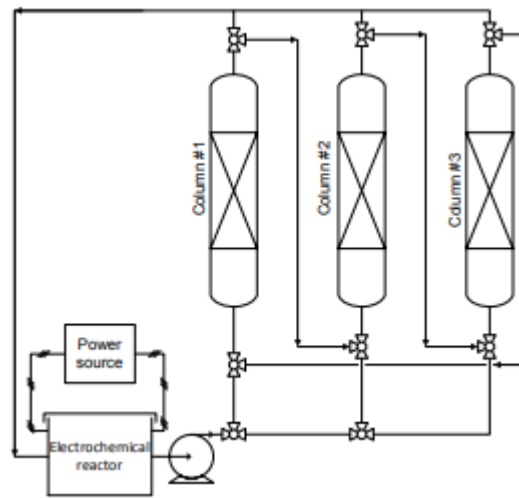


Figure 2 – Detailed explanation of the electrochemical recovery (ER) technique for extracting base metals from discarded electronic equipment

Producing AgCl from silver by oxidation by Fe³⁺ in a chloride medium is another possibility. Taking advantage of the fact that AgCl has a poor solubility, the majority of the silver is maintained inside the extraction column so that it may be extracted in a second step by complexation with sodium hyposulfite. An elemental examination of the recovered deposit of base metals, which is given as Figure 3a, reveals that a trace amount of silver is also present in the deposit together with the base metals. On the other hand, considering the initial composition of Ag on tiny IT e-waste that was published in a previous study (Diaz et al., 2015) as well as the production rate of deposit, this only accounts for 13% of the total Ag that is accessible.

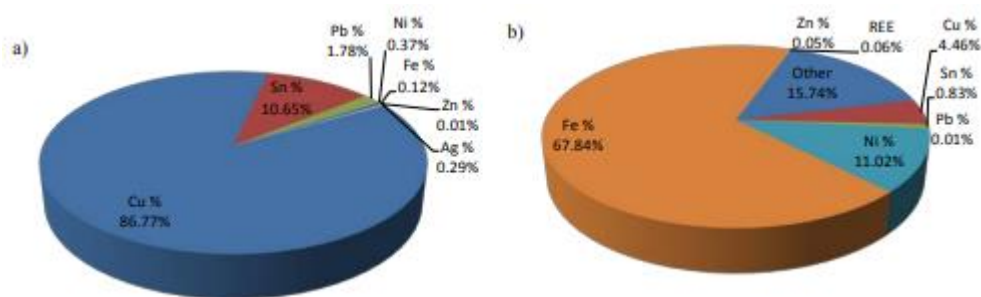


Figure 3 – The composition of a) the recovered base metals, and b) the steel stream derived from electronic trash

The composition of the metals in the deposit, which is illustrated in Figure 3a, also suggests that it may be valued as bronze or lead-tin bronze, depending on the exact percentages of the two metals (lead is now mostly engineered out of electronics). The extraction of base metals is going to have a revenue value assigned to it, and this feature is going to be utilised to determine that value.

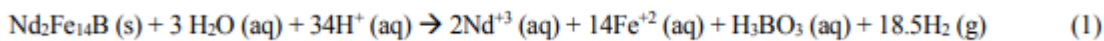
Precious Metals Extraction

When the silver has been complexed with sodium sulfite, it may be reclaimed from the extraction columns as was stated before. Experimentation with a solution of 0.1 M Na₂S₂O₃ with a liquid to solid ratio of 1:1 has been carried out. After extraction, silver is bonded to zinc powder, and then the bonded silver is digested with 1 M hydrochloric acid in order to yield pure silver. After accounting for the quantity of silver that was wasted during the extraction of base metals, recovery efficiencies have risen to more than 80 percent. Figure 1 illustrates the reagent needs for the process, which are determined by the quantity of electronic trash that must be processed.

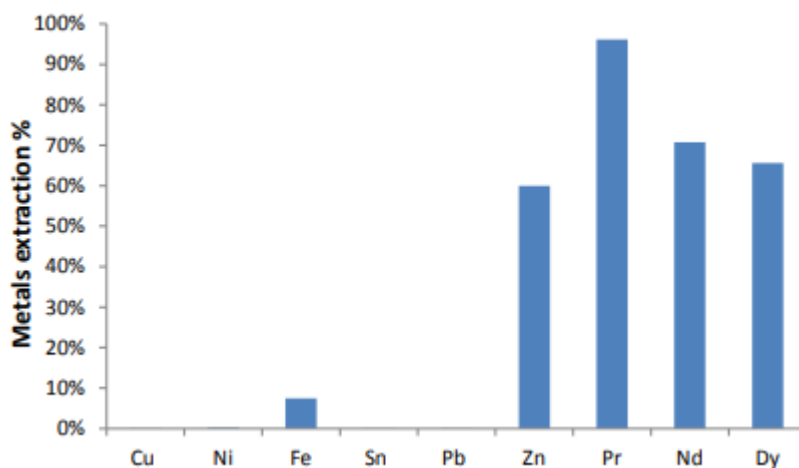
The extraction and recovery method for gold and platinum group metals is still in the process of being developed. For the sake of the techno economic analysis, a recovery efficiency of one hundred percent has been assumed. This is done on the basis of the encouraging results achieved using the extraction chemical and described elsewhere (Cheng et al., 2013). A sensitivity analysis based on the extraction efficiency is included in the techno economic evaluation because Au and Pd represent the greatest revenue value of the metal recovery process. This is because of the fact that Au and Pd represent the highest revenue value.

RARE EARTH EXTRACTION

As reported in other places, rare earth element extraction has been accomplished on the ferromagnetic portion of modest amounts of IT garbage (Diaz et al., 2015). According to Equation 1, the REE extraction process takes place in an atmosphere devoid of oxygen, and water serves as the oxidant in this reaction. It is expected that the elimination of oxygen in the leaching environment would prevent the corrosion of iron, as shown in Equation 2.



An overall REE extraction efficiency of 73% was attained, as shown by preliminary investigations conducted in a leaching solution consisting of 1M H₂SO₄, which was also reported in our earlier work (Diaz et al., 2015). Figure 4 illustrates the percentages of extraction for the various metals that may be found in the ferromagnetic stream. As can be seen, the amount of Fe extracted is quite modest in comparison to that of the REEs. Since the quantity of Fe removed is so near to being proportional to what is anticipated from Nd₂Fe₁₄B magnets, this suggests that the majority of the Fe taken originates from the magnet alloy.



anything of crucial and value

Mass and energy balances generated from bench scale experiments and from results previously reported on (Behnamfard, Salarirad, & Veglio, 2013; Cheng et al., 2013; Diaz et al., 2015) were used for the calculation of equipment specifications and the operating costs for the two process alternatives. Energy consumptions for pumps, heat exchangers, and agitation tanks were calculated using heuristic rules (Peters & Timmerhaus, 1991; Smith, 2005; Walas, 1990). Pressure drop of the fluid through the packed beds were calculated based on the bulk density of the milled cell phone material (0.827 kg/L) and the particle density obtained using the ASTM D845 method (1.43 kg/L).

The cost of the equipment was estimated by using cost-capacity tables and by employing proportional estimating techniques (Peters & Timmerhaus, 1991; Smith, 2005). The price adjustment was carried out utilising several indices that were accessible ("Financial Calculator," 2015). The total cost of the capital investment includes the multiplicative factors for installation, piping, and instrumentation, as well as a 10% cushion for unexpected expenses. Table 1 presents an estimate of the capital expenditures required for each of the two procedures. An accuracy of 30% is anticipated for the prices that have been calculated (Smith, 2005). Table 2 provides a summary of the primary assumptions that were taken into consideration in order to get the cash flow of the processes for the purpose of the economic evaluation.

Table 1 – Estimated Cost of equipment

	ER process	Hydrometallurgical process
	Cost \$/te-waste	Cost \$/te-waste
Shredder	4.91	4.91
Mill	7.80	7.80
Electrolyzer	2.78	2.78
Columns	10.52	
Batch reactor 1		97.57
Batch reactor PM extraction		18.97
Reactor Ag cementation and digestion	13.55	13.55
Reactor Au/Pd precipitation	9.76	9.76
Vacuum filter	66.63	66.63
Vacuum pump 10 kW	4.87	4.87
Pump ER	1.82	

Pump PM	1.08	
Balance pumps	2.61	2.61
REE Extraction system	10.52	10.52
REE precipitation tank	16.26	16.26
REE(OH) ₃ tank	2.71	2.71
Oven	13.33	13.33
Equipment cost	169.16	272.27
Total capital cost	405.98	653.46

Table 2 – Plant assumptions for the techno-economic assessment

Assumption	Assumed value
Plant financing debt/equity	100% Capital investments + 40 % First year operational costs
Term of debt financing	5 years
Interest for debt financing	10% annually
Evaluation period for IRR	5 years
Depreciation term	7 years
Income tax rate	35%
Inventory	10% Reagents and feedstock
Startup time	6 months
Revenue and costs during startup	Revenue= 50% of normal
	Operational costs = 50 % normal
	Administrative costs = 100% of normal
Operating time	300 days a year (7200 hours)

TECHNO ECONOMIC ASSESMENT RESULTS AND DISCUSSION

The elimination of several separation steps is made possible by the implementation of the ER process, which can treat the material while it is kept inside the extraction columns throughout the entire process. This is demonstrated by a straightforward comparison of the process flow diagrams shown in Figures 1 and 5, which can be found below. In spite of this, a comparison of the cumulative cash flow throughout the time in which the project is being evaluated might provide a more accurate evaluation of both processes for the sake of making economic judgements. The cash flow trends for both projects over the course of the five year period are shown in Figure 6. This recovery of gold and platinum group metals is assumed to be 100%. Since the expected amount of money borrowed for the hydrometallurgical project was nearly 1.4 times the amount of money borrowed for the ER-based process (\$8,567,675 vs. \$6,084,769), similar cash flows were seen after the first year of operation.

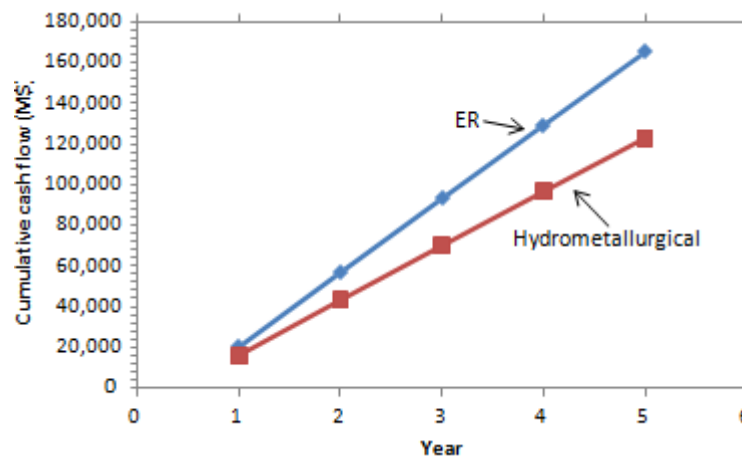


Figure 6 – Estimated cash flow patterns for the ER based and hydrometallurgical processes

In order to compute the cash flow shown in Figure 6, the revenue streams for both processes must be the same (\$63,321.385/year). From this total, 85% of the income must go to the Au streams, while the remaining 7% must relate to the Pd streams. The contribution of the REE to the overall income is just 0.53%, which is equivalent to \$336,900 per year. This indicates that the financial sustainability of the REE extractions is dependent on the recovery of precious metals, particularly gold. The disparities in cash flows between the two processes that are shown in Figure 6 are mostly attributable to the different production costs associated with each of the processes. A graphical comparison of the primary operating expenses associated with the ER-based process and the hydrometallurgical process is shown in Figure 7. Figure 7 also includes a comparison of the amounts spent on capital expenditures. The predicted results of significant cost savings in energy, water, and capital expenditures were seen. However, one of the most significant benefits of the ER-based process is that the extraction chemicals are kept within the cycle loop, and it is not necessary to add any additional chemicals beyond those that are required to initiate the process. This eliminates one of the most time-consuming steps of the process. This results in a large reduction in the total process's chemical consumption, which in turn results in a reduction in the expenses of operation.

The examination of the operating cost distributions that are shown in the inserts of Figure 7 enables us to derive a number of other significant findings. It has been found that the value of the feedstock, which was estimated to be \$7.79/kg ("SCRAPREGISTER," 2015), represents over 90% of the entire operating expenses for the ER-based process. Hence, a collection chain for electronic trash that is both effective and efficient may

drastically save expenses. To promote the responsible recycling of electronic trash, one method that may be employed is to provide a financial incentive. Nonetheless, generous incentives have the potential to have a discernible impact on the economic performance of the recovery process.

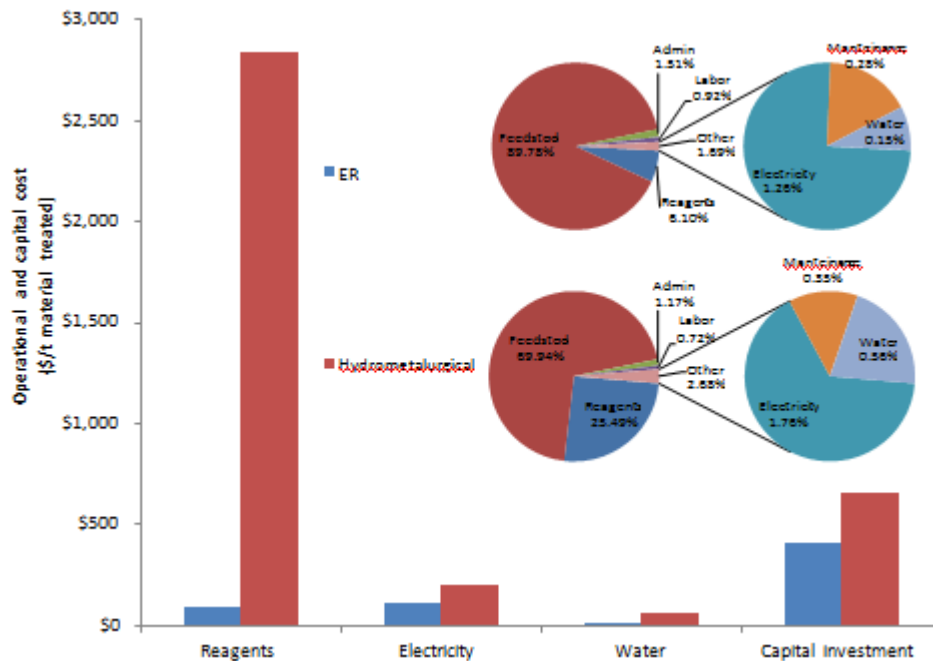


Figure 7 – Comparison of operational and capital costs for the ER based and hydrometallurgical processes.

Inserts the breakdown of total operating costs for the ER-based a) and hydrometallurgical process b) operations respectively

Sensitivity Analysis

A sensitivity analysis was performed recognizing the dependence of the precious metals streams in the process revenues, and the price of the feedstock in the operating expenses. streams in the process revenues. Figure 8 a and b illustrate, respectively, the influence of the Au/Pd recovery efficiencies and feedstock cost on the internal rate of return (IRR) of the ER-based process during the course of the assessment period of five years. According to the findings, an average gold recovery efficiency of 60% is necessary in order to achieve financial stability throughout the course of the five-year period. When the gold recovery concentration is less than or equal to 60%, the Pd recovery efficiency becomes important. In the final scenario, a Pd recovery of at least 60% is necessary in order to achieve financial neutrality throughout the course of the five-year term. Estimates of the effects of the recovery efficiencies were made using the price that was cited for e-waste.

The second scenario that is used for the feedstock cost sensitivity analysis is one in which recovery efficiencies of sixty percent are attained for both gold and platinum (Figure 8b). The internal rate of return (IRR) may be increased from 10% to 86.7% during the first five years by a feedstock price decrease of as little as 10%. This is a clear observation.

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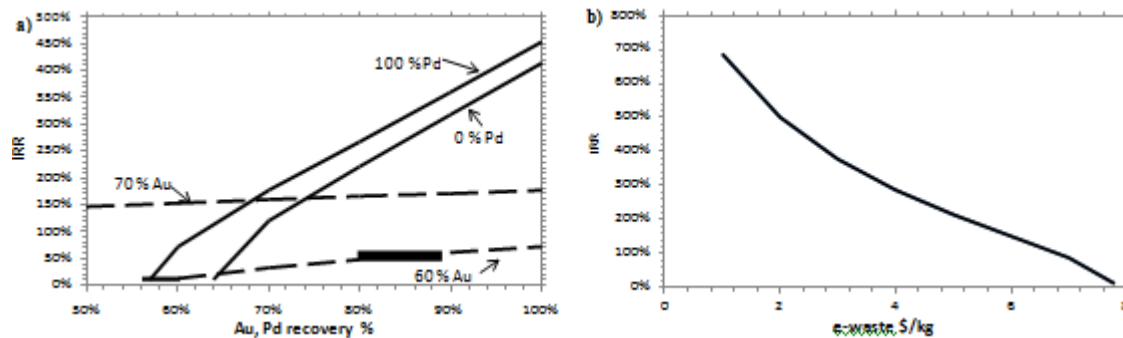


Figure 8 - Sensitivity analysis for the IRR for the recovery process based on recovery efficiencies for the precious metals revenue streams a), and the cost of the electronic waste b)

CONCLUSIONS

The recovery of rare and precious metals from e-waste is a complex process that requires the use of various techniques and strategies. Mechanical separation, hydrometallurgy, pyrometallurgy, and biometallurgy are the most common strategies used to recover these metals from e-waste. Each strategy has its own advantages and disadvantages, and the choice of strategy depends on the type of e-waste, the concentration of metals, and the desired end-product. While the recovery of rare and precious metals from e-waste is essential for the sustainable use of resources and reducing environmental impacts, it also presents a significant economic opportunity. The demand for these metals is increasing due to their use in various industries, and the availability of these metals from traditional sources is limited. Therefore, the recovery of these metals from e-waste can contribute to the circular economy and reduce the dependence on virgin resources. However, the recovery of rare and precious metals from e-waste is still facing several challenges, such as the lack of proper e-waste management, the high cost of recycling, and the low concentration of metals in e-waste. These challenges can be overcome by promoting proper e-waste management practices, developing cost-effective recycling technologies, and improving the efficiency of metal recovery processes.

In conclusion, the recovery of rare and precious metals from e-waste is a crucial process that requires the collaboration of various stakeholders, including policymakers, manufacturers, recyclers, and consumers. By working together, we can create a sustainable and circular economy that benefits both the environment and the economy.

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