COMPARATIVE LIFE CYCLE ANALYSIS FOR VALUE RECOVERY OF PRECIOUS METALS AND RARE EARTH ELEMENTS FROM ELECTRONIC WASTE

by

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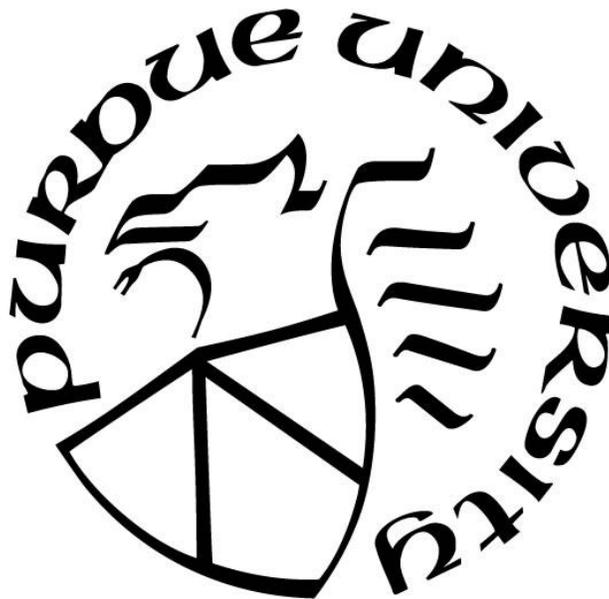
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Comparative Life Cycle Analysis for Value Recovery of Precious Metals and Rare Earth Elements from Electronic Waste

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LIST OF ABBREVIATIONS

EEE	Electrical or electronic equipment
ER	Electrochemical recovery
E-waste	Electronic waste
ILCD	International Reference Life Cycle Data system
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PCB	Printed circuit board
REE	Rare Earth Element
REO	Rare Earth Oxidant
TRACI	Tool for Reduction and Assessment of Chemicals and other environmental Impacts
WEEE	Waste electrical or electronic equipment

ABSTRACT

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There is an ever-increasing concern regarding electronic waste (e-waste), which is the fastest growing waste stream in the world. E-waste contains highly toxic materials such as halogenated flame retardants and heavy metals, as well as precious metals like gold, silver, and platinum. Its proper management and disposition are paramount. Incentivized by various legislations and the intrinsic value of critical metals inside, recycling of e-waste is becoming an attractive business opportunity that also benefits the environment. A novel electrochemical recovery (ER) process has been developed as a promising alternative to the existing pyrometallurgical and hydrometallurgical processes-based technologies to recover base metals, precious metals, and rare earth elements (REEs) from e-waste. Experimental results indicate that the ER process has lower chemical consumption, enhanced control, and reduced energy demand compared to the pyrometallurgical and the hydrometallurgical processes. To quantify and compare the environmental performances of the three technologies, life cycle analysis has been conducted. The baseline comparison used $1000 revenue from the e-waste recovery as a functional unit. Results show that the ER process outperforms the other two processes in almost all impact categories adopted in TRACI and ILCD while there is no clear winner between the hydrometallurgical and the pyrometallurgical processes. The life cycle analysis helped identify the significant inputs for different processes. The highest impactful input for the ER method is hydrochloric acid, and for the pyrometallurgical method is copper scrap, while for the hydrometallurgical method, it is hydrogen peroxide, an oxidizer that accelerates base metal extraction process that dominates the overall environmental footprint. Other than the baseline case, the environmental impacts of recovering REE from e-waste with different processes and from other method were studied. The results indicate REE recovered from e-waste has a lower environmental footprint than virgin extraction. Overall, the ER process has the lowest impacts on the environmental side among the three e-waste treatment processes. The

environmental viability of the ER process warrants the further development of the ER process at industrial scale.

1. INTRODUCTION

The rapid technological developments in the information and communication technology sector has allowed the consolidation of a highly competitive industry that fuels consumers to keep up with the latest available technology, but at the expense of a significant decrease in the lifespan of the electronic devices (Işıldar, Rene, van Hullebusch, & Lens, 2018). As a consequence, electronic waste (e-waste) has rapidly positioned as the fastest growing waste stream in the world (Awasthi et al., 2018). Around 44.7 million tons of e-waste was generated globally in 2017 and the amount is forecasted to be 52 million tons by the year 2021 (UN & World Business Council for Sustainable Development, 2019). This scenario has generated widespread concern among researchers and legislators regarding the management and disposition of e-waste, due to the high toxicity of some components and the valuable components.

From the European Union Waste Electronic and Electrical Equipment (EU WEEE) Directive (Parlamento Europeo, 2003), e-waste is defined as 'Electrical or electronic equipment (EEE) which is waste, including all components, sub-assemblies, and consumables, which are part of the product at the time of discarding'. The e-waste includes electrical and electronic scrap of varying sources, such as cell phones, tables, recorders, computers and televisions (Abdelbasir, Hassan, Kamel, & El-Nasr, 2018). Kumar et al., (2017) provided a review for the statistics for the e-waste, including the data for source and types of e-waste, generation of e-waste by regions and the lifespan for different electronics. Figure 1 shows the material composition by weight of the e-waste recycled by the SWICO recycling system in Switzerland. Metals account about 60% of the total weight, followed by 12% of plastics (Widmer, Oswald-Krapf, Sinha-Khetriwal,

Schnellmann, & Böni, 2005). A periodic table below helps to understand materials inside in term of metals and others.
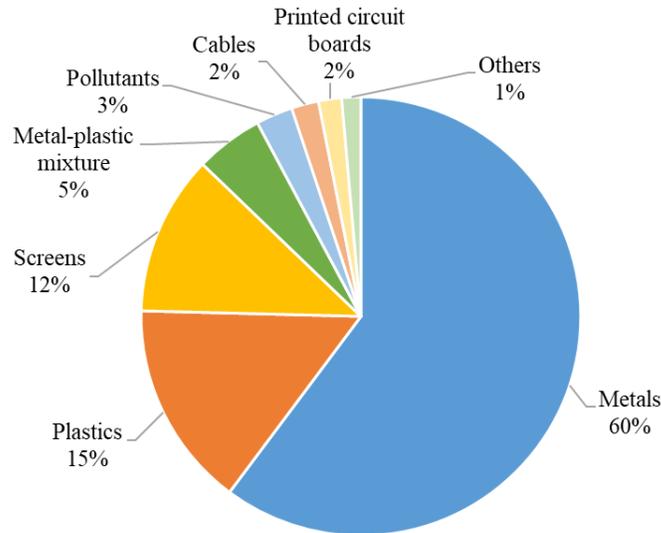
Figure 1 E-waste material compositions. Source: Adapted from Widmer et al., (2005)

From the global e-waste monitor 2017 report, around 60 elements from the periodic table can be found in complex electronics and many components are technically recoverable (Balde, Forti, Gray, Kuehr, & Stegmann, 2017). In Figure 2, colored elements are those can be found in e-waste. Precious metals are grouped in yellow and REEs are labeled with blue. Among these elements, precious metals have high value while some heavy metals (eg. Cadmium) are hazardous for human health and the environment. The opportunities and issues of the e-waste rise the concern of its end-life fate.

| | Precious metals | | Rare earth elements | | Others found in e-waste |

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La - Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac - Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Figure 2. Elements found in e-waste
(Modified from UN & World Business Council for Sastainable Development, (2019))

Motivated by the value and critical materials from the e-wastes, extensive studies are being conducted on optimizing processes, such as hydrometallurgical process and hydrometallurgical (Jelea, Jelea, & Hotea, 2010; Perkins, Brune Drisse, Nxele, & Sly, 2014; K. Zhang, Schnoor, & Zeng, 2012; W. H. Zhang, Wu, & Simonnot, 2012). In recent, a novel e-waste treatment, the electrochemical recovery (ER) process, has been developed to recycle the precious metals and REEs with less consumption of chemicals. Considering the different e-waste treatments, it is intuitive to question which process is the most beneficial. As the e-waste treatment processes consume a large number of chemicals and energy, the environmental impact can be used for processes comparison. Life cycle assessment (LCA) is a useful tool to evaluate and quantify the environmental footprint of a process over the lifetime. Even a lot of research was focused on the LCA of either the pyrometallurgical or the hydrometallurgical processes (Bigum, Brogaard, &

Christensen, 2012; Boyden, Soo, & Doolan, 2016; Xue, Kendall, Xu, & Schoenung, 2015), the comparative LCA studies are limited. The main reason is researchers used varying e-waste feedstock, which has different material fractions, and they took different approaches for calculating the environmental impacts. Therefore, there is a lack of LCA studies comparing the environmental impacts of different e-waste recycle technologies using consistent methodologies and boundary conditions, as well as reliable data for each process step in different technologies.

To fill these gaps, this research investigated and compared the environmental impacts of recovering precious metals and rare earth elements from e-waste using three different recycling approaches. Life cycle impact assessment was carried out on the hydrometallurgical, pyrometallurgical and the novel comprehensive ER technologies following the ISO 14040 standard. With the results of the LCA, the key contributors of each process to the environmental impacts were identified, will help to optimize the recovery process and decrease the environmental footprint. Furthermore, the precious metal recovery and REEs from e-waste were assessed and an economic comparison was presented.

2. LITERATURE REVIEW

This chapter provides a literature review of this study. It addresses the background of e-waste recycling and several typical processes to recycle the e-waste, such as the pyrometallurgical process and the hydrometallurgical process. Followed by the discussion of the e-waste treatments, research about the life cycle study of the recycling process is reviewed.

2.1. Motivation of E-waste Recycling

Several motivations for e-waste recycling are: 1) The economic values of inside precious metals are significate. 2) Recycling has lower environmental impacts and higher energy efficiency. 3) E-waste stream contains hazardous chemicals which can threaten human health (Kumar et al., 2017).

As indicated earlier, metal is the dominating fraction of the e-waste, which includes base and valuable metals, such as gold, silver, and copper. This provides the business opportunities to recover metals from the e-waste. Due to the broad range of e-waste, the fraction of different metals varies a lot. Table 1 shows the metal contents and valuable components for 1 ton of small IT and the data sources are labeled in the table. In terms of weight, steel and copper rank as top two of the metals and rare earth elements (REEs) in the e-waste. The estimated value of per ton small IT e-waste is shown in Table 1 is around $26,000. Considering the price of these elements, precious metals including gold, silver, and pallidum account for more than 90% of the value. Studies showed the more complex process is required for mining to meet the metals demand due to the declining ore grade (Abdelbasir et al., 2018). Metals in the e-waste have a higher concentration than the mineral ores. The average grade of copper, gold, and silver in waste electronics is significantly higher than which extracted with conventional mining. For instance, the

concentration of gold in electronics is above 100 ppm while the mine one only around 1 ppm. (Kumar et al., 2017)

Table 1. The elements weight and value of small IT e-waste (per ton)

Element	Weight (kg)	Unit price ($/kg)	Value percentage (%)	Value ($)
Cu	160.06	6.17[a]	3.74	988
Sn	16.57	21.13[b]	1.33	350
Pb	1.89	2.09[b]	0.01	4
Ni	20.36	14.10[b]	1.09	287
Fe	166.64	0.15[c]	0.09	25
Zn	12.38	2.54[b]	0.12	31
Ag	2.39	527.27[d]	4.78	1,262
Au	0.48	41043.60[e]	74.46	19,652
Pd	0.08	45139.00[b]	13.65	3,602
Pr	0.22	86.70[f]	0.07	19
Nd	1.82	69.00[f]	0.48	125
Dy	0.20	236.00[f]	0.18	48
			Total	$ 26,393

[a] Copper scrap price was from citation ("Today's Current Scrap Metal Prices - Rockaway Recycling," n.d.); [b] Sn, Pb, Ni, Zn, and Pd prices were from citation ("The London Metal Exchange," n.d.) [c] Steel price was from citation ("Steel - Rockaway Recycling," n.d.); [d] Silver price was from citation ("Silver Prices Today | Current Price of Silver | Silver Spot Price Chart History | APMEX," n.d.); [e] Gold price was from citation ("Gold Prices Today | Price of Gold Per Ounce | Gold Spot Price Chart | APMEX," n.d.); [f] Rare earth elements prices were from citation (Jin et al., 2018)

Other than the potential revenue of recovery materials, the scarcity of critical elements in the e-waste also motives the e-waste recycling business. Consider the availability of materials for future use, around half of the elements colored in the periodic table (Figure 2) would be limited available and have risks for future supply and some of them have serious scarcity in next 100 years (UN & World Business Council for Sustainable Development, 2019). Recycling the scarce materials is beneficial for maintaining the availability of the elements.

The recycling of e-waste benefits the environment in energy saving and hazardous waste removing. Recycled metals from e-waste not only have higher grade but consume less energy compared to virgin materials. They are two to 10 times more energy efficient than mined metals.

For instance, recycling aluminum provides a 95% energy saving and for iron is 70% saving in virgin material use (Mmereki, Li, Baldwin, & Hong, 2016). The energy saving also decreases greenhouse gas emission and other related environmental impacts.

On the other hand, recycling e-waste helps to keep the hazardous elements out of disposal with landfilling, which is important to environment protection and human health. Discarded electronics contain many toxic elements, such as lead and mercury. The improper treatment for these elements would risk the human and environment. Table 2 shows the several common hazardous materials in the e-waste with the occurrence and their effects on human health. Some materials can cause irreversible effects and accumulate in the human body (Kumar et al., 2017; Namias, 2013; Toffolet, 2016).

Table 2. Effect of the hazardous materials in e-waste

Materials	Component in e-waste	Effect on human health
Antimony	Flame retardant	Severe skin problems
Cadmium	printer inks and toners and photocopying-machines	Damage to kidneys and bone structure accumulate in the body
Lead	Cathode ray tubes and solder	Irreversible effects on the nervous system especially, accumulate in the body
Mercury	Fluorescent lamps, alkaline batteries	Highly toxic, damage to central nervous systems and kidneys, get converted to an organic methylated form that is highly bio-accumulative
Polybrominated diphenyl ether	Plastics	Interfere with growth hormones and sexual development, effect on immune systems, interfere with brain development in animals
Polychlorinated biphenyls	Condensers, transformers	Suppression of the immune system, liver damage, cancer promotion, damage to the nervous system,

Although recycling is encouraged for the economic, environment, and human health benefits, the complexity and expensive cost of the recycling processes makes the portion of recycling lower. It is notable the recycling rates for precious metals and base metals are comparative higher, which can be above 50% while recycling rates for REEs are normally less than 1% (Binnemans et al., 2013). In worldwide, an average of 20% of the e-waste is recycled and the remaining e-waste mostly ends up with landfill. Even in Europe, the leader in e-waste recycling, only around 35% of e-waste is properly collected and recycled. In the US, few regulations mandating to recycle electronic waste, and the portion of recycling e-waste in end processing is not high as desired (Namias, 2013). Optimizing the recycling processes of e-waste to make it more efficient and economic could make the recycling choice to be widespread.

2.2. End-processing for Metal Recovery

The recycling industry has seen a business opportunity in the surge of e-waste, mainly associated with the intrinsic value of the metals present in e-waste as indicated early. Moreover, process development has made the mining of metals from e-waste more cost-effective than the extraction of minerals from natural sources (Zeng, Mathews, & Li, 2018), with additional environmental benefits toward the stabilization of mineral supplies and the reduction of extractive mining. After the e-waste collected, the processing technologies to reclaim metals from e-waste can be divided into two basic steps: pre-processing, which is based on physical transformations, includes dismantling, sorting, and shredding; and end-processing i.e. chemical transformation that allow the separation and recovery of the metals in different streams. Among these steps, the highest value generation can be attributed to end-processing. Pyrometallurgical, hydrometallurgical, and combination of both processes dominate the literature and industrial implementation of e-waste end-processing (Kaya, 2016; Kumar et al., 2017).

With the focus on the environmental impacts of metal recovery with metal recovery processes, the following of this chapter shows the reviews related to the end-processing. Table 3 summarizes the advantages and issues of these treatments (Ebin & Isik, 2016; Kumar et al., 2017; Namias, 2013; Tunsu & Retegan, 2016)

Table 3. Comparison of difference metallurgy treatments

Process	Advantage	Limitation
Pyrometallurgy	-Higher reaction rates -Easier separation of valuable and waste	-Require more energy -Plastic cannot be recycled -Iron and aluminum are hard to be recovery -Require large investment -Hazardous emissions are generated in smelting which has harmful impacts on the environment
Hydrometallurgy	-Accurate and predictable -Easily controllable -Less energy intensive	-Slow and time-consuming -Require fine size in pre-processing -Require more chemicals and make the process is high toxicity
ER	-Fewer chemicals -Higher efficient -Low investment and operation cost	- Less practical applications

The pyrometallurgical process is the most common process for recovering metal from e-waste and includes a high-temperature furnace for melting. It is used to recover silver, gold, and copper. The high temperature makes this process has a high reaction rate and the wastes are easy to be separated (Ebin & Isik, 2016).

The general pyrometallurgical process begins with sorting. In this stage, hazardous components like batteries are removed firstly, then the remaining e-waste is shredded to appropriate size. This step is known as size reduction. To know the metal content of the shredded

particles, a sample will be collected. After sorting, the e-waste is sent to the smelter and converter and obtains impure copper. The following steps, anode Furnace, electro-fining and precious metals refining, recover precious metals and copper (Namias, 2013). As indicated early, the pyrometallurgical process causes some environmental issues, researchers are continuing to effort on making it cleaner (Cui & Zhang, 2008; Ghosh, Ghosh, Parhi, Mukherjee, & Mishra, 2015).

Hagelüken et al. (2005) integrated lead and copper smelters that currently operate for the processing of e-waste in the Umicore's integrated metals smelter and refinery plant in Belgium, which is a widely accepted approach for pyrometallurgical process. Figure 3 shows the flow diagram for the pyrometallurgical process evaluated in this study, which is also called black copper smelting (BCS) routine (Diaz & Lister, 2018). This process recovers fine copper from copper scrap with benefits on recovering gold, silver, and REEs from e-waste. In the first stage, magnetic fraction separated the ferromagnetic components, which are packed to the steel, and REEs processing section and non- ferromagnetic components. For the non- ferromagnetic components, they are sent to the reduction furnace with the copper scrape. Then impurity metals are isolated from the crude copper in the oxidation furnace, followed by the fire refining process, in which the oxygen content is reduced with the agent of natural gas. To obtain fine copper, the electro refining process is followed. In this process, the precious metals are released as slime and transported to the precious metals refining process. Owing to the lack of literature on the palladium recovery, this study excludes it in the analysis. A more detailed description of this process as well as techno economic analysis of the process applied to electronic waste are available in the referenced literature (Diaz & Lister, 2018; Ghodrat, Rhamdhani, Brooks, Masood, & Corder, 2016).
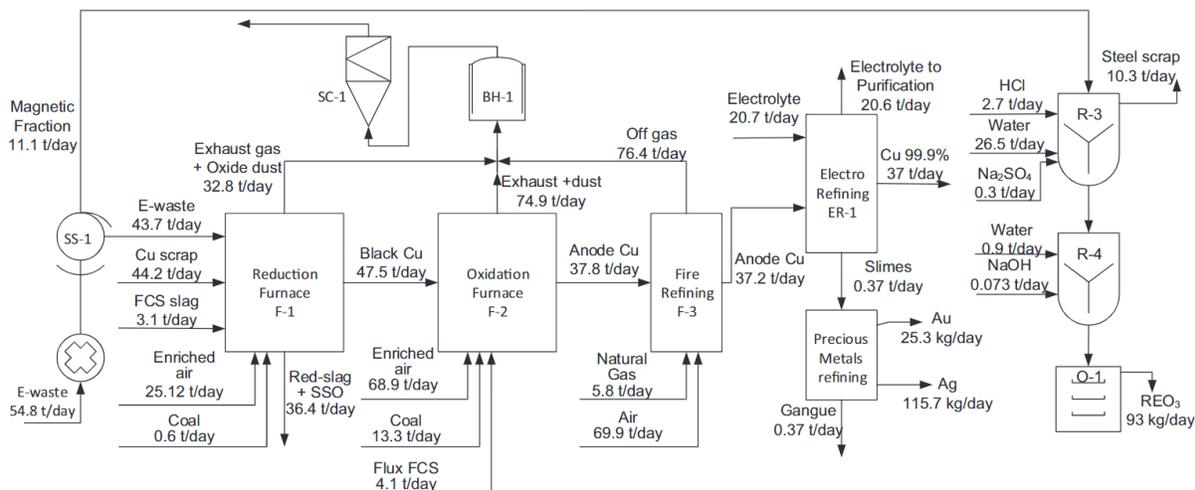
Figure 3. Process flow diagram for pyrometallurgical process (Diaz & Lister, 2018)

Due to the emission regulations, the pyrometallurgical process always requires a larger scale facility. It also has an issue of high energy requirement. The minimum viable smelting operation requires an annual throughput of 30 kt/year (Diaz, Lister, Parkman, & Clark, 2016) and the capital investment is around $ 15 million (Diaz & Lister, 2018). Most of the leading companies use this process are located in Europe and some moderate size facilities are located in Japan and South Koran (Namias, 2013).

Compared to the pyrometallurgical process, the hydrometallurgical process is more economical and environmentally friendly. The hydrometallurgical process involves leaching and can be applied at a small scale (Ghosh et al., 2015; Tunsu & Retegan, 2016). Three main steps of the hydrometallurgical treatment are leaching, separation and metals recovery. Many studies have been conducted on the leaching agent (Cui & Zhang, 2008; Kamberovic, Korac, & Ranitovic, 2011; Tunsu & Retegan, 2016). Acid is the most efficient agent as it can leach both precious and base metals. The common leaching agents for gold and silver are thiourea or cyanide. Cui and

Zhang (2008) provided a review on the leaching agents for different metals in hydrometallurgical treatments as well as the chemical reactions between agents and metals.

Figure 4 shows the flow diagram for the hydrometallurgical process evaluated in this study. This process is developed based on available literature (Behnamfard, Salarirad, & Veglio, 2013; Cheng et al., 2013). Similar to the pyrometallurgical process, precious metals extraction and REEs extraction are separated after shredding and magnetic separation. In the base metal extraction part, sulfuric acid with hydrogen peroxide is used to leach metal. After this step, copper is extracted with electro winning method and precious metals fraction is extracted with metabisulfite and thiosulfate oxidant. Finally, silver is cemented on zinc powder and digested with hydrochloric acid to obtain pure silver.
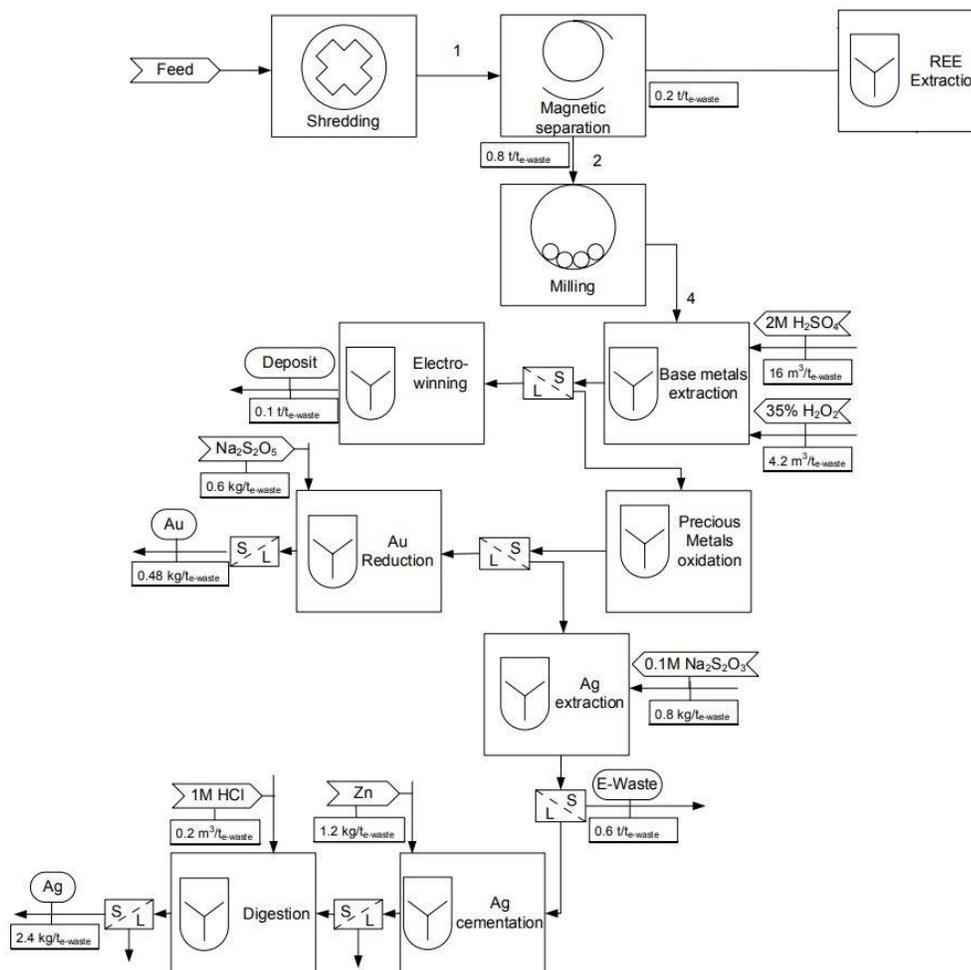
Figure 4. Process flow diagram for hydrometallurgical process(T.E. Lister, Diaz, Clark, & Keller, 2016)

However, despite that hydrometallurgical process is much less energy-intensive, its issues with long processing time and toxicity cannot be neglected. Electrochemical methods have been developed to reduce the use of reagents (Ghosh et al., 2015).

Due to the low chemical consumption, enhanced control, and reduced energy demand, electrochemical based processes are being developed as an alternative to existing pyrometallurgical and hydrometallurgical techniques. In this study, the novel ER process using a weak oxidizer (Fe^{3+}) is chosen for the analysis which can be renewed electrochemically. The

chemical reaction and detailed process description will be presented in the methodology chapter. To have an overview of this process, Figure 5 shows the flow diagram of the ER process. The non-magnetic fraction is processed in the extraction column, where it can reactive with the weak oxidant generated in the electrochemical reactor. The least noble metals like copper and steel are extracted in the first extraction column. The second extraction column is for silver, which is oxidized by the weak oxidant in chloride media. Similar to the hydrometallurgical process, the pure silver will be obtained after cementation and digestion. For the gold recovery, same hydrometallurgical steps applied here (Diaz, Clark, & Lister, 2017; Tedd E. Lister, Wang, & Anderko, 2014).
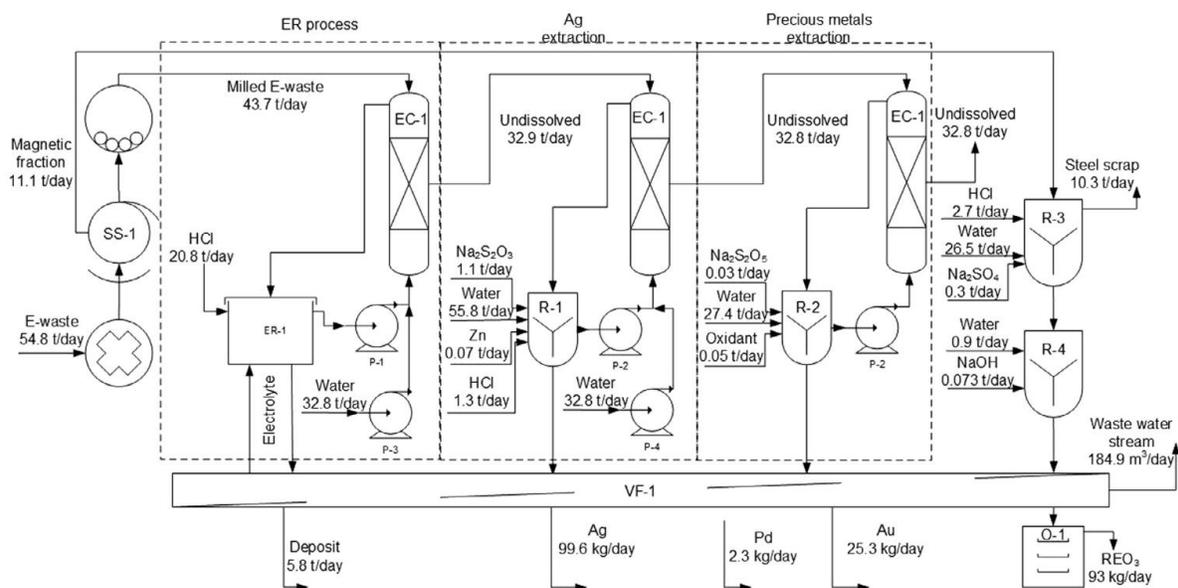
Figure 5. Process flow diagram for ER process

This process has lower capital investment than the pyrometallurgical route while using fewer chemicals than the hydrometallurgical route. Diaz et al., (2017) conducted a techno economic analysis of the ER process and black copper smelting routine for the recovery of metals

from e-waste. A base scenario of 20,000 ton/year of cell phone material is considered for the simulation and the capital investment is around $ 6.8 million (Diaz & Lister, 2018).

The REEs extraction for these processes is similar, the magnetic fraction is firstly performed in hydrochloric acid or sulfuric acid to dissolve the REEs and sodium sulfate is added to recover the rare earth content as a precipitate. Finally, this precipitate is converted to rare-earth oxides by reacting with sodium hydroxide. The experiment showed the extraction efficiency can achieve above 70% (Diaz et al., 2016).

Other than the abovementioned three processes, biometallurgical process using the interactions between microbes and metals can also be applied to recover metals from e-waste. Bioleaching and biosorption are two main interactions utilized to leach metal like copper (Das & Sen, 2001; Sethurajan, Lens, Horn, Figueiredo, & van Hullebusch, 2017). As the recovery of precious metals has not been achieved, this study did not include the biometallurgical process for the comparison (Namias, 2013).

2.3. LCA Study of E-waste Recycling

Life cycle assessment is an environmental management tool to access the environmental impacts of a product, process, or service (Rodriguez-Garcia & Weil, 2016). Depending on the study objectives, LCA can follow a cradle-to-grave, cradle-to-gate, gate- to-grave, or gate-to-gate approach. ISO, which standardizes the LCA, provides the general methodology for performing LCA (ISO, 2006). Figure 6 shows the framework for LCA methodology and the relationship in different stages.
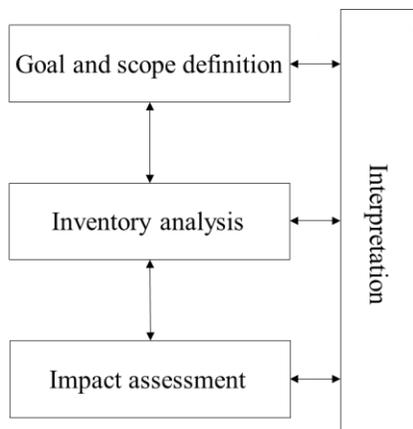
Figure 6. LCA framework

The first step is defining the goal and scope of the project, such as the objective and system boundary for this study. The second step is collecting the inputs and outputs for the process or system, including raw materials, energy usage, products, and wastes. With the data collected in the inventory analysis, the potential environmental impacts can be evaluated. This step is called the life cycle impact assessment (LCIA), and different environmental categories can be selected for the evaluation. The final step is concluding the study and interpreting results, and it may include the new case study or sensitivity analysis (Rodriguez-Garcia & Weil, 2016).

Considering the chemicals and energy required for the metal recovery processes from e-waste, it is highly recommended to perform LCA on the recovery process. The environmental benefits of metal extraction from e-waste over primary sources, using either the pyrometallurgical or the hydrometallurgical processes, have been documented in multiple studies in recent years using LCA (Bailey, 2016; Bigum et al., 2012; Ghodrat, Rhamdhani, Brooks, Rashidi, & Samali, 2017; Hong, Shi, Wang, Chen, & Li, 2015; Iannicelli-Zubiani et al., 2017; Rocchetti, Vegliò, Kopacek, & Beolchini, 2013; Rubin, Castro, Brandão, Schalch, & Ometto, 2014; Xue et al., 2015) Bigum et al., (2012) studied the environmental impacts of recovering metals from high-grade WEEE with pyrometallurgical processes via using data from the literature review. Gold, silver,

palladium, copper, aluminum, iron, and nickel were recovered. In this study, the is1000 kilogram of high-grade WEEE with the pre-treatment. The preprocessing such as shredding and sorting of the WEEE was included in the system boundary. LCI in this study was from five literatures and separated into five stages, which is from pre-treatment to the precious metal refining. EASEWASTE model using the EDIP method was used for the LCIA and the impacts categories are global impacts, region, and local impacts, human toxicity, and persistent toxicity. In this study, mass allocation and economic allocation are considered to analyze the environmental impacts. The results showed e-waste recycling has significant environmental savings compared with mining and refining virgin metals and precious metals contributed more than the common metals in environmental impact. As not all the data can be found, an uncertainty analysis is desired to support their conclusion.

Ghodrat et al., (2017) conducted LCA on recycling precious metals from waste PCB with smelting method for Australia. The goal of this study was to evaluate the environmental impacts of recovering precious metals in PCBs. The functional unit is 12.5 ton/ hour feed inputs. Two scenarios with different inputs and system boundaries were developed: 1) recycling of precious metal out of waste PCBs with adding copper scrap which included precious metals refining process, and 2) refining copper out of the copper scrap without adding e-waste. The inventory analysis referred to literature and available Australian data and the ReCiPe method was for the LCIA. The results of LCIA implied that the impacts of recovering precious metals from e-waste are higher than the impacts of the second scenario. However, considering the second scenario excluded precious metal refining, this comparison is limited as the final products of these two scenarios have a significant difference in terms of value and types.

LCA of hydrometallurgical processes studied metal recovery from a variety of e-waste streams such as printed circuit board (PCB) (Xue et al., 2015), physically treated residue of WEEE (Rocchetti et al., 2013), and mobile phones (Iannicelli-Zubiani et al., 2017).

Xue et al. (2015) applied LCA methodology to assess a hydrometallurgical PCB recycling process that includes product collection, preprocessing, heavy metal recovery, and precious metal recovery. Results highlighted the environmental benefits of metal recycling from e-wastes than primary metal production from virgin materials. As for the recycling process, leaching in the refining stage contributed most of the environmental impacts in the recycling chain. Rocchetti et al. (2013) studied the environmental impacts of recovering metals including yttrium, cobalt, gold, and silver from the physically treated residue of WEEE using hydrometallurgical processes. The global warming potential of value recovery from different e-waste demonstrated a significant reduction of carbon footprint compared with primary metal production. Iannicelli-Zubiani et al. (2017) assessed the environmental impacts of recovering copper, silver, and gold from a mobile phone in a hydrometallurgical pilot plant. Their LCA was conducted from cradle-to-gate and the results showed nitric acid leaching in gold recovery contributed most of the environmental impacts, which pointed out the critical steps for eco-design improvement.

The LCA is also applied to a single process or specific materials other than the whole process (Hong et al., 2015; Rubin et al., 2014). Rubin et al., (2014)compared the environmental impacts of recovering copper from PCB scrap with mechanical and electrochemical combined methods using either sulfuric acid or aqua regia (nitric and chloridric acid). 102 kg copper was chosen as the functional units and the boundary included electrochemical process. With the data from literature and the experiments, they conducted LCIA and concluded acqua regia has better environmental performance than sulfuric acid. As the electrochemical process always combined

with the other treatment, this paper would be more comprehensive by expanding the system boundary. Hong et al., (2015) conducted the LCA of e-waste treatment in China and compared the environmental impacts of recycling with and without the end-life disposal. They performed a gate-to-gate analysis of 1 ton of e-waste. Researchers collected operation and emission data from an e-waste recycling facility, China and the without the end-life disposal e-waste sample in a small town. LCIA results were calculated with the ReCiPe method and the results showed e-waste recycling with end-life disposal is beneficial by lowing the environmental burden. The without disposal scenario has a high potential impact on human health, marine eutrophication, and etcetera. The main contributors to each environmental category of the two scenarios were also discussed. Furthermore, sensitivity analysis and uncertainty analysis were conducted to make this study more reliable.

Despite their contribution, the aforementioned studies did not directly compare the life cycle impacts of different e-waste processing technologies for precious metals recovery. Existing literature focused on either the pyrometallurgical or the hydrometallurgical methods, or the environmental impacts of disposal with primitive e-waste recycling operations.

Bailey (2016) conducted a comparative LCA for recycling neodymium magnets from e-waste with hydrometallurgical and pyrometallurgical techniques. His results showed there is no winner between the two techniques. However, this study was limited to recycling a particular element from e-waste. Rodriguez-Garcia and Weil (2016) provided a statistical overview of LCA literature related to waste electrical and electronic equipment (WEEE) recycling in recent years. They reviewed 47 related LCA studies of e-waste and only 13 of them focused on the recycling processes. Additionally, around 50% of the 47 studies did not provide the life cycle inventory (LCI), which is one step for slandered LCA. Therefore, there is a lack of LCA studies comparing

the environmental impacts of different e-waste recycle technologies using consistent methodologies and boundary conditions, as well as reliable data for each process step in different technologies.

To fill these research gaps, this research investigated and compared the environmental impacts of recovering precious metals and rare earth elements from e-waste using three different recycling approaches. Life cycle impact assessment was carried out on the hydrometallurgical, pyrometallurgical and the novel comprehensive ER technologies following the ISO 14040 standard. Impacts of precious metals recovery from e-waste with these processes were assessed, and the key contributors to the environmental issues were identified.

3. METHODOLOGY

ISO standard LCA methodology is used for this study, which includes four steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation (ISO, 2006). This chapter presents the goal and scope in this study, inventory analysis along with the description three e-waste recycling processes, and environmental categories for the life cycle assessment.

3.1. Goal and Scope

This research was performed to evaluate the environmental impacts of different methods to recover precious metals from e-waste. The goals were to 1) quantify the environmental impacts of recovering precious metals from the ER, the hydrometallurgical, and the pyrometallurgical technologies and compare within the different methods, and 2) identify the key process or material in each method for e-waste recycling that contributes the most significant impact on the environment. The geographic region of e-waste recycling is assumed to be in the United States as the ER process is developed for the application in the U.S. As the goal is to highlight the differences in processing technologies than confounding the impacts with reverse logistics, a single country was selected for the analyses. Account for the final outputs include a variety of materials such as gold (Au), silver (Ag), copper (Cu) and REEs that are extracted at different stages of the recycling processes and the difference in recovery efficiency, the functional unit is defined as $1000 worth of materials recovered from e-waste. Therefore, the life cycle impacts of recycling $1000 products from e-waste are compared for different value recovery technologies.

Among the recovered materials, gold represents the single largest revenue source. Therefore, additional analyses have been conducted for assessing the environmental impacts of recovering 1kg of gold from e-waste.

The system boundary of this LCA is grave-to-gate for three recycling routes: the ER process, the hydrometallurgical process, and the pyrometallurgical process. Detailed processes flows are provided in the following section. All processes start with the feedstock material of e-waste, which undergoes preprocessing and size reduction. The starting material compositions were assumed to be the same so that the three methods can be compared without bias. The LCA ends at the precious metals and REE materials extraction stage. As metals recovered from the three processing technologies, such as Au and Ag, are of similar qualities but their amounts are different due to variations in the recovery efficiencies, an equal product value ($1000) and equal mass of the product (1kg of gold) as the base to conduct the LCA study.

3.2. Life Cycle Inventory

In this work, a comparative life cycle analysis among the traditional pyrometallurgical/ hydrometallurgical processes and an electrochemical based alternative has been performed. The material inputs, energy flow, and emission data were gathered at Idaho National Laboratory based on the lab scale experiments on the electrochemical recovery. The corresponding data for the hydrometallurgical and the pyrometallurgical processes were based on available literature (Behnamfard et al., 2013; Ghodrat, Rhamdhani, Brooks, Masood, & Corder, 2016). It was assumed that the facility can process 10 ton/day of small IT e-waste using hydrometallurgical methods and 54.8 ton/ day using the other two methods (Diaz & Lister, 2018; T.E. Lister et al., 2016). The detailed process diagrams are discussed in the literature review chapter. A brief description of the processes alternatives is presented below to understand the materials and waste flows.

3.2.1. Hydrometallurgical Process

Hydrometallurgical processes are based on the oxidation of the metals using mineral acids, caustic leaching agents or suitable oxidants. The oxidation (extraction) of metals is performed in a series of steps that allow the selective recovery of different value streams. Acid leaching is commonly employed for the removal of base metals (Cu, Ni, Sn, Zn, etc.), while stronger oxidants like halides or complexing agents, such as cyanide, thiosulfates, and thiourea are used for the extraction of precious metals. After extraction, the respective leaching solutions could go through a purification/concentration step using either solvent extraction, adsorption or ion-exchange, or directly to metal recovery through chemical reduction or electro-refining (Cui & Zhang, 2008). The main steps and flows for a hydrometallurgical process option are presented in Figure 7.
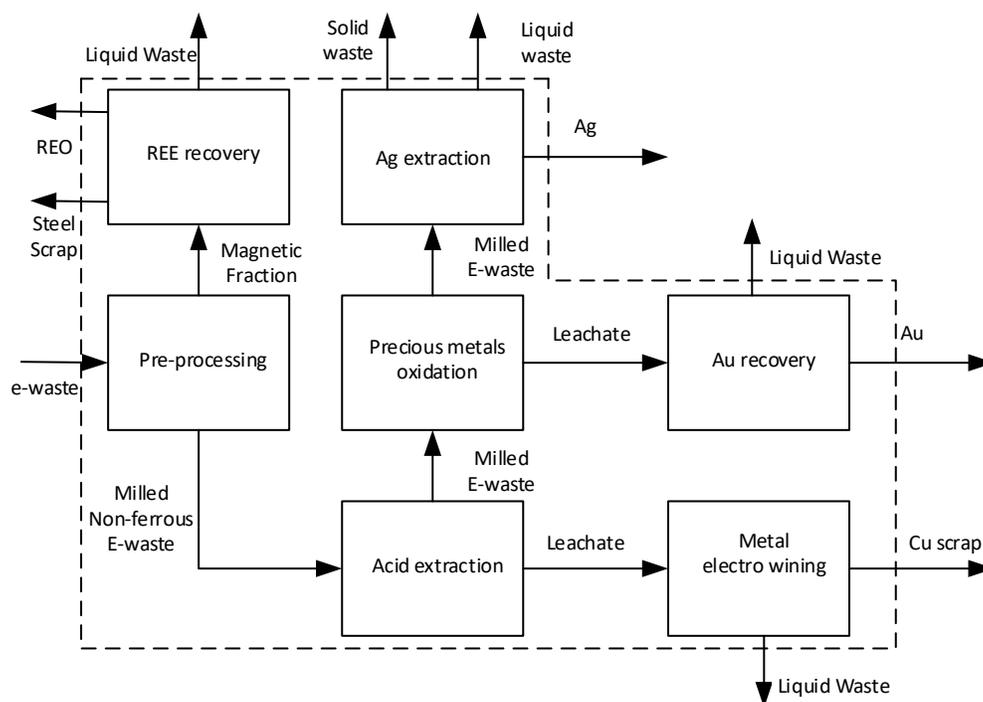
Figure 7. System boundary of hydrometallurgical processing

Based on the techno economic analysis presented by Lister et al. (2016), the amount of major materials, energy inputs as well as emissions for all three extraction processes to obtain

$1000 value product are organized in tables for inventory analysis. Table 4 is the inventory table for the hydrometallurgical process. The oxidant can be recycled in this process and here assumed it can use10 times. Limestone does not react with e-waste for metal recovering and it is included to neutralize the remaining acid in the solution.

Table 4. Life cycle inventory to obtain $1000 for the hydrometallurgical process

Input / Output	Consumption	Unit	Unit Process
Inputs from technosphere			
Electricity	63.59	kWh	Electricity, medium voltage, at grid, 2015/US US-EI U
Hydrochloric acid	1.2272	kg	Hydrochloric acid, 30% in H_2O, at plant/US- US-EI U
Hydrogen peroxide	226.14	kg	Hydrogen peroxide, without water, in 50% solution state {GLO}| market for	APOS, U
Sodium thiosulfate	0.168	kg	Sodium persulfate {GLO}| market for	APOS, U
Sodium sulfate	0.2630	kg	Sodium sulfate, anhydrite {RoW}| market for	APOS, U
Sulfuric acid	164.78	kg	Sulphuric acid, liquid, at plant/US- US-EI U
Sodium hydroxide	0.064	kg	Sodium hydroxide, without water, in 50% solution state {GLO}| market for	APOS, U
Zinc	0.0614	kg	Zinc {RoW}| primary production from concentrate	APOS, U
Sodium metabisulfite	0.0277	kg	Sodium persulfate {GLO}| market for	APOS, U
Oxidant ($FeCl_3$)	0.0439	kg	Iron (III) chloride, 40% in H_2O, at plant/US* US-EI U
Calcium carbonate	148.13	kg	Limestone, crushed, washed {RoW}| market for limestone, crushed, washed	APOS, U
Direct emissions			
Residue	28.75	kg	Solid waste
Water	163.66	L	Waste water, to water

3.2.2. Pyrometallurgical Process

Pyrometallurgical processing for the reclamation of metals from waste streams has been a well-established technology for over two decades. Cu smelters rather than lead smelters are more suitable for the processing of e-waste since in the lead smelters produce a copper matte product that still needs to be refined through black copper smelting (Khaliq, Rhamdhani, Brooks, & Masood, 2014). Additional advantages of Cu smelters over lead smelters include the production of less harmful fumes and the alternative to recover precious metals using conventional electro-

refining. For this LCA, the boundary for the BCS routine is shown in Figure 8. The process can be described in four consecutive steps: a reduction furnace where coal and/or the polymers present on the e-waste are used as reducing agent to obtain the crude black Cu, an oxidation furnace that allow the separation of metal impurities as oxide slag, the fire refining where natural gas is used to remove the oxygen in the molten Cu to produce Cu anode, and the electro refining processes, which include Cu and precious metals electro-refining.
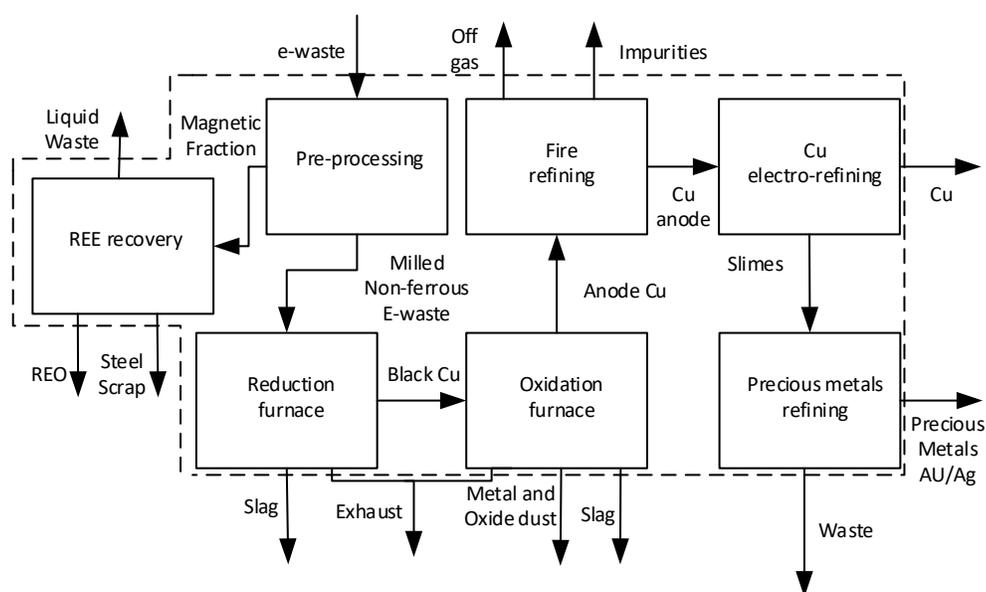
Figure 8. System boundary of pyrometallurgical processing

Similar to the hydrometallurgical process, the inventory for the pyrometallurgical process are listed in Table 5. In this process, the enriched air contains 70% oxygen. Followed by one study of enriched air (Belaissaoui et al, 2014), here assumed 1kg of enriched air consumes 2.5 kg air and 0.15 kWh electricity. FCS slag is an abbreviation of ferrous calcium silicate slag, which is consisted of FeO_x, CaO, and SiO_2. This study used the ratio of 44%-20%-36% for the FSC slag

(Ghodrat et al., 2016). As the natural gas in the LCA database does not include carbon dioxide emission, CO_2 released is added in the LCI.

Table 5. Life cycle inventory to obtain $1000 for the pyrometallurgical process

Input / Output	Consumption	Unit	Unit Process
Inputs from nature			
Water	21.27	kg	Water, cooling, surface
Air	50.846	kg	Air
Inputs from technosphere			
Electricity	107.61	kWh	Electricity, medium voltage, at grid, 2015/US US-EI U
Copper scrap	24.23	kg	Copper scrap, sorted, pressed {GLO}| market for	APOS, U
Coal	10.11	kg	Charcoal {GLO}| market for	APOS, U
Enriched air	68.39	kg	Air and energy data from (Belaissaoui et al., 2014)
FCS slag	3.55	kg	Iron ore, 65% Fe, at beneficiation/GLO US-EI U
	1.32	kg	Activated silica {GLO}| market for	APOS, U
	1.61	kg	Calcium silicate, blocks and elements, production mix, at plant, density 1400 to 2000 kg/m^3 RER S
Natural gas	5.27	m^3	Natural gas, high pressure {RoW}| market for	APOS, U
Hydrochloric acid	0.687	kg	Hydrochloric acid, 30% in H_2O, at plant/US- US-EI U
Sodium hydroxide	0.053	kg	Sodium hydroxide, without water, in 50% solution state {GLO}| market for	APOS, U
Sodium sulfate	0.22	kg	Sodium sulfate, anhydrite {RoW}| market for	APOS, U
Electrolyte	0.047	kg	Sulphuric acid, liquid, at plant/US- US-EI U
Calcium carbonate	1.135	kg	Limestone, crushed, washed {RoW}| market for limestone, crushed, washed	APOS, U
Direct emissions			
Slag (Precious metal refining)	0.27	kg	Solid waste
Slag (Reduction furnace)	26.46	kg	Solid waste
Slag (Oxidation furnace)	10.86	kg	Solid waste
CO_2 release (Natural gas) [a]	147.62	kg	Carbon dioxide
Exhaust gas	133.92	kg	Exhaust to air

[a] CO_2 release value calculation is based on reference (Vahidi, Navarro, & Zhao, 2016).

3.2.3. Electrochemical Recovery Process

The ER process (Figure 9) is based on the integration of the metal's extraction and metal electrowinning steps, which are separated in a traditional hydrometallurgical process. This process

integration allows completely different extraction chemistry to be used for the extraction of base metals.
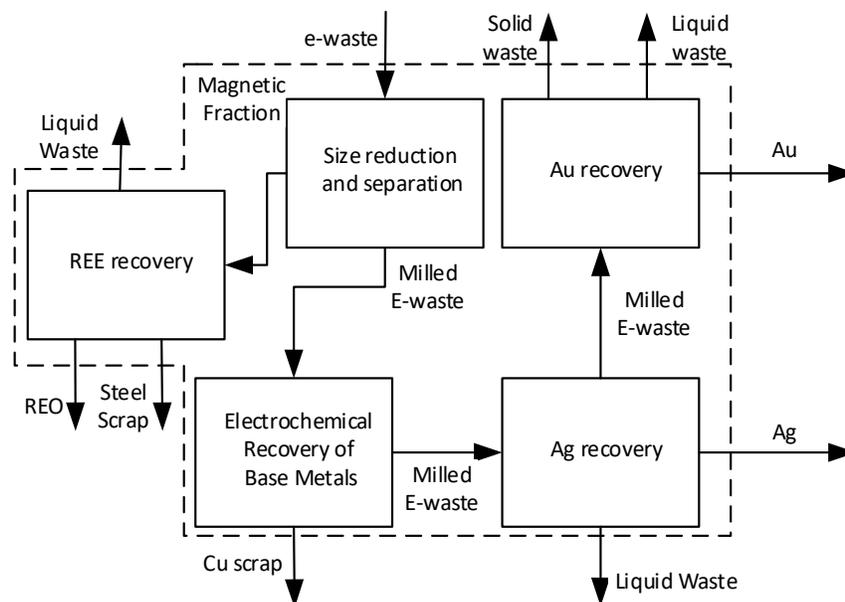
Figure 9. System boundary of ER processing

In the ER process, Fe^{3+} is generated at the anode of a flow-through electrochemical cell (Equation 1) from a leaching solution containing $FeCl_2$ and HCl. The leaching solution with the oxidant is fed to a series of e-waste packed columns where the base metals (Cu, Sn, Zn, Ni, etc.) are oxidized (Equation 2).

After leaving the extraction columns the leachate returns to the cathode side of the electrochemical cell, where the base metals are electrowon and recovered (Equation 3). Ag from the e-waste is also oxidized but the low solubility of the AgCl maintains most of the oxidized silver within the columns. A series of at least three columns help to maintain the silver within the extraction system (due to galvanic reactions) and assure the complete reaction of the oxidant before it is returned to the electrochemical cell. Spent e-waste material is removed from the extraction

series and replaced with a new column to continue the cycle. Ag is then selectively recovered

through complexation with Na_2SO_3.

$$Fe^{2+} \rightarrow Fe^{3+} + e^- \qquad E^0 = 0.771 \text{ V vs. SHE} \tag{1}$$

$$nFe^{3+} + M \rightarrow M^{n+} + nFe^{2+} \tag{2}$$

$$M^{n+} + ne^- \rightarrow M \tag{3}$$

A significant reduction in chemical consumption can be achieved due to the regeneration

of the oxidant used to extract the base metals, which represent over 90% of the total metal content

in the e-waste. Precious metals are then selectively extracted and recovered as in the traditional

hydrometallurgical processes. The inventory for the ER process is shown in Table 6.

Table 6. Life cycle inventory to obtain $1000 for the ER process

Input / Output	Consumption	Unit	Unit Process
Inputs from nature			
water	156	kg	Water, cooling, surface
Inputs from technosphere			
Electricity	25.35	kWh	Electricity, medium voltage, at grid, 2015/US US-EI U
Hydrochloric acid	7.684	kg	Hydrochloric acid, 30% in H_2O, at plant/US- US-EI U
Sodium hydroxide	0.065	kg	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | APOS, U
Sodium thiosulfate	0.974	kg	Sodium persulfate {GLO}| market for | APOS, U
Sodium sulfate	0.266	kg	Sodium sulfate, anhydrite {RoW}| market for | APOS, U
Zinc	0.062	kg	Zinc {RoW}| primary production from concentrate | APOS, U
Sodium metabisulfite	0.027	kg	Sodium persulfate {GLO}| market for | APOS, U
Oxidant ($FeCl_3$)	0.044	kg	Iron (III) chloride, 40% in H_2O, at plant/US* US-EI U
Calcium carbonate	10.53	kg	Limestone, crushed, washed {RoW}| market for limestone, crushed, washed | APOS, U
Direct emissions			
Residue	29.03	kg	Solid waste
Water	163.66	L	Waste water, to water

The LCA was carried out by using SimaPro 8.3. The Ecoinvent 3 database was used for

most of the unit processes except for electricity, water, hydrochloric acid, and sulfuric acid. Since

the experiment was conducted in the United States, the datasets from the "US- US-EI U" are used to match the location. "Electricity, medium voltage, at grid, 2015/US US-EI U" was used to consider the mix-produced electricity and processed water (RER S) was used as the water usage in the electrochemical recovery process. Direct emissions to the environment in the three processes were roughly categorized as solid waste, air emission, and waste water.

Table 7 shows the recycling efficiencies per element and global based on Equation 4, it considered all inlets and outlets. In this case, the weight of inlets are the same and it is the weight of the total e-waste. The column for weight is the original weight in 1 ton of e-waste. The recovery efficiency for gold is 97% for all three processes if compared the extracted gold with the gold contained in the e-waste.

$$\eta = \frac{\sum m_{i,out}}{\sum m_{i,in}} \times 100\%$$

(4)

Table 7. Recycling efficiencies per ton e-waste of different elements in three processes

	Weight (kg)	ER	Hydro	Pyro
Cu	160.1	15.9%	15.9%	37.7%
Sn	16.6	1.7%	1.7%	0.1%
Pb	1.9	0.2%	0.2%	0.0%
Ni	20.4	1.5%	1.5%	0.8%
Fe	166.6	14.8%	14.8%	8.2%
Zn	12.4	0.1%	0.1%	0.0%
Ag	2.4	0.2%	0.2%	0.1%
Au	0.5	0.0%	0.0%	0.0%
Pr	0.2	0.0%	0.0%	0.0%
Nd	1.8	0.1%	0.1%	0.1%
Dy	0.2	0.0%	0.0%	0.0%
Total	383.0	0.345	0.345	0.470

It should be mention that the efficiency is higher for Cu in the pyrometallurgical process because there is a significant input of copper scrap as feedstock to the process. Convert to the

efficiency of metal recovery rate, the %Cu recovery for the pyrometallurgical process is around 240%. For the ER and hydrometallurgical processes, the Pb and Sn are 100% recycled.

3.3. Life Cycle Impact Assessment

To fully facilitate the use of results, TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) and ILCD (International Reference Life Cycle Data) methods were used to assess the environmental burdens. Both methods are widely used in LCA studies, they provide characterization factors for LCIA. TRACI is developed by the United States Environmental Protection Agency (EPA) and it is widely used in the U.S. ILCD is developed by the Institute for Environment and Sustainability in the European Commission Joint Research Centre, in co-operation with the Environment DG which is widely used in Europe. To show more details in the impact assessment categories, ILCD method for midpoint impact assessment was used.

3.4. Environmental Impacts Allocation

As mentioned in the goal and scope, the final products of precious metals extraction are not limited to gold. Table 8 shows the amount of gold, silver, and some other products during the extraction. Values in the parenthesis are ratios which are corresponded to share values in the revenue stream. It shows the amount of silver extracted in the pyrometallurgical process is larger than the other processes, while the ER method has the least silver extracted. In the LCA study, economic allocation is a good approach to evaluate the environmental impacts when the material values are different. Based on the value of different elements, the allocation factors are calculated based on the market price and the number of elements.

Table 8. Allocation factors used for metal recovery

Extract	hydrometallurgical		pyrometallurgical		ER		Unit price
	Weight (kg)	% Price	Weight (kg)	% Price	Weight (kg)	% Price	$/kg
Gold (kg)	1	91.02%	1	75.53%	1	91.92%	41043.6[a]
Silver (kg)	5	5.85%	4.57	4.43%	3.94	4.65%	527.27[b]
REE (kg)	3.54	0.52%	3.676	0.45%	3.67	0.54%	66[c]
Steel (kg)	395.8	0.13%	407.11	0.11%	407.1	0.14%	0.15[d]
Copper scrap (kg)	181.25	2.48%	-	-	198.7	2.75%	6.17[e]
Copper (kg)	-	-	1462.1	19.47%	-	-	7.24[f]
Total revenue							
Revenue ($)	45,091		54,338		44,650		-

[a] Gold prices was from citation ("Gold Prices Today | Price of Gold Per Ounce | Gold Spot Price Chart | APMEX," n.d.); [b] Silver prices was from citation ("Silver Prices Today | Current Price of Silver | Silver Spot Price Chart History | APMEX," n.d.); [c] REE prices was from citation (Diaz & Lister, 2018) ; [d] Copper scrap prices was from citation ("Today's Current Scrap Metal Prices - Rockaway Recycling," n.d.); [e] Steel prices was from citation ("Steel - Rockaway Recycling," n.d.); [f] Copper prices was from citation ("1 Week Copper Prices and Copper Price Charts - InvestmentMine," n.d.)

Aforementioned, the alternative case study uses 1kg gold as the functional unit because gold is the main value for all three technologies. In this case study, three scenarios for gold and REE recovery are considered. In scenario 1, allocation within all final products based on their revenue to analyze the environmental impacts of each metal is applied. In scenario 2, it separated the precious metals recovery and REEs recovery processes and evaluated their impacts as the REEs recovery for each method are the same. In this scenario, REEs are assumed as by-products. The energy consumed in the pre-processing step will be only included in the precious metals' recovery. In scenario 3, the energy consumed in pre-processing would be allocated based on the value of metals and REE. The other processes are the same as scenario 2. These three scenarios are used to evaluate the environmental impacts of recovering gold and REE under difference considerations.

4. RESULTS

4.1. Life Cycle Assessment: Baseline

Table 9 and Table 10 show the comparative life cycle impact of extracting precious metals with the ER method, the hydrometallurgical method and the pyrometallurgical method by using TRACI and ILCD in SimaPro 8.3 separately. Overall, the ER process (column ER of both Table 9 and Table 10) has lower environmental impacts than the hydrometallurgical process (column H of both Table 9and Table 10) for all categories. Compared to the pyrometallurgical process (column P of both Table 9and Table 10), ER has significantly lower impacts for all categories expect ozone depletion. Considering the operational cost and capital cost, ER has the lowest cost among the three processes.

As for the hydrometallurgical method and the pyrometallurgical method, there is no clear winner between them. In the TRACI method, six categories have the impact of the hydrometallurgical process higher than that of the pyrometallurgical process. For the ILCD method, 11 out of 16 categories have a higher impact on the hydrometallurgical process compared to the pyrometallurgical process. Other than the environmental impacts, the hydrometallurgical method has higher capital cost and lower operational cost compared to the pyrometallurgical method.

Table 9. Overall results for the different processes per $1000 products (TRACI)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Ozone depletion [kg CFC-11 eq]	1.76E-03	4.38E-04	402%	3.48E-04	79%
Global warming [kg CO_2 eq]	1.79E+04	5.79E+04	31%	1.23E+03	2%
Smog [kg O_3 eq]	8.77E+02	4.42E+02	199%	5.90E+01	13%
Acidification [kg SO_2 eq]	1.68E+02	4.61E+01	364%	5.93E+00	13%
Eutrophication [kg N eq]	5.18E+01	1.11E+02	47%	3.45E+00	3%
Carcinogenics [CTUh]	3.85E-03	1.08E-03	356%	6.81E-05	6%
Non carcinogenics [CTUh]	5.97E-03	2.91E-02	21%	4.92E-04	2%
Respiratory effects [kg PM2.5 eq]	1.92E+01	8.11E+00	236%	4.72E-01	6%
Ecotoxicity [CTUe]	2.38E+05	5.40E+05	44%	7.16E+03	1%
Fossil fuel depletion [MJ surplus]	2.72E+04	8.00E+03	340%	1.35E+03	17%

Table 10. Overall results for the different processes per $1000 products (ILCD)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Climate change [kg CO_2 eq]	4.04E+02	1.05E+03	39%	2.75E+01	3%
Ozone depletion [kg CFC_{-11} eq]	3.17E-05	6.00E-06	528%	7.38E-06	123%
Human toxicity, non-cancer effects [CTUh]	1.32E-04	5.35E-04	25%	1.10E-05	2%
Human toxicity, cancer effects [CTUh]	8.53E-05	1.99E-05	429%	1.53E-06	8%
Particulate matter [kg PM2.5 eq]	3.81E-01	9.87E-02	386%	9.41E-03	10%
Ionizing radiation HH [kBq U_{235} eq]	4.06E+01	3.01E+01	135%	7.79E+00	26%
Ionizing radiation E (interim) [CTUe]	8.80E-05	1.65E-05	534%	1.49E-06	9%
Photochemical ozone formation [kg NMVOC eq]	2.25E+00	1.92E+00	117%	5.01E-01	26%
Acidification [molc H^+ eq]	4.68E+00	1.03E+00	453%	1.60E-01	15%
Terrestrial eutrophication [molc N eq]	3.48E+00	1.57E+00	222%	2.17E-01	14%
Freshwater eutrophication [kg P eq]	1.30E-01	2.76E-01	47%	9.80E-03	4%
Marine eutrophication [kg N eq]	3.67E-01	1.46E-01	251%	2.14E-02	15%
Freshwater ecotoxicity [CTUe]	5.28E+03	9.99E+03	53%	1.61E+02	2%
Land use [kg C deficit]	3.76E+02	3.05E+02	123%	1.40E+01	5%
Water resource depletion [m^3 water eq]	9.54E+01	1.17E+02	81%	3.65E+01	31%
Mineral, fossil & ren resource depletion [kg Sb eq]	3.07E-02	1.27E-02	242%	1.70E-02	134%

To identify the major source of the environmental impact for different processes, the contribution of each component in all processes was analyzed. Figure 10 to Figure 12 show the detailed LCA results for individual inputs and outputs of the three processes with the TRACI method.
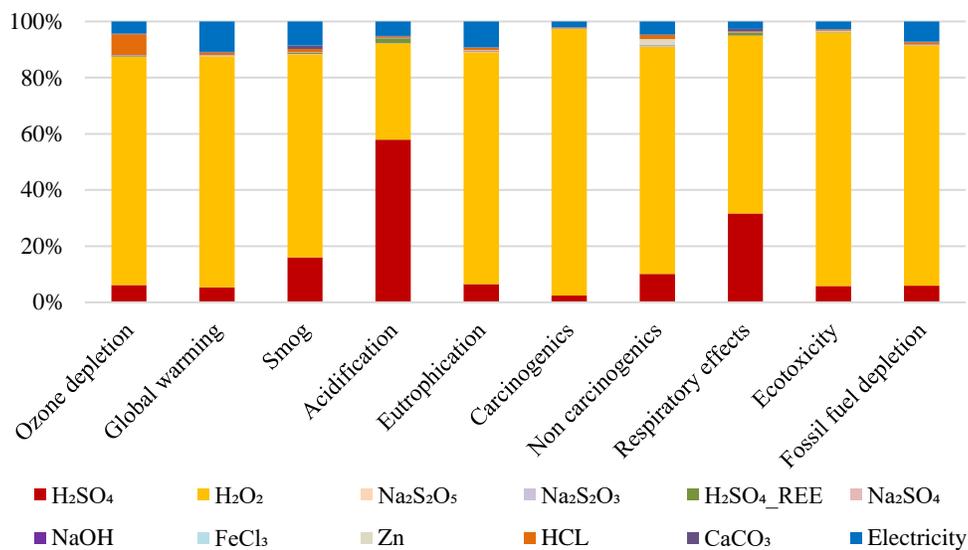
Figure 10. Environmental impact of each component in the hydrometallurgical method for $1000

Two input materials that contributed significantly to the environmental impacts of the hydrometallurgical process are as follows: 1) Hydrogen peroxide in the base metal extraction process, which has meaningful impacts on almost all environmental categories; 2) Sulfuric acid which takes around 60% of the total impact for the acidification and 30% for the respiratory effects. It is worth mentioning that the hydrogen peroxide and sulfuric acid in the extraction procedure were assumed to not have been recycled. For that reason, these two components have higher impacts on the environment.
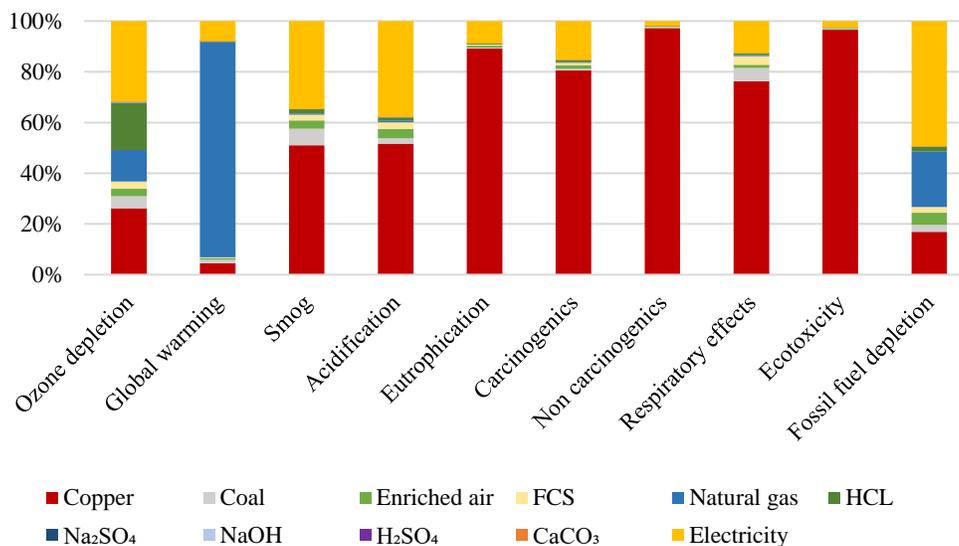
Figure 11. Environmental impact of each component in the pyrometallurgical method for $1000

Copper scrap added in the reduction furnace contributed significantly to most of the environmental impacts. In terms of global warming, natural gas has the biggest contribution because it has carbon dioxide emission. Electricity is another significant item that has higher impacts and it has the biggest contribution to the ozone depletion and fossil fuel depletion.
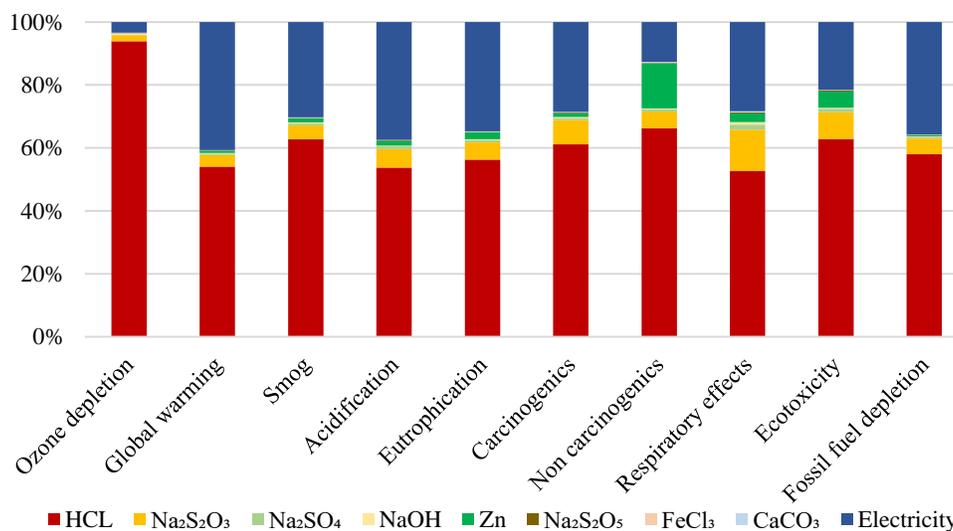
Figure 12. Environmental impact of each component in the ER method for $1000

For the ER process, two input materials also contributed significantly to environmental impacts. Firstly, hydrochloric acid contributes more than 50% of the total impact of all categories. Especially for ozone depletion, it amounts to 90% of the total impact. Secondly, electricity in the ER process constitutes 5% to 40% impact in each environmental category. In this analysis, most of the hydrochloric acid is used in the process to extract REEs. If only precious metal recovery is considered, hydrochloric acid will have a lower impact. Moreover, similar to the hydrometallurgical process, recycling of the acid was not considered.

4.2. Alternative Scenarios

Contrary to Section 4.1 where the functional unit is $1,000 worth of metals recovered from e-waste, one may be interested in knowing the environmental impacts associated with one specific precious metal recovery. To answer this question, the functional unit of this case study is set as 1kg of gold recovered from e-waste as gold represents the highest value in the final product (scenario 1). It should be noted that after magnetic separation, the initial feedstock (i.e., e-waste) are divided into two groups of materials: one group that contains precious metals and the other that contains REEs. Therefore, the REE recovery process can be considered as a separate process than the precious metal recovery after magnetic separation (i.e., we can recover precious metals without including the REE recovery process). Accordingly, this case study examines the environmental impacts of precious metal recovery excluding the impacts of REE recovery. A special precaution should be taken during the pre-processing steps that are common for both precious metals and REE recovery. Scenarios 2 and 3 are created as follows: In scenario 2, all the energy required in the pre-processing (like size reduction and magnetic fraction) is assumed to be accounted for the precious metal production only. Scenario 3 separates the pre-processing impacts accounted for precious metal recovery using the allocation factors established in Table 8.

Table 11 and Table 12 are the results for the LCA to produce 1kg of gold with price allocation of all products (Scenario 1). The result and percentage are mostly matched with the result based on the $1000 value analysis because they both considered the price of each product. Overall, the ER method is the best one to recycle gold if consider environmental impacts.

Besides, Table 13 and Table 14 show the life cycle impact to product 1kg REEs under scenario 1. Due to scenario 1 uses the price allocation and the amount of REEs is similar for all three methods when obtaining 1kg of gold, the ratio did not change significantly compared to Table 11 and Table 12. For the pyrometallurgical and ER methods, the amount of REEs is almost the same when obtaining 1kg of gold, while the hydrometallurgical process has fewer REEs. These can explain why the H/P column in Table 13 is slightly lower than the same column in Table 11.

Table 11. Comparative life cycle impact of producing 1 kilogram gold (Scenario 1, TRACI)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Ozone depletion [kg CFC-$_{11}$ eq]	1.60E-03	3.31E-04	484%	3.20E-04	97%
Global warming [kg CO_2 eq]	1.63E+04	4.37E+04	37%	1.13E+03	3%
Smog [kg O_3 eq]	7.98E+02	3.34E+02	239%	5.42E+01	16%
Acidification [kg SO_2 eq]	1.53E+02	3.48E+01	439%	5.45E+00	16%
Eutrophication [kg N eq]	4.71E+01	8.38E+01	56%	3.17E+00	4%
Carcinogenics [CTUh]	3.50E-03	8.16E-04	430%	6.26E-05	8%
Non carcinogenics [CTUh]	5.43E-03	2.20E-02	25%	4.52E-04	2%
Respiratory effects [kg PM2.5 eq]	1.75E+01	6.13E+00	285%	4.34E-01	7%
Ecotoxicity [CTUe]	2.17E+05	4.08E+05	53%	6.58E+03	2%
Fossil fuel depletion [MJ surplus]	2.48E+04	6.04E+03	410%	1.24E+03	21%

Table 12. Comparative life cycle impact of producing 1 kilogram gold (Scenario 1, ILCD)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Climate change [kg CO_2 eq]	1.66E+04	4.30E+04	39%	1.13E+03	3%
Ozone depletion [kg CFC_{-11} eq]	1.30E-03	2.46E-04	528%	3.03E-04	123%
Human toxicity, non-cancer effects [CTUh]	5.43E-03	2.20E-02	25%	4.52E-04	2%
Human toxicity, cancer effects [CTUh]	3.50E-03	8.16E-04	429%	6.26E-05	8%
Particulate matter [kg PM2.5 eq]	1.56E+01	4.05E+00	386%	3.86E-01	10%
Ionizing radiation HH [kBq U_{235} eq]	1.67E+03	1.23E+03	135%	3.20E+02	26%
Ionizing radiation E (interim) [CTUe]	3.61E-03	6.76E-04	534%	6.10E-05	9%
Photochemical ozone formation [kg NMVOC eq]	9.24E+01	7.87E+01	117%	2.06E+01	26%
Acidification [molc H^+ eq]	1.92E+02	4.24E+01	453%	6.57E+00	15%
Terrestrial eutrophication [molc N eq]	1.43E+02	6.44E+01	222%	8.92E+00	14%
Freshwater eutrophication [kg P eq]	5.32E+00	1.13E+01	47%	4.02E-01	4%
Marine eutrophication [kg N eq]	1.51E+01	5.99E+00	251%	8.77E-01	15%
Freshwater ecotoxicity [CTUe]	2.17E+05	4.10E+05	53%	6.62E+03	2%
Land use [kg C deficit]	1.54E+04	1.25E+04	123%	5.76E+02	5%
Water resource depletion [m^3 water eq]	3.91E+03	4.80E+03	81%	1.50E+03	31%
Mineral, fossil & ren resource depletion [kg Sb eq]	1.26E+00	5.21E-01	242%	6.96E-01	134%

Table 13. Comparative life cycle impact of producing 1 kilogram REE (Scenario 1, TRACI)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Ozone depletion [kg CFC-$_{11}$ eq]	2.59E-06	5.36E-07	482%	5.12E-07	95%
Global warming [kg CO_2 eq]	2.63E+01	7.09E+01	37%	1.81E+00	3%
Smog [kg O_3 eq]	1.29E+00	5.41E-01	238%	8.68E-02	16%
Acidification [kg SO_2 eq]	2.47E-01	5.64E-02	437%	8.73E-03	15%
Eutrophication [kg N eq]	7.61E-02	1.36E-01	56%	5.08E-03	4%
Carcinogenics [CTUh]	5.66E-06	1.32E-06	428%	1.00E-07	8%
Non carcinogenics [CTUh]	8.77E-06	3.56E-05	25%	7.24E-07	2%
Respiratory effects [kg PM2.5 eq]	2.82E-02	9.93E-03	284%	6.94E-04	7%
Ecotoxicity [CTUe]	3.50E+02	6.61E+02	53%	1.05E+01	2%
Fossil fuel depletion [MJ surplus]	4.00E+01	9.79E+00	408%	1.99E+00	20%

Table 14. Comparative life cycle impact of producing 1 kilogram REE (Scenario 1, ILCD)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Climate change [kg CO_2 eq]	2.67E+01	6.97E+01	38%	1.81E+00	3%
Ozone depletion [kg CFC_{-11} eq]	2.10E-06	3.99E-07	526%	4.85E-07	121%
Human toxicity, non-cancer effects [CTUh]	8.77E-06	3.56E-05	25%	7.24E-07	2%
Human toxicity, cancer effects [CTUh]	5.65E-06	1.32E-06	427%	1.00E-07	8%
Particulate matter [kg PM2.5 eq]	2.53E-02	6.56E-03	385%	6.18E-04	9%
Ionizing radiation HH [kBq U_{235} eq]	2.69E+00	2.00E+00	134%	5.12E-01	26%
Ionizing radiation E (interim) [CTUe]	5.83E-06	1.10E-06	531%	9.76E-08	9%
Photochemical ozone formation [kg NMVOC eq]	1.49E-01	1.28E-01	117%	3.29E-02	26%
Acidification [molc H^+ eq]	3.10E-01	6.88E-02	451%	1.05E-02	15%
Terrestrial eutrophication [molc N eq]	2.30E-01	1.04E-01	221%	1.43E-02	14%
Freshwater eutrophication [kg P eq]	8.58E-03	1.84E-02	47%	6.44E-04	4%
Marine eutrophication [kg N eq]	2.43E-02	9.70E-03	250%	1.40E-03	14%
Freshwater ecotoxicity [CTUe]	3.50E+02	6.64E+02	53%	1.06E+01	2%
Land use [kg C deficit]	2.49E+01	2.03E+01	123%	9.22E-01	5%
Water resource depletion [m^3 water eq]	6.32E+00	7.79E+00	81%	2.40E+00	31%
Mineral, fossil & ren resource depletion [kg Sb eq]	2.04E-03	8.45E-04	241%	1.11E-03	132%

Table 15 and Table 16 are the results for the LCA in Scenario 2 where 1kg of gold was produced without considering the REE recovery process. Although all the energy consumption during the pre-process was counted in the precious metal recovery process, the total impacts were still lower than the results in scenario 1 without the REE recovery. The H/P was lower in scenario 2 than in scenario 1 as the fraction of revenue contributed from gold (75.53%) of the pyrometallurgical process was lower than in the hydrometallurgical process (91.02 %) and ER (91.92%). In this scenario, the ER process had lower environmental impacts with the ozone depletion impact similar to the pyrometallurgical process and the other impacts much lower than the other two methods. There was still no obvious winner between the hydrometallurgical and pyrometallurgical methods in this scenario.

Table 17 and Table 18 show the life cycle impact producing REE as a separate process following the precious metal recovery in scenario 2. The energy consumption in pre-processing was not considered in evaluating the environmental impacts of REE production in this scenario. The values in the tables are converted to be based on 1kg REEs. As the pyrometallurgical process and the ER process has the same input materials and similar amount REEs output, the environmental impacts of recovery 1kg REEs in these two methods are the same. The hydrometallurgical process had a higher impact due to the use of sulfuric acid in REEs extraction, which led to high acidification and respiration effect as shown in the H/P column in Table 17 and Table 18.

Table 15. Comparative life cycle impact of producing 1 kilogram gold (Scenario 2, TRACI)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Ozone depletion [kg CFC-$_{11}$ eq]	1.72E-03	4.01E-04	429%	3.12E-04	78%
Global warming [kg CO_2 eq]	1.78E+04	5.77E+04	31%	1.15E+03	2%
Smog [kg O_3 eq]	8.68E+02	4.37E+02	199%	5.46E+01	12%
Acidification [kg SO_2 eq]	1.65E+02	4.57E+01	360%	5.51E+00	12%
Eutrophication [kg N eq]	5.15E+01	1.11E+02	47%	3.21E+00	3%
Carcinogenics [CTUh]	3.84E-03	1.08E-03	357%	6.33E-05	6%
Non carcinogenics [CTUh]	5.92E-03	2.90E-02	20%	4.57E-04	2%
Respiratory effects [kg PM2.5 eq]	1.89E+01	8.07E+00	235%	4.32E-01	5%
Ecotoxicity [CTUe]	2.37E+05	5.40E+05	44%	6.60E+03	1%
Fossil fuel depletion [MJ surplus]	2.70E+04	7.90E+03	342%	1.26E+03	16%

Table 16. Comparative life cycle impact of producing 1 kilogram gold (Scenario 2, ILCD)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Climate change [kg CO_2 eq]	1.81E+04	5.67E+04	32%	1.15E+03	2%
Ozone depletion [kg CFC_{-11} eq]	1.39E-03	2.91E-04	478%	2.94E-04	101%
Human toxicity, non-cancer effects [CTUh]	5.92E-03	2.90E-02	20%	4.57E-04	2%
Human toxicity, cancer effects [CTUh]	3.84E-03	1.08E-03	357%	6.33E-05	6%
Particulate matter [kg PM2.5 eq]	1.70E+01	5.32E+00	318%	3.84E-01	7%
Ionizing radiation HH [kBq U_{235} eq]	1.81E+03	1.61E+03	112%	3.28E+02	20%
Ionizing radiation E (interim) [CTUe]	3.96E-03	8.89E-04	445%	6.01E-05	7%
Photochemical ozone formation [kg NMVOC eq]	9.96E+01	1.03E+02	97%	2.10E+01	20%
Acidification [molc H^+ eq]	2.07E+02	5.57E+01	372%	6.65E+00	12%
Terrestrial eutrophication [molc N eq]	1.55E+02	8.46E+01	184%	9.02E+00	11%
Freshwater eutrophication [kg P eq]	5.80E+00	1.50E+01	39%	4.07E-01	3%
Marine eutrophication [kg N eq]	1.64E+01	7.86E+00	209%	8.86E-01	11%
Freshwater ecotoxicity [CTUe]	2.37E+05	5.42E+05	44%	6.64E+03	1%
Land use [kg C deficit]	1.68E+04	1.65E+04	102%	5.72E+02	3%
Water resource depletion [m^3 water eq]	4.17E+03	6.26E+03	67%	1.53E+03	24%
Mineral, fossil & ren resource depletion [kg Sb eq]	1.38E+00	6.84E-01	202%	7.51E-01	110%

Table 17. Comparative life cycle impact of producing 1 kilogram REE (Scenario 2, TRACI)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Ozone depletion [kg CFC-11 eq]	1.13E-05	9.96E-06	113%	9.96E-06	100%
Global warming [kg CO_2 eq]	3.07E+01	2.17E+01	141%	2.17E+01	100%
Smog [kg O_3 eq]	2.43E+00	1.20E+00	203%	1.20E+00	100%
Acidification [kg SO_2 eq]	9.35E-01	1.13E-01	827%	1.13E-01	100%
Eutrophication [kg N eq]	9.65E-02	6.57E-02	147%	6.57E-02	100%
Carcinogenics [CTUh]	2.15E-06	1.31E-06	164%	1.31E-06	100%
Non carcinogenics [CTUh]	1.49E-05	9.44E-06	158%	9.44E-06	100%
Respiratory effects [kg PM2.5 eq]	6.20E-02	1.07E-02	579%	1.07E-02	100%
Ecotoxicity [CTUe]	2.73E+02	1.51E+02	180%	1.51E+02	100%
Fossil fuel depletion [MJ surplus]	3.93E+01	2.49E+01	158%	2.49E+01	100%

Table 18. Comparative life cycle impact of producing 1 kilogram REE (Scenario 2, ILCD)

Impact category	Hydro (H)	Pyro (P)	H/P	ER	ER/P
Climate change [kg CO_2 eq]	3.05E+01	2.15E+01	142%	2.15E+01	100%
Ozone depletion [kg CFC_{-11} eq]	1.07E-05	9.62E-06	111%	9.61E-06	100%
Human toxicity, non-cancer effects [CTUh]	1.49E-05	9.44E-06	158%	9.44E-06	100%
Human toxicity, cancer effects [CTUh]	2.15E-06	1.31E-06	164%	1.31E-06	100%
Particulate matter [kg PM2.5 eq]	6.62E-02	9.71E-03	681%	9.70E-03	100%
Ionizing radiation HH [kBq U_{235} eq]	6.66E+00	5.51E+00	121%	5.52E+00	100%
Ionizing radiation E (interim) [CTUe]	1.98E-06	1.71E-06	116%	1.70E-06	99%
Photochemical ozone formation [kg NMVOC eq]	5.51E-01	3.63E-01	152%	3.63E-01	100%
Acidification [molc H^+ eq]	1.20E+00	1.37E-01	880%	1.37E-01	100%
Terrestrial eutrophication [molc N eq]	4.03E-01	1.87E-01	215%	1.87E-01	100%
Freshwater eutrophication [kg P eq]	1.17E-02	8.22E-03	142%	8.22E-03	100%
Marine eutrophication [kg N eq]	3.85E-02	1.87E-02	206%	1.87E-02	100%
Freshwater ecotoxicity [CTUe]	2.74E+02	1.52E+02	180%	1.52E+02	100%
Land use [kg C deficit]	2.96E+01	1.51E+01	196%	1.51E+01	100%
Water resource depletion [m^3 water eq]	3.80E+01	2.64E+01	144%	2.65E+01	100%
Mineral, fossil & ren resource depletion [kg Sb eq]	2.24E-03	1.78E-03	126%	1.78E-03	100%

Scenario 3 allocated the electricity consumption during pre-processing between precious metal and REEs based on the price. The results for scenario 3 are not listed in this paper as they were very similar to scenario 2 as the total impact of pre-processing electricity consumption turned out to be relatively small. In scenario 3, the impacts of producing 1kg of gold from all three processes were slightly lower than scenario 2 as some of the energy consumed is distributed to the REEs extraction.

5. DISCUSSION

As the processing of REE recovery from e-waste from the three processes is similar, a comparison between the recovered REE and virgin processed REE is conducted. In addition, a discussion within the results of this study and other literature is included. Finally, the assumptions, limitations and potential works are presented.

To credit the REE recovery from e-waste, a comparison of life cycle impacts to produce 1kg REEs with the ER method and the virgin method is discussed (Arshi, Vahidi, & Zhao, 2018). Since the ER method was identified to have the least environmental impacts when extracting gold from e-wastes, its results in scenario 1 and 2 were compared with the virgin method. The results are shown in Table 19.

Table 19. Comparative life cycle impacts of producing 1 kilogram REE

Impact category	Unit	ER 1 (Scenario 1)	ER 2 (Scenario 2)	REO from ion adsorption clay (Virgin)	ER 1/ Virgin	ER2/ Virgin
Ozone depletion	kg CFC-$_{11}$ eq	5.12E-07	9.96E-06	1.21E-05	4%	82%
Global warming	kg CO_2 eq	1.81E+00	2.17E+01	2.26E+02	1%	10%
Smog	kg O_3 eq	8.68E-02	1.20E+00	7.09E+00	1%	17%
Acidification	kg SO_2 eq	8.73E-03	1.13E-01	1.51E+01	0%	1%
Eutrophication	kg N eq	5.08E-03	6.57E-02	6.23E+00	0%	1%
Carcinogenics	CTUh	1.00E-07	1.31E-06	4.91E-06	2%	27%
Non carcinogenics	CTUh	7.24E-07	9.44E-06	3.84E-05	2%	25%
Respiratory effects	kg PM2.5 eq	6.94E-04	1.07E-02	1.24E-01	1%	9%
Ecotoxicity	CTUe	1.05E+01	1.51E+02	5.82E+02	2%	26%
Fossil fuel depletion	MJ surplus	1.99E+00	2.49E+01	1.41E+02	1%	18%

Considering the REEs by-product of recycling gold, the impact of producing 1kg REEs is ignorable compared to extract REEs from ion adsorption clay (Arshi et al., 2018; Diaz et al., 2016).

If account the potential of recycling acid in the ER process, it is much more environmentally friendly than extracting REEs from ion adsorption clay.

However, if only recovery REEs by the ER process, even the impacts are lower than the virgin method for all categories, it is still higher than the results of the impacts in scenario 1. This shows only recover REE from e-waste is costly for the environment. It is necessary to include precious metals recycling into the REE recovery pathway for e-waste recycling to ensure the environmental sustainability of REE recycling.

Vahidi et al., (2016) discussed and summarized the environmental profiles of several REEs studies which the REEs produced via the bastnasite/monazite route. For instance, the study of Sprecher et al. (2014) indicated the global warming impacts for 1kg of REEs is in the range of 12-16 kg CO_2 eq and Ozone depletion is around 2 E-06~3.5E-06, and study of Zaimes et al.(2015) showed the respiratory effect of 1kg REE production is around 0.16~0.18 kg PM2.5 eq. Compared to the results for the bastnasite/monazite route with the above alternative studies, recover REE from the ER process has lower environmental impacts.

Compare the pyrometallurgical process with the hydrometallurgical process, the trend of results are similar to the study of Bailey (2016). The pyrometallurgical process has less impacts in more categories as it used fewer chemicals which are toxic and harmful for human health. As for the categories which the pyrometallurgical process ranks the top, most of them were dominated by the input of copper scrap. Only global warming impacts were due to natural gas consumption. As mentioned in the recovery efficiency table, the Cu can be recovered more than 200% in the process. The added copper scrap was processed to higher level copper, and the revenue for the pyrometallurgical process is 20% more than the others. In the scenario 1, which used allocation to compare the impacts of recovering 1kg of gold, the impacts of the pyrometallurgical process

decreased more than the other two processes compared with the results in the baseline case. If the copper product can be reused as copper scrap, the overall environmental impacts will decrease dramatically. As for the ER process, even this study concluded it is environmental than the other two methods, the current state is under the laboratory study and the applications of the ER process still need to be researched.

In this LCA study, the factories for processing and collecting e-waste were assumed at the U.S., thus the transportation of the materials are not included in the boundary. When considering the distance and methods for transportation, the LCA results may vary. In addition, the unit process 'Electricity, medium voltage, at grid, 2015/US US-EI U' is used. Even each process used electricity for metal recovery, it has the largest impact on the ER process. In Figure 10, the electricity (red) contributed much for the ER process, especially for global warming and fossil fuel depletion categories. Alternative green energy source would make the ER process more attractive in terms of environmental impacts.

Since some components and compounds were not in the Simapro database, assumptions and user-defined component were used in this study. Sodium persulfate ($Na_2S_2O_8$) was used in the place of sodium thiosulfate ($Na_2S_2O_3$) and sodium pyrosulfate ($Na_2S_2O_5$) in SimaPro, as the latter two were not in the database. FSC slag used in the reduction furnace of the pyrometallurgical process is a mixture of FeO_x -CaO-SiO_2, and it was created in SimaPro with given the ratio of the three existing components: Fe, activated silica and calcium silicate (Table 5).

To cut off original materials (like e-waste from cell phone) from the system boundary, some self-defined inputs and outputs were used. The emission of the hydrometallurgical extraction process was mostly waste water with little solid waste produced. "Waste water" in the SimaPro database was used for this water borne emission. This waste water can be further processed to

reduce the environmental impact; however, the water treatment was not included in our system boundary.

In terms of chemicals, the oxidant for the ER process is recycled, which make it more efficient. The chemical consumption (hydrochloric acid, hydrogen peroxide, and sulfuric acid) in both the ER and the hydrometallurgical process are the key factors with the greatest contribution to the environmental impacts. Refer the inventory tables, the lower overall environmental impact in the ER process compared with the hydrometallurgical process can be attributed to its significantly lower chemical consumption. Furthermore, the acid used in the hydrometallurgical process makes it has 3 times more impacts than the pyrometallurgical and the ER process in the category of acidification.

6. CONCLUSION

This study provides a comparative LCA on recovering precious metals from e-waste with the hydrometallurgical, the pyrometallurgical and the ER processes. SimaPro 8.3 was used for the inventory analysis with the database like Ecoinvent 3.0 and US- US-EI U. EPA TRACI (USA 2008) and ILCD were used to assess environmental impacts. Final products for recovery include gold, silver, REEs, steel, and copper. Gold is the main product due to the high market price. Several scenarios were discussed with different system boundaries and functional units. Based on the baseline analysis, which used $1000 value product as the functional unit and the alternative case study, which used 1kg of gold as functional unit, it is found the ER process has the lowest environmental impacts compared to the other two processes, only except the higher ozone depletion impacts than the pyrometallurgical process. As for the pyrometallurgical and hydrometallurgical processes, they are competitive with each other in term of environmental impacts. In addition, the LCA on recovering 1kg REEs was conducted and the results show recovering REEs by the ER process has less environmental impacts than the in-situ extraction. As the recycle of input materials in all processes were not considered, the hydrometallurgical, the pyrometallurgical and the ER processes have the potential to have less life cycle impacts on recovering precious metals and REEs.

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APPENDIX A. WASTE FLOWS

Table 20. Breakdown for the ER process

Stream	e-waste	Magnetic fraction	Milled e-waste	Cu scrap	Liquid waste 1	Milled e-waste 2	Ag	Liquid waste 2
Flow t/tewaste	1.00E+00	2.02E-01	7.98E-01	1.73E-01	6.23E-01	6.00E-01	1.96E-03	
Flow m³/tewaste					9.18E-01			1.28E+00
Cu kg/tewaste	1.60E+02	5.41E+00	1.55E+02	1.53E+02	1.55E+00	0.00E+00	0.00E+00	0.00E+00
Sn kg/tewaste	1.66E+01	1.01E+00	1.56E+01	1.56E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pb kg/tewaste	1.89E+00	1.21E-02	1.87E+00	1.87E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni kg/tewaste	2.04E+01	1.38E+01	6.54E+00	1.44E+00	5.10E+00	0.00E+00	0.00E+00	0.00E+00
Fe kg/tewaste	1.67E+02	1.59E+02	7.50E+00	6.00E-01	6.90E+00	0.00E+00	0.00E+00	0.00E+00
Zn kg/tewaste	1.24E+01	1.21E+00	1.12E+01	2.23E-01	1.09E+01	0.00E+00	0.00E+00	1.24E+00
Ag kg/tewaste	2.39E+00	0.00E+00	2.39E+00	3.09E-01	0.00E+00	2.08E+00	1.96E+00	1.22E-01
Au kg/tewaste	4.79E-01	0.00E+00	4.79E-01	0.00E+00	0.00E+00	4.79E-01	0.00E+00	0.00E+00
Pr kg/tewaste	2.22E-01	2.22E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nd kg/tewaste	1.82E+00	1.82E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dy kg/tewaste	2.02E-01	2.02E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
non-metals	6.17E+02	0.00E+00	5.98E+02	0.00E+00	0.00E+00	5.98E+02	0.00E+00	0.00E+00

Stream	Milled e-waste 3	Au	Liquid waste 3	Solid waste	Steel scrap	REEO	Liquid waste 4	Recycling efficiency
Flow t/tewaste	5.98E-01	4.62E-04		5.98E-01	1.88E-01	9.30E+01		
Flow m³/tewaste			1.20E+00				5.41E-01	
Cu kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.41E+00	0.00E+00	9.35E-05	16%
Sn kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.01E+00	0.00E+00	6.97E-04	2%
Pb kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.21E-02	0.00E+00	2.44E-06	0%
Ni kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.38E+01	0.00E+00	4.08E-02	2%
Fe kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E+02	0.00E+00	1.19E+01	15%
Zn kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.85E-01	0.00E+00	7.27E-01	0%
Ag kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0%
Au kg/tewaste	4.79E-01	4.62E-01	1.68E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0%
Pr kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.60E-03	2.14E-01	8.60E-03	0%
Nd kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.31E-01	1.29E+00	5.31E-01	0%
Dy kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.95E-02	1.33E-01	6.95E-02	0%
non-metals	0.00E+00	0.00E+00	0.00E+00	5.98E+02	1.92E+01	0.00E+00	0.00E+00	
							Total	35%

Table 21. Breakdown for the hydrometallurgical process

Stream	e-waste	Magnetic fraction	Milled e-waste	Cu scrap	Liquid waste 1	Milled e-waste 2	Ag	Liquid waste 2
Flow t/tewaste	1.00E+00	2.02E-01	7.98E-01	1.73E-01	6.23E-01	6.00E-01	1.96E-03	
Flow m³/tewaste					9.18E-01			1.28E+00
Cu kg/tewaste	1.60E+02	5.41E+00	1.55E+02	1.53E+02	1.55E+00	0.00E+00	0.00E+00	0.00E+00
Sn kg/tewaste	1.66E+01	1.01E+00	1.56E+01	1.56E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pb kg/tewaste	1.89E+00	1.21E-02	1.87E+00	1.87E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni kg/tewaste	2.04E+01	1.38E+01	6.54E+00	1.44E+00	5.10E+00	0.00E+00	0.00E+00	0.00E+00
Fe kg/tewaste	1.67E+02	1.59E+02	7.50E+00	6.00E-01	6.90E+00	0.00E+00	0.00E+00	0.00E+00
Zn kg/tewaste	1.24E+01	1.21E+00	1.12E+01	2.23E-01	1.09E+01	0.00E+00	0.00E+00	1.24E+00
Ag kg/tewaste	2.39E+00	0.00E+00	2.39E+00	3.09E-01	0.00E+00	2.08E+00	1.96E+00	1.22E-01
Au kg/tewaste	4.79E-01	0.00E+00	4.79E-01	0.00E+00	0.00E+00	4.79E-01	0.00E+00	0.00E+00
Pr kg/tewaste	2.22E-01	2.22E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nd kg/tewaste	1.82E+00	1.82E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dy kg/tewaste	2.02E-01	2.02E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
non-metals	6.17E+02	0.00E+00	5.98E+02	0.00E+00	0.00E+00	5.98E+02	0.00E+00	0.00E+00

Stream	Milled e-waste 3	Au	Liquid waste 3	Solid waste	Steel scrap	REEO	Liquid waste 4	Recycling efficiency
Flow t/tewaste	5.98E-01	4.62E-04		5.98E-01	1.88E-01	9.30E+01		
Flow m³/tewaste			1.20E+00				5.41E-01	
Cu kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.41E+00	0.00E+00	9.35E-05	16%
Sn kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.01E+00	0.00E+00	6.97E-04	2%
Pb kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.21E-02	0.00E+00	2.44E-06	0%
Ni kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.38E+01	0.00E+00	4.08E-02	2%
Fe kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E+02	0.00E+00	1.19E+01	15%
Zn kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.85E-01	0.00E+00	7.27E-01	0%
Ag kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0%
Au kg/tewaste	4.79E-01	4.62E-01	1.68E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0%
Pr kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.60E-03	2.14E-01	8.60E-03	0%
Nd kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.31E-01	1.29E+00	5.31E-01	0%
Dy kg/tewaste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.95E-02	1.33E-01	6.95E-02	0%
non-metals	0.00E+00	0.00E+00	0.00E+00	5.98E+02	1.92E+01	0.00E+00	0.00E+00	
							Total	35%