Project Notes:

Project Title: Recycling Printed Ciruit Boards to Recover Valuable Metals
Name: Ethan Zhou

Note Well: There are NO SHORT-cuts to reading journal articles and taking notes from them. Comprehension is paramount. You will most likely need to read it several times, so set aside enough time in your schedule.

Contents:

Knowledge Gaps:
This list provides a brief overview of the major knowledge gaps for this project, how they were resolved and where to find the information.

Knowledge Gap	Resolved By	Information is located	Date resolved
How to improve both organic photovoltaic efficiencies and their service life			
What causes Lithium Ion Battery safety issues.	A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards	https://www.sciencedirect.com/science/article/pii/S2095495620307075	8/10/23
How to monitor the health of Lithium Ion Battery			
E-waste recycling methods	Metal recovery from high-grade WEEE: a life cycle assessment	https://doi.org/10.1016/j.jhazmat.2011.10.001	9/10/23
Electrical Component removal methods	Novel techniques for electronic component removal	https://www.emerald.com/insight/content/doi/10.1108/09540919910265622/full/pdf?title=novel-techniques-for-electronic-component-removal	10/5/23

Literature Search Parameters:
These searches were performed between 07/04/2023 and 10/2/2023.
List of keywords and databases used during this project.

Database/search engine	Keywords	Summary of search
Google Scholar	Li-ion battery, safety, health monitoring	Generated about 30,000 results, when narrowed to from 2020 to present, still received over 17,800 results. Further narrowing down to review articles only, received 4,730 results. Picked a recent one with very high citation numbers (cited by 681) to start my reading.
Google Scholar	E-waste, e-waste management, recycling, challenges and opportunities, recycling process, environmental, solutions, machine learning, leaching, sorting, printed circuit boards, electrical components removal, hydrometallurgy, electrochemistry	Using E-waste management, recycling process, environmental, solutions, as key words, narrowing the time to from 2019 (past five years), returned 342 results. The first returned article has been cited 151 times and was used as my starting point. The search of other articles under the same topic used more specific key words to address specific questions stemmed from trying to synthesis the information from previous references and imaging devising the recovering of valuable material process.
Scopus	Organic photovoltaic, efficiency, cell	Using the key words generated 3196 results, when narrowed to from2019 to present (past five years), received 897 results, ranking by numbers cited, the one with the highest cited numbers was my starting point.

Tags:

Tag Name	

Article # Notes:

Article notes should be on separate sheets

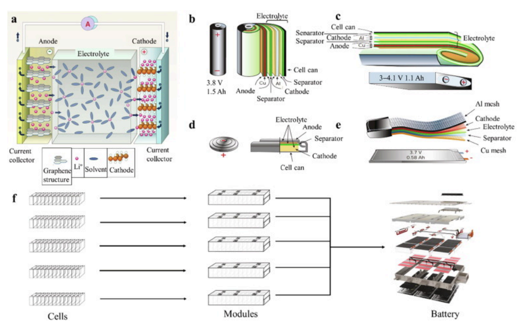
KEEP THIS BLANK AND USE AS A TEMPLATE

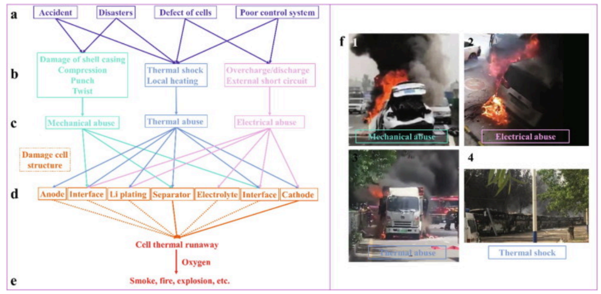
Source Title	
Source citation (APA Format)	
Original URL	
Source type	
Keywords	
#Tags	
Summary of key points + notes (include methodology)	
Research Question/Problem/ Need	
Important Figures	
VOCAB: (w/definition)	
Cited references to follow up on	
Follow up Questions	

Article #1 Notes: A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards

Article notes should be on separate sheets

KEEP THIS BLANK AND USE AS A TEMPLATE

Source Title	A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards
Source citation (APA Format)	Chen, Y., Kang, Y., Zhao, Y., Wang, L., Liu, J., Li, Y., Liang, Z., He, X., Li, X., Tavajohi, N., & Li, B. (2021). A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards. *Journal of Energy Chemistry*, *59*, 83–99. https://doi.org/10.1016/j.jechem.2020.10.017
Original URL	https://www.sciencedirect.com/science/article/pii/S2095495620307075
Source type	Review
Keywords	Lithium-ion batteries, Standards, Safety, Thermal abuse, Mechanical abuse, Electrical abuse
#Tags	#Batteries, #Safety, #Lithiumion
Summary of key points + notes (include methodology)	This article provides an overview of lithium-ion batteries as well as the safety concerns associated with them. The review delves into the various challenges and potential hazards posed by these batteries, offering insights into strategies for enhancing their safety. It also examines existing measures to ensure the reliability and performance of lithium-ion batteries, contributing to a better understanding of the critical factors involved in their safe utilization.
Research Question/Problem/ Need	How can the safety of lithium-ion batteries be enhanced through different strategies?
Important Figures	 Schematic diagram of the fundamental structure of a LIB cell, which is the same for different cell types

<table>
<tr><td></td><td>

An overview of battery safety issues.</td></tr>
<tr><td>VOCAB: (w/definition)</td><td>Cathodes and anodes are the charge carriers contributing to LIB energy storage and release.
The separator: physically divides the electrodes to prevent internal short-circuits while allowing Li+ flow.
The electrolyte: carries ions, including Li+.
Intercalate: insert (something) between layers in a crystal lattice, in LIB, it refers to the insertion of Li+ into the crystal lattice of electrodes.
De-intercalate: Antonym of intercalate
Thermal runaway: is one of the primary risks related to lithium-ion batteries. It is a phenomenon in which the lithium-ion cell enters an uncontrollable, self-heating state.</td></tr>
<tr><td>Cited references to follow up on</td><td>Ren, D., Feng, X., Lu, L., Ouyang, M., Zheng, S., Li, J., & He, X. (2017). An electrochemical-thermal coupled overcharge-to-thermal-runaway model for lithium ion battery. Journal of Power Sources, 364, 328–340. https://doi.org/10.1016/j.jpowsour.2017.08.035</td></tr>
<tr><td>Follow up Questions</td><td>What recent findings offer novel insights into mitigating safety concerns related to lithium-ion batteries?
What would an ideal lithium-ion battery content and setup look like?
How do we detect if a lithium-ion battery is aging too quickly?</td></tr>
</table>

Article notes:

LIB safety issues:

1. caused by undesirable chemical reactions: At high-temperature and high-voltage conditions, the electrochemical reactions become more complex, including decomposition of the solid electrolyte interface (SEI) film, oxygen release at the cathode side, and additional electrolyte/electrode parasitic side reactions. These reactions eventually lead to LIB thermal runaway, which causes battery rupture and explosion due to the reaction of hot flammable gases from the battery with the ambient oxygen
2. Thermal runaway: Breakage of the separator and the oxygen evolution from the cathode side are the root causes to batteries' thermal runaway. There are five types of causes for this phenomenon. The first type is uncontrollable internal heat generation, which causes oxygen release from the cathode material, leading to numerous side reactions. In the second type, separator defects (due to thermally-induced shrinkage or mechanical damage) create short

circuits in the battery and rapid discharge of the energy stored in it, accompanied by undesirable chemical chain reactions and release of massive amounts of heat. The third type is electrical abuse. Electrolyte decomposition, especially in a high state of charge (SOC), occurs at the cathode interface. This leads to heat accumulation and consequently release of oxygen from the cathode and damage to the separator. The fourth type consists of electrochemical side reactions caused by local thermal abuse. If the heat generated during normal LIB operations cannot be dissipated quickly enough, the separator in that specific place will shrink or rupture. The fifth type occurs during mechanical battery damage, which causes short circuits and/or air to penetrate the battery. The main causes of battery safety accidents among these five categories are short-circuiting due to separator damage, electrical abuse, and mechanical abuse. Overcharge is the most dangerous types of electrical abuse and one of the most frequently observed reasons for LIB safety accidents.

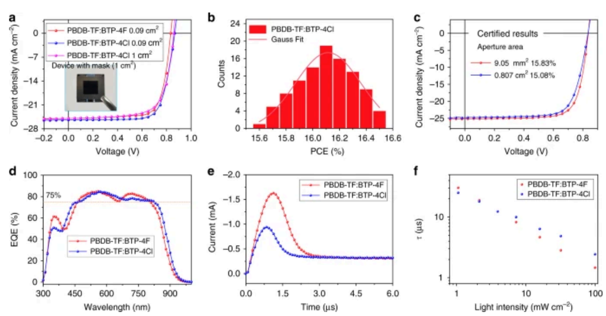
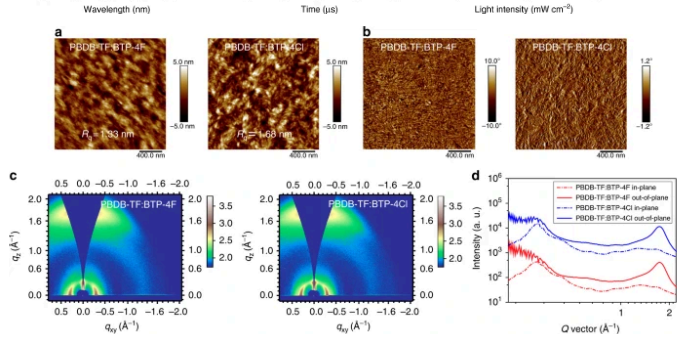
Strategies for LIB safety improvements:

Internal strategies include safety enhancement of each LIB component: active materials, separator, and electrolyte. Adding appropriate additives to any of these components might also improve LIB safety performance.

External strategies for LIB safety improvements include cooling and cell balance. It is difficult to produce totally identical battery cells, due to variations during the manufacturing and assembly processes, as well as surrounding environment. Thus, during battery operation, even little differences between each single cell will intensify and accumulate if no measures are taken. In the absence of an appropriate balancing system, the voltage differences between the individual cells will amplify, severely compromising battery safety. To achieve a high-performance battery system, the cells need to be continuously balanced for minimizing the variations between them.

Most countries and international organizations have developed LIB-safety oriented standards. The various safety test standards apply different methodologies. Different standards have distinct and very specific test parameters, but with overlaps in their methodologies. The test standards are formulated to reduce the probability of thermal runaway accidents in actual use. Thus, they are intended to assess responses of batteries in real potential situations, with continuous updates and upgrades in accordance with the ongoing development of LIB technology, which reflects concerns about the causes and hazards of accidents that have occurred.

Article #2 Notes: Over 16% efficiency organic photovoltaic cells enabled by a chlorinated acceptor with increased open-circuit voltages.

Source Title	Over 16% efficiency organic photovoltaic cells enabled by a chlorinated acceptor with increased open-circuit voltages
Source citation (APA Format)	Cui, Y., Yao, H., Zhang, J., Zhang, T., Wang, Y., Hong, L., Xian, K., Xu, B., Zhang, S., Peng, J., Wei, Z., Gao, F., & Hou, J. (2019). Over 16% efficiency organic photovoltaic cells enabled by a chlorinated acceptor with increased open-circuit voltages. *Nature Communications, 10*(1), 1–8. https://doi.org/10.1038/s41467-019-10351-5
Original URL	https://www.nature.com/articles/s41467-019-10351-5
Source type	Journal Article
Keywords	Organic photovoltaics, Bandgap acceptors, Chlorinated acceptors, Solar
#Tags	#Sustainability, #Solar, #Globalwarming
Summary of key points + notes (include methodology)	This article highlights the advantages of organic photovoltaic cells and focuses on methods to enhance their efficiency. Overall, the research focuses on the design, fabrication, and characterization of high-performance OPV cells using chlorinated low bandgap acceptors, specifically BTP-4Cl, showcasing the potential of this strategy for improving the efficiency and viability of organic photovoltaic technology.
Research Question/Problem/ Need	How does the newly developed BTP-4Cl material enhance the efficiency of OPVs?
Important Figures	  Device performance. (a) J−V curves of the PBDB-TF:IT-4X-based devices. (b)

	Statistical diagram of PCEs for 100 PBDB-T:BTP-4Cl-based cells. (c) J−V curves of the devices measured by the NIM, China.(d) EQE curves of the PBDB-TF:BTP-4X blend cells. (e) Photo-CELIV curves of the devices for carrier mobility calculations.(f) Carrier lifetimes under varied light intensities obtained from TPV measurements
VOCAB: (w/definition)	Fullerene:an allotrope of carbon whose molecule consists of carbon atoms connected by single and double bonds to form a closed or partially closed mesh, with fused rings of five to seven atoms. Morphology: the study of form comprising shape, size, and structure in materials science Centrosymmetric: symmetric with respect to a central point Debye: a unit used to express electric dipole moments of molecules. One debye is equal to 3.336×10^{-30} coulomb meters. named in honor of the physicist Peter J. W. Debye Redshift: an increase in the wavelength, and corresponding decrease in the frequency and photon energy, of electromagnetic radiation (such as light). EQE: External quantum efficiency. Jsc: short-circuit current density PCE: power conversion efficiencies
Cited references to follow up on	Olle Inganäs. (2018). Organic Photovoltaics over Three Decades. *Advanced Materials*, *30*(35), 1800388–1800388. https://doi.org/10.1002/adma.201800388
Follow up Questions	What methods can be utilized to further increase the efficiency of OPVs beyond the improvements offered by BTP-4Cl material? What other OPV materials can be constructed with chlorination? How does the size of the PV cell affect the PCE?

Article notes:

- A chlorinated non-fullerene acceptor BTP-4Cl and achieve record PCEs of 16.5% and 15.3% for OPV cells with 0.09 and 1 cm2 active areas, respectively, was obtained.
- The ultraviolet–visible (UV–Vis) absorption spectra of BTP-4X in diluted solutions and as thin films were measured. Broader optical absorption range and higher absorption coefficient of BTP-4Cl compared with that of BTP-4F were observed, which are beneficial for the more effective utilization of the solar photon.
- To obtain the best device performance, fabrication conditions, including the donor:acceptor ratio, additive, and thermal annealing temperature, were optimized.
- It was shown that the chlorination method broads the optical absorption and helps to obtain a high J_{SC} of 25.4 mA cm−2. The calculated non-radiative energy loss is as low as 0.206 eV.
- This study shows that an extended optical absorption and improved output voltage can be achieved simultaneously by the molecular design of chlorination. These results imply that the non-radiative energy loss in OPV cells can be modified by chemical modification of the photoactive materials, which provides opportunities to design of highly efficient OPV materials with low bandgap–voltage offsets.

Article #3 Notes: E-waste management: A review of recycling process, environmental and occupational health hazards, and potential solutions

Source Title	E-waste management: A review of recycling process, environmental and occupational health hazards, and potential solutions.
Source citation (APA Format)	Ahirwar, R., & Tripathi, A. K. (2021). E-waste management: A review of recycling process, environmental and occupational health hazards, and potential solutions. *Environmental Nanotechnology, Monitoring & Management, 15*, 100409. https://doi.org/10.1016/j.enmm.2020.100409
Original URL	https://doi.org/10.1016/j.enmm.2020.100409
Source type	Journal Article
Keywords	E-waste management; Environmental pollution; Heavy metals; Persistent organic pollutants; Public health; E-waste legislation
#Tags	#E-waste management; # E-waste recycling; #environmental
Summary of key points + notes (include methodology)	This review article provides an overview of the global e-waste generation and management, discusses opportunities and constraints in e-waste management via recycling, summarizes environmental and public health concerns due to unsafe recycling practices, and suggests strategies to make e-waste recycling efficient and safer. It provides a comprehensive account of the current trend in global e-waste generation, the latest approaches in e-waste recycling, environmental and occupational health concerns, opportunities and constraints in effective e-waste management, and solutions for improved e-waste recycling.
Research Question/Problem/ Need	What are the opportunities, constraints, concerns, solutions, and trends in e-waster management?

Important Figures	 **Fig. 4.** Enrichment of valuable material from e-waste. (A) Industrial scale machines used for shredding, crushing, grinding, and separating e-waste into metallic and non-metallic fractions. (B) E-waste fractions of various sizes. Images reproduced with permission from (Sarvar et al., 2015). Enrichment of valuable material from e-waste. (A) Industrial scale machines used for shredding, crushing, grinding, and separating e-waste into metallic and non-metallic fractions. (B) E-waste fractions of various sizes. Images reproduced with permission from (Sarvar et al., 2015).
VOCAB: (w/definition)	precious metals: gold, platinum, palladium, ruthenium, rhodium, iridium, silver etc. Flame Retardant: chemicals that are added to manufactured materials (e.g., textiles and plastics) and surface finishes and coatings to inhibit combustion or delay the spread of fire after ignition primary e-waste toxicants: hazardous substances present in e-waste, e.g. Pb, Cd, Hg, etc. secondary e-waste toxicants: produced during processing and recycling of e-waste, e.g. PAHs, dioxins and difurans, etc.
Cited references to follow up on	Sarvar, M., Salarirad, M. M., & Shabani, M. A. (2015). Characterization and mechanical separation of metals from computer Printed Circuit Boards (PCBs) based on mineral processing methods. *Waste Management*, *45*, 246–257. https://doi.org/10.1016/j.wasman.2015.06.020 Zhang, S., & Forssberg, E. (1997). Mechanical separation-oriented characterization of electronic scrap. *Resources, Conservation and Recycling*, *21*(4), 247–269. https://doi.org/10.1016/s0921-3449(97)00039-6
Follow up Questions	1. Recipe for density separation 2. Mechanical separation instrumentation, efficiency and issues

Article notes:

1. E-waste, produced from obsolete electronic and electrical equipment, poses environmental and health risks from inadequate recycling. In 2019, the world generated 53.6 Mt of e-waste, expected to rise to 74.7 Mt by 2030.
2. Asia, with China, India, and Japan, leads in e-waste generation. Europe follows with rigorous recycling, whereas Africa and Oceania contribute minimally.
3. Exposure to e-waste can cause health issues, including thyroid disorders, DNA mutations, respiratory problems, and neurodevelopmental concerns.
4. E-waste recycling involves collection, processing, and recovery of metals using techniques like hydrometallurgy and pyrometallurgy.

Challenges and Opportunities in E-waste Management:

Challenges:

E-waste is complex, with both precious materials and toxic chemicals. Separation, household disposal, lack of awareness, and limited recycling infrastructure compound the issue.

Key Opportunities:

Recycling e-waste offers economic, environmental, and societal advantages, reducing waste and greenhouse gas emissions and conserving energy.

Strategies for Effective E-waste Management:

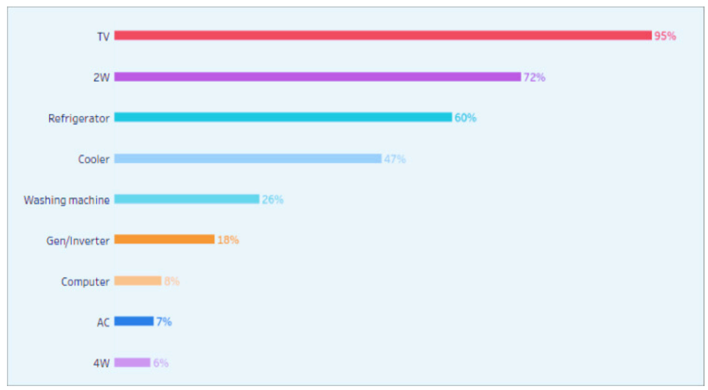
1. Enhancing e-waste collection can be achieved by raising consumer awareness and providing economic incentives. Informal recycling, while economically viable, poses environmental risks. Integrating formal and informal sectors can optimize e-waste recycling. Several case studies in India have shown the benefits of such collaborations.

1. Advancing product design, such as emphasizing recyclability, using sustainable materials, and designing for extended product life, can reduce waste generation. Collaborations between manufacturers, scientists, and e-waste experts can facilitate this.
2. Traditional recovery methods release harmful substances. Alternatives like bioleaching, using less toxic chemicals and harnessing microorganisms, can offer safer recycling avenues.
3. Proper protective gear, especially N95 masks, can mitigate exposure to hazardous particles during recycling.

Article #4 Notes: E-waste management in Nepal: A case study overcoming challenges and opportunities

Source Title	E-waste management in Nepal: A case study overcoming challenges and opportunities
Source citation (APA Format)	Bishal KHATIWADA, Rattana JARIYABOON, & Kuaanan TECHATO. (2023). *E-Waste Management in Nepal: A Case Study Overcoming Challenges and Opportunities. 4*, 100155–100155. https://doi.org/10.1016/j.prime.2023.100155
Original URL	https://www.sciencedirect.com/science/article/pii/S2772671123000505?via%3Dihub
Source type	Journal article
Keywords	E-waste management; Deep learning algorithm; Global warming; Environment Cleaning; Image processing
#Tags	#E-waste #Machine-learning #Electronics #Recycling
Summary of key points + notes (include methodology)	This paper addresses the limitations of manual Waste Management Systems (WMS) by designing and implementing an innovative Automatic E-Waste Management System using machine learning algorithms. While traditional WMS, supplemented by an IoT sensor-based alert system, has been insufficient in terms of time and cost efficiency, it also neglects the crucial aspect of electronic waste (E-waste) disposal and recycling. The exponential increase in electronic device usage has contributed to the growing E-waste problem, but it also offers an opportunity for extracting valuable recycled minerals. To optimize E-waste management, the paper introduces a deep learning model utilizing Convolutional Neural Networks (CNN) for feature extraction, coupled with a Restricted Boltzmann Machine (RBM) model to enhance prediction accuracy. The model is validated using an open-source dataset and demonstrates an impressive 96% accuracy in predicting E-waste, surpassing the performance of existing approaches. This research offers a promising solution to the challenges posed by E-waste management in our technology-driven world.
Research Question/Problem/ Need	How can we improve Waste management through an Automatic E-Waste Management System?

<table>
<tr><td>Important Figures</td><td>



Different types of Electronic E-waste.</td></tr>
<tr><td>VOCAB: (w/definition)</td><td>CNN: Convolutional Neural Network, a type of Deep Learning neural network architecture commonly used in Computer Vision
Workflow: a series of steps related to processing data
Binarization: converting a grayscale pr RGB image into a black and white image
Confusion Matrix: a table that summarizes the performance of a classification algorithm. It is used to evaluate the accuracy of a classifier by comparing the predicted labels to the actual labels of a set of test data</td></tr>
<tr><td>Cited references to follow up on</td><td>Starter: e-waste dataset 93b07fb8-a. (n.d.). Kaggle.com. Retrieved October 13, 2023, from https://www.kaggle.com/code/kerneler/starter-e-waste-dataset-93b07fb8-a/notebook</td></tr>
<tr><td>Follow up Questions</td><td>Are there other ML algorithms that could be possibly more effective?</td></tr>
</table>

Article notes:

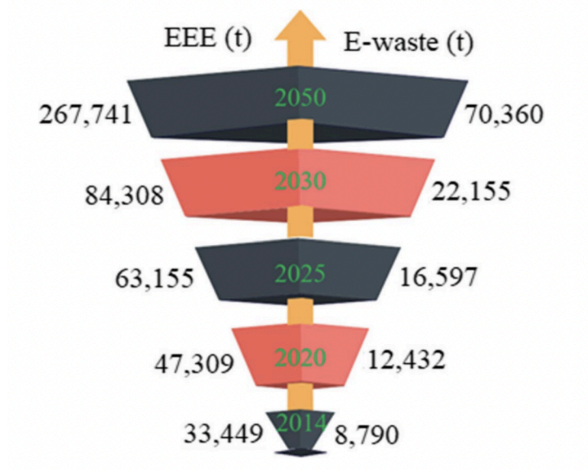
The workflow comprises multiple stages, such as image capturing, image preprocessing to improve the quality, image color conversion, classification using CNN, image separation, disposal, and recycling based on the separation.

Binarization method was used to process the images
The input images of the e-waste are fed into the proposed CNN model.
The dataset for the simulation process is taken from the Kaggle open source database in the link https://www.kaggle.com/code/kerneler/starter-e-waste-dataset-93b07fb8-a/notebook [13], which provides the images of the different e-wastes with pictures.
The confusion matrix was used to show the efficiency of the prediction model.
The accuracy of the prediction model obtained is 96%, comparable to other existing works with similar algorithms.

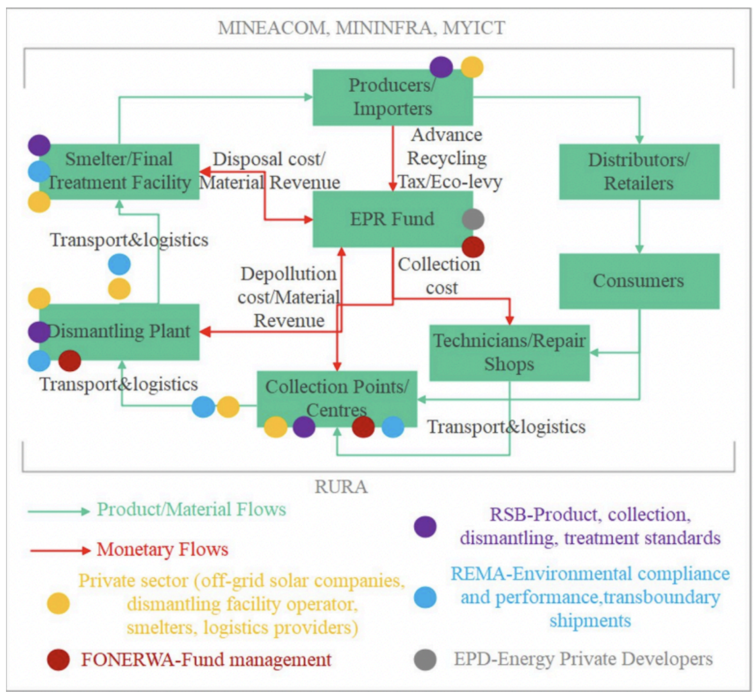
Article #5 Notes: Towards a sustainable and green approach of electrical and electronic waste management in Rwanda: a critical review

Source Title	Towards a sustainable and green approach of electrical and electronic waste management in Rwanda: a critical review
Source citation (APA Format)	Gratien Twagirayezu, Abias Uwimana, Huang, K., Christian Sekomo Birame, Olivier Irumva, Jean Claude Nizeyimana, & Cheng, H. (2023). Towards a sustainable and green approach of electrical and electronic waste management in Rwanda: a critical review. *Environmental Science and Pollution Research, 30*(32), 77959–77980. https://doi.org/10.1007/s11356-023-27910-5
Original URL	https://link.springer.com/article/10.1007/s11356-023-27910-5
Source type	Journal
Keywords	E-waste; Electrical equipment; Electronic equipment; Information; Technology
#Tags	#e-waste #e-waste managment
Summary of key points + notes (include methodology)	This review focuses on the concerning issue of electrical and electronic equipment (EEE) consumption in developing countries, specifically in Rwanda, and its resultant electronic waste (e-waste) generation. Rwanda's national plans emphasize the importance of information communication and technology (ICT) tools, driving the demand for various EEE devices. In 2014, EEE amounted to 33,449 tonnes, projected to reach 267,741 tonnes by 2050, growing annually at a rate of 5.95%. Consequently, outdated EEE is increasingly being discarded as e-waste across Rwanda, often ending up in uncontrolled landfills along with other household waste. To address this growing environmental and health hazard, the paper advocates for proper e-waste management, which includes sorting and separation from other waste, repairs, reuse, recycling, remanufacturing, and responsible disposal as essential measures.
Research Question/Problem/ Need	What is the current state of e-waste management in underdeveloped countries such as Rwanda?

<table>
<tr>
<td>Important Figures</td>
<td>



EEE and e-waste patterns in Rwanda.



Government-private recycling scheme hybrid of e-waste

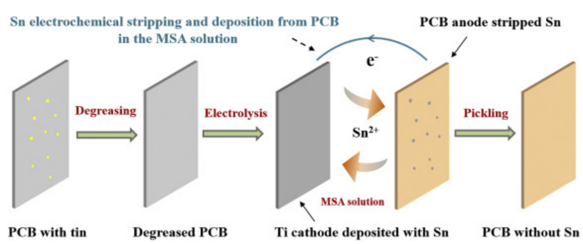
</td>
</tr>
<tr>
<td>VOCAB: (w/definition)</td>
<td>EEE: Electrical and electronic equipment
ICT: Information communication and technology
LCIA: The life cycle impact assessment, a qualitative and quantitative assessment of the environmental effect of data from an inventory study
LCA: life cycle assessment, the process of evaluating the environmental impacts associated with all aspects of the life of a commercial product, process, or service</td>
</tr>
<tr>
<td>Cited references to follow up on</td>
<td>Zhu, M., Li, X., Ma, J., Xu, T., & Zhu, L. (2021). Study on complex dynamics for the waste electrical and electronic equipment recycling activities oligarchs closed-loop</td>
</tr>
</table>

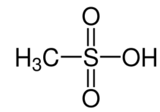
	supply chain. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-021-15979-9 Xavier, L. H., Giese, E. C., Ribeiro-Duthie, A. C., & Lins, F. A. F. (2019). Sustainability and the circular economy: A theoretical approach focused on e-waste urban mining. *Resources Policy*, *74*, 101467. https://doi.org/10.1016/j.resourpol.2019.101467
Follow up Questions	The amount of e-waste in US and globally and the approaches to address it.

Article notes:

- ➔ E-waste is now among the fastest-growing pollution issues worldwide due to several harmful substances that can contaminate human health and the environment. More than 1000 potentially dangerous chemicals, including organic compounds and heavy metals, are found in e-waste, categorized into 26 distinct types that pose a risk to the environment and human health if disposed of incorrectly.
- ➔ the rapid evolution of the EEE results in a product being obsolete before it reaches its end of life.
- ➔ Lack of strong oversight and legal institutions, associated with technical and socioeconomic challenges, is an obstacle for the government in De (DC)veloped Countries to effectively manage e-waste.
- ➔ financial difficulties faced by DCs prevent the creation of organized recycling facilities, resulting in a large volume of e-waste handled by illegal and informal recyclers that may pose a danger to the health of people and the environment
- ➔ E-waste should not be dumped together with other types of waste. But many businesses still need an e-waste disposal strategy
- ➔ The global e-waste quantity is predicted to increase to a massive 74.7 Mt by 2030
- ➔ Presently, e-waste is one of the most concerning environmental problems on a global scale.
- ➔ Rwanda has an alarmingly high rate of e-waste creation. For example, mobile phone penetration increased from 0.0046 in 2000 to 56.8% in 2013
- ➔ Rwanda urgently needs better management of e-waste. This study suggests that collaboration between all institutions involved in putting their respective duties into practice is essential. The existing waste laws in Rwanda need to be more precise and expressly include a comprehensive e-waste management strategy. The current legislative framework has to be reformed with a comprehensive plan for managing e-waste.
- ➔ neither the public nor the private sectors in Rwanda are equipped to manage and dispose of e-waste in a way that is safe for the environment. E-waste management systems are insufficient in Rwanda.
- ➔ advanced recycling approach associated with metal recovered from e-waste should be encouraged because it is a lucrative source of money for recyclers, which might lead to additional employment in the organized sector.

Article #6 Notes: Electrochemical dissolution and recovery of tin from printed circuit board in methane–sulfonic acid solution

Source Title	Electrochemical dissolution and recovery of tin from printed circuit board in methane–sulfonic acid solution
Source citation (APA Format)	Tang, C., Deng, X., Chen, Y., Li, Y., Deng, C., Zhu, Q., Liu, J., & Yang, S. (2021). Electrochemical dissolution and recovery of tin from printed circuit board in methane–sulfonic acid solution. *Hydrometallurgy, 205*, 105726. https://doi.org/10.1016/j.hydromet.2021.105726
Original URL	https://www.sciencedirect.com/science/article/pii/S0304386X21001754?via%3Dihub
Source type	Journal Article
Keywords	Printed circuit board; Electrochemical removal; Tin recycling; Methane-sulfonic acid; NOX gas pollutant reduction
#Tags	#printed circuit board # recycling #electrochemical
Summary of key points + notes (include methodology)	This study developed a process for recovery of valuable metals and nitric acid from the spent solder-stripping solution. Even though this paper mainly focuses on a methane–sulfonic acid solution based electrochmical process to remove Sn, it also provides a starting recipe of pickling solution to remove electronic componments from PCBs for further processing.
Research Question/Problem/ Need	How to create a novel and high-efficient Sn electrochemical stripping and recovery process?
Important Figures	 Scheme of the electrochemical dissolution and deposition of Sn from the PCB in the MSA system.
VOCAB: (w/definition)	Pickling solution: comprises 40 vol% nitric acid (HNO3), 40 g/L ferric nitrate (Fe(NO3)3), 5 g/L ferric chloride (FeCl3), 5 g/L sodium chloride (NaCl), 10 g/L benzotriazole (C6H5N3), and 5 g/L sulfamic acid (NH2SO3H). Methanesulfonic acid: an organosulfuric, colorless liquid with the molecular

	formula CH3SO3H and structure H3C−S(=O)2−OH. 
Cited references to follow up on	*Scopus preview - Scopus - Welcome to Scopus*. (n.d.). Www.scopus.com. Retrieved October 14, 2023, from https://www.scopus.com/record/display.uri?eid=2-s2.0-84937801599&origin=inward&txGid=80b52936b1381eeaea0c7281281212db
Follow up Questions	What are the mechanism of the additives? Can the spent pickling solution be reused to improve the environmental friendliness? Can the pickling solution recipe be optimized to use less nitric acid thus improve its environmental friendliness?

Article notes:

1. Methane–sulfonic acid (MSA) was used as the medium for extracting metals;
2. Electrochemistry as an environment-friendly and highly energy efficient method was used to extract metals.
3. Sn coating from PCB Cu plate was removed by electrochemical method using MSA as the electrolyte to dissolve Sn from the anodic PCB and deposit it at the cathode.
4. Studied the influence of factors such as temperature, Sn2+ concentration, MSA concentration, current density, and inter-electrode spacing.
5. Obtained an optimized recipe to remove Sn by electrolysis.
6. Initially, more than 90% of the tin was successfully recovered as high-purity SnO2 by thermal precipitation at 80 °C for 3 hours.
7. About 94% of the nitric acid was regenerated effectively from the spent solutions by diffusion dialysis, after which there remained copper, iron, and lead in solution.
8. The concentration of the regenerated nitric acid was about 5.1 N.

Article #7 Notes: Predicting the specific size yield of crushed WPCBs based on the breakage probability model

Source Title	Predicting the specific size yield of crushed WPCBs based on the breakage probability model
Source citation (APA Format)	Gao, Y., Zhang, M., Sun, Z., Zhang, Z., & Zhang, B. (2023). Predicting the specific size yield of crushed WPCBs based on the breakage probability model. *Powder Technology, 428*, 118801–118801. https://doi.org/10.1016/j.powtec.2023.118801
Original URL	https://doi.org/10.1016/j.powtec.2023.1188010.1016/j.powtec.2023.118801
Source type	Journal Article
Keywords	Breakage probability; Yield; Crushing production; Specific size; Waste PCBs
#Tags	#e-waste #printed circuit board #recycling
Summary of key points + notes (include methodology)	The paper proposed a method for specific size yield calculation of crushed WPCBs, conducted the fitting comparison among various breakage probability models, verified the prediction effect of breakage probability model on specific size yield, and proposed the use of this model for the guidance of pre-concentration effect..
Research Question/Problem/ Need	Find a calculation method for the specific size yield in crushed products and to verify its feasibility.
Important Figures	Logistic model [19] $P = 1 - \frac{1}{1+(E/b_1)^{a_1}}$ P represents the breakage probability. E represents the input energy and can be replaced by force, specific force and specific energy under various breakage ways. a1 and b1 are the fitting parameters.

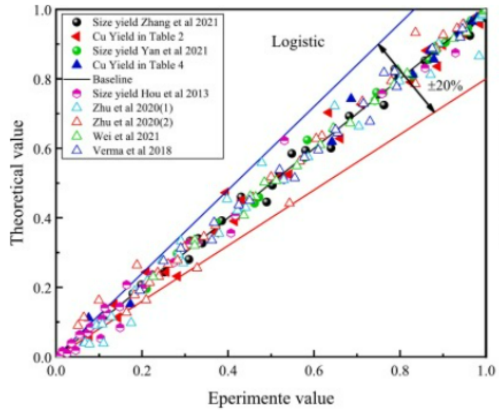
<table>
<tr><td></td><td>

Fig. 2. Comparison of the theoretical mass yield to the experimental ones.</td></tr>
<tr><td>VOCAB: (w/definition)</td><td>breakage probability model: a model that describes the extent of particle breakage subject to impact loading</td></tr>
<tr><td>Cited references to follow up on</td><td>Dinç, N. İ., Tosun, A. U., Baştürkcü, E., Özer, M., & Burat, F. (2021). Recovery of valuable metals from WPCB fines by centrifugal gravity separation and froth flotation. Journal of Material Cycles and Waste Management, 24(1), 224–236. https://doi.org/10.1007/s10163-021-01310-8

Zhang, B., Guo, J., Zhang, Z., Zhao, P., & Yan, G. (2021). A method for quality improvement of waste printed circuit boards based on overall crushing pre-concentration effect. Journal of Cleaner Production, 285, 125496. https://doi.org/10.1016/j.jclepro.2020.125496</td></tr>
<tr><td>Follow up Questions</td><td>This paper confirms that it is typical to have a range of different sizes after milling or shredding PCBs. Will the size of milling products affect the following processing efficiency? This may be studied experimentally.</td></tr>
</table>

Article notes:
-The rapid progression of electronic technology has escalated e-waste production, with circuit boards forming a significant part of this waste.
-PCBs contain valuable metals in higher concentrations than naturally occurring minerals, making them a vital resource.
-Recovering these metals can help decrease the exploitation of natural resources.
-Among the methods for resource extraction from PCBs – like pyrometallurgy, hydrometallurgy, and physical separation – the latter has gained attention due to its simplicity and energy efficiency.
-Physical separation is based on differences in properties such as density, size, and electrical properties. For efficiency, controlling the size of crushed products is essential.
-Crushing is the first step for PCBs' extraction and recovery. Multiple crushing technologies exist, and understanding the breakage characteristics of particles is essential for process optimization.
-Controlling the crushing process can produce products that meet separation requirements.

-The paper introduces a model to predict that yield of particles in specific sizes ranges for crushing WPCBs, using the yield under a particular size as the breakage criterion. I.e. The crushed products smaller than a certain size is regarded as broken, and the contents of broken products are regarded as the breakage probability.

Article #8 Notes: Metal recovery from high-grade WEEE: a life cycle assessment

Source Title	Metal recovery from high-grade WEEE: a life cycle assessment
Source citation (APA Format)	Bigum, M., Brogaard, L., & Christensen, T. H. (2012). Metal recovery from high-grade WEEE: A life cycle assessment. *Journal of Hazardous Materials, 207-208*, 8–14. https://doi.org/10.1016/j.jhazmat.2011.10.001
Original URL	https://doi.org/10.1016/j.jhazmat.2011.10.001
Source type	Journal Article
Keywords	Waste electrical and electronic equipment (WEEE); Life cycle assessment (LCA); Metal recovery
#Tags	#e-waste #recycling # metal recovery
Summary of key points + notes (include methodology)	The paper used available data in the literature to model the LCA for the recovery of aluminium, copper, gold, iron, nickel, palladium and silver from high-grade WEEE. The pre-treatment of WEEE included manual sorting, shredding, magnetic sorting, Eddy-current sorting, air classification and optical sorting. The modeled metallurgical treatment facility included a Kaldo plant, a converter aisle, an anode refinery and a precious metal refinery. The model is useful to quantitatively assess the environmental impacts connected to the recovery of metals from high-grade WEEE including the avoidance of extraction of similar metals from virgin sources.
Research Question/Problem/ Need	How to quantify environmental savings of the metal recovery from e-waste?

Important Figures

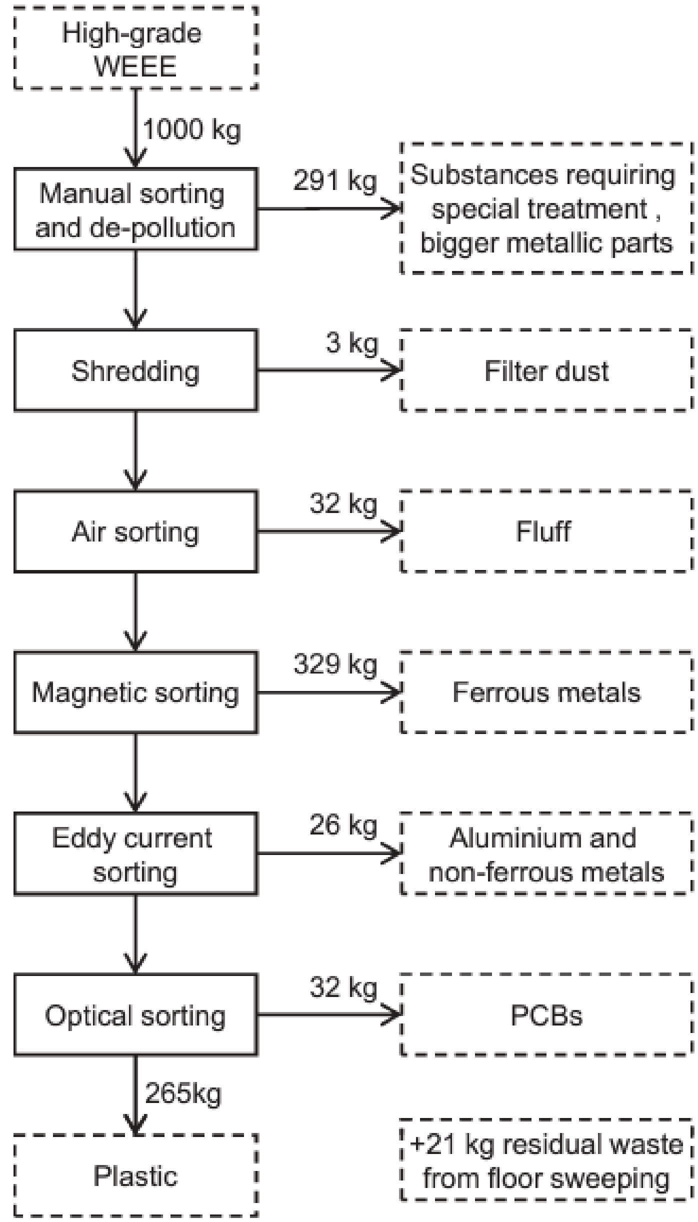
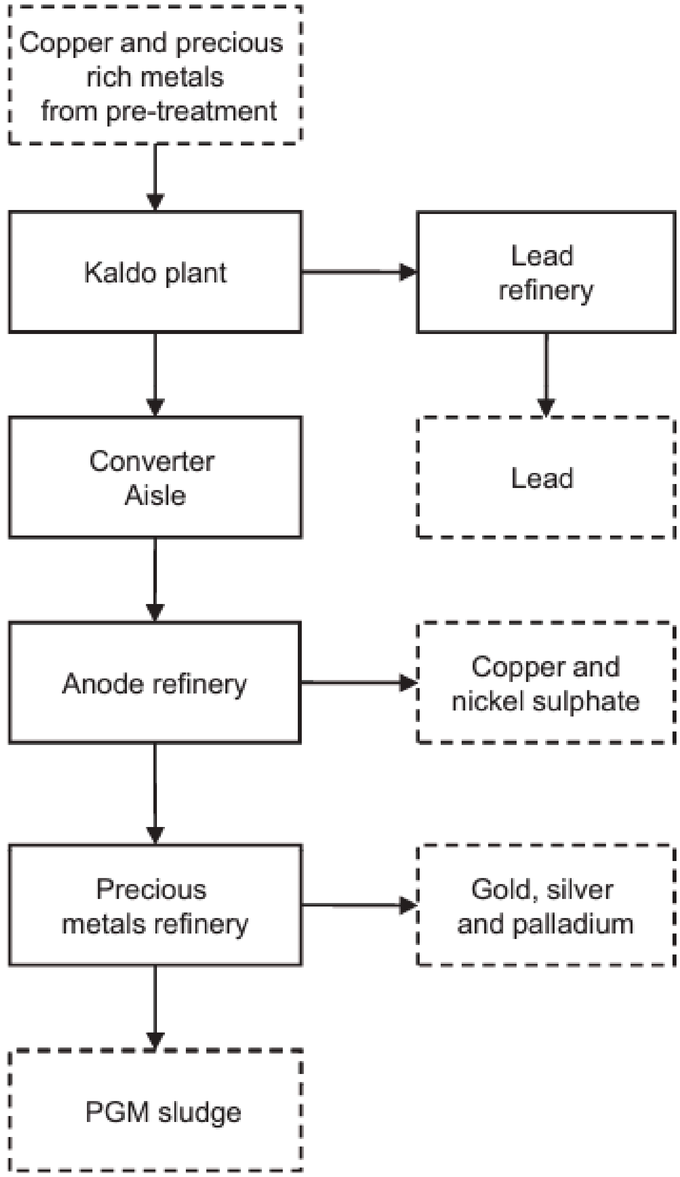


Fig. 1. Schematical view of the modeled pre-treatment facility and its output.

	 **Fig. 2.** Schematical view of the modeled metallurgic facility and its output.
VOCAB: (w/definition)	High-grade WEEE: the fraction of WEEE richest on precious metals Eddy-current separation: a process uses a powerful magnetic field to separate non-ferrous metals from an input waste or ore stream. PGM: platinum group metals Sludge: a semi-solid slurry that can be produced from a range of industrial processes, including waste treatment and refining processes
Cited references to follow up on	Hischier, R., Wäger, P., & Gauglhofer, J. (2005). Does WEEE recycling make sense from an environmental perspective? *Environmental Impact Assessment Review*, *25*(5), 525–539. https://doi.org/10.1016/j.eiar.2005.04.003

Follow up Questions	What are other efforts and methods to quantitatively assess the environmental impact of e-waste recycling processes? How to design a recycling process to maximize the environmental savings? Where to find the input data needed for such quantitative assessment of specific recycling processes?

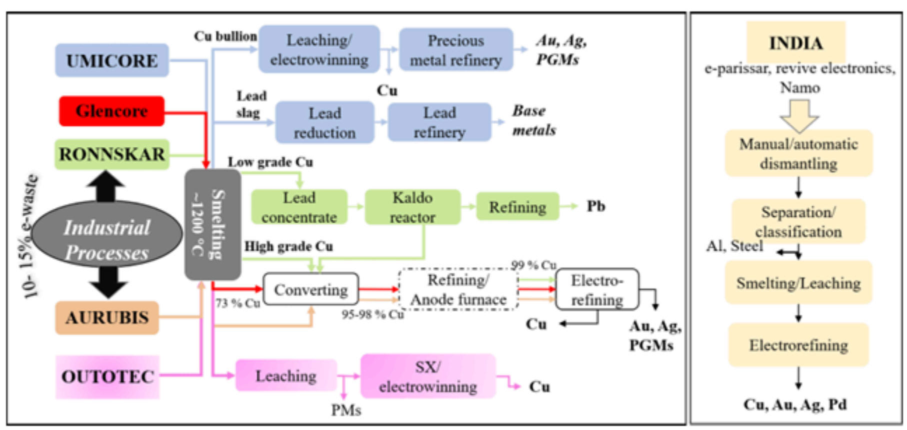
Article notes:

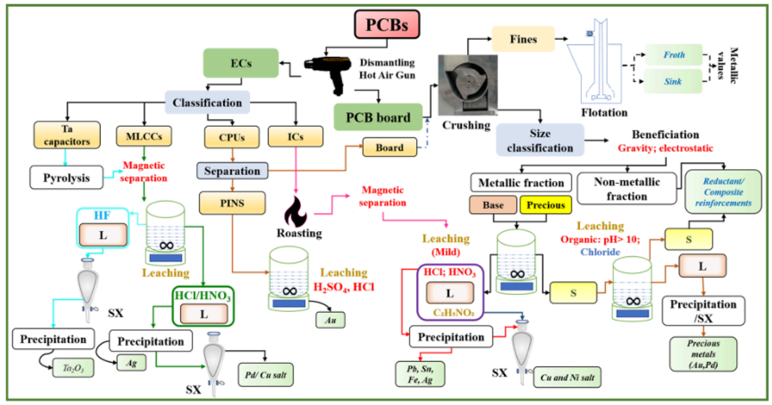
1. Life-cycle-assessment (LAC) is used to model the recovery of aluminium, copper, gold, iron, nickel, palladium and silver from high-grade Waste electrical and electronic equipment (WEEE).
2. It was found that the recovery of Cu, Au, Ni, Pd and Ag is of large environmental benefit.

Approach and Methods:

-High-grade WEEE is sent to pre-treatment facilities for sorting, de-pollution, shredding, and classification.
-Major outputs of pre-treatment include manually sorted components, magnetic iron, and plastic fractions.
-Precious-metal rich fractions are processed at integrated metallurgical treatment facilities.
-Life Cycle Inventories (LCIs) are collected environmentally relevant information.
-LCIs were established for WEEE treatment processes, and two allocation methods, mass and economic allocation, were considered.

Article #9 Notes: A comprehensive review on the recycling of discarded printed circuit boards for resource recovery

Source Title	A comprehensive review on the recycling of discarded printed circuit boards for resource recovery
Source citation (APA Format)	Mir, S., & Dhawan, N. (2022). A comprehensive review on the recycling of discarded printed circuit boards for resource recovery. *Resources, Conservation and Recycling, 178*, 106027. https://doi.org/10.1016/j.resconrec.2021.106027
Original URL	https://www.sciencedirect.com/science/article/pii/S0921344921006352
Source type	Journal Article
Keywords	E-waste; Recycling; PCB; Post-treatment; Precious metals; Electronic components; Value addition
#Tags	#Wasteprinted circuit board; # resource recovery
Summary of key points + notes (include methodology)	This study provide a comprehensive review on the metal recycling processes, the recycling of electronic components (an integral part) of PCBs and the value-added generation of end-products. It critically discusses the systematic and sequential processes adopted for PCB metallic recoveries via physical, pyrometallurgical, hydrometallurgical, and combined technologies.
Research Question/Problem/ Need	What are the prevailing processing method of recycling e-waste in industry? What are some recently adopted technologies?
Important Figures	 Fig. 4. A process flow diagram for major commercial recycling operations. A process flow diagram for major commercial recycling operations.

	 Fig. 5. Overall recycling flowsheet for the metal recovery from the discarded PCBs. ECs are primarily separated and treated individually for constituent valuables, while the PCB board is subjected to physical separation and sequential leaching to separate non-metallic fractions, base metal, and precious metals, respectively. ECs- electronic components; $C_2H_5NO_2$-Glycine; SX- solvent extraction. Overall recycling flowsheet for the metal recovery from the discarded PCBs. ECs are primarily separated and treated individually for constituent valuables, while the PCB board is subjected to physical separation and sequential leaching to separate non-metallic fractions, base metal, and precious metals, respectively. ECs-electronic components; $C_2H_5NO_2$-Glycine; SX- solvent extraction.
VOCAB: (w/definition)	ECs: electronic components Incineration: common waste to energy generation technology that uses the combustion of solid fuel to recover energy including both heat and electricity from it. Solvent Extraction: also known as leaching, the technique of removing one constituent from a solid by means of a liquid solvent.
Cited references to follow up on	Amit Barnwal, Mir, S., & Dhawan, N. (2020). Processing of Discarded Printed Circuit Board Fines via Flotation. *Journal of Sustainable Metallurgy*, *6*(4), 631–642. https://doi.org/10.1007/s40831-020-00304-4
Follow up Questions	Is it possible to develop an overall recycling process for PBCs to recover as much useful materials as possible?

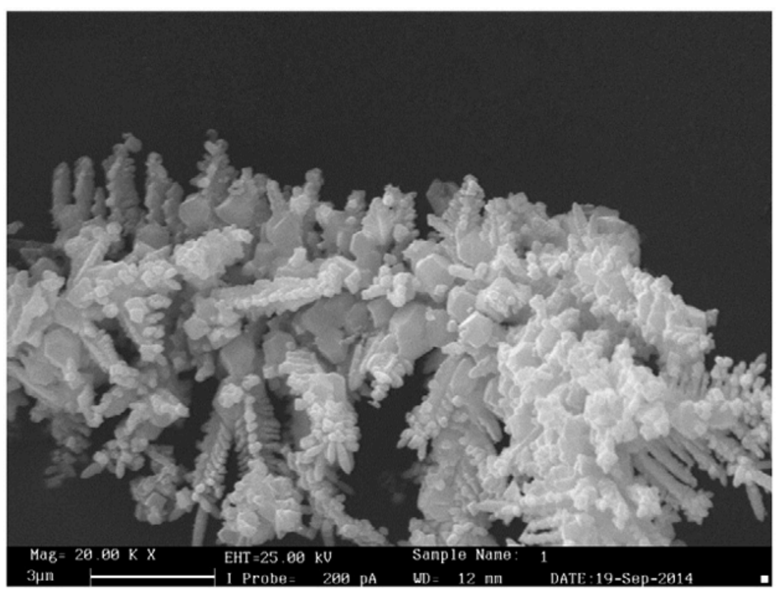
Article notes:

-Printed circuit boards (PCBs) are a significant component of electronic waste.
-Rapid resource depletion and metal-rich end-of-life PCBs necessitate recycling.
-Review covers metal recovery processes: physical, pyrometallurgical, hydrometallurgical, and combined methods.
-Pre-treatments enhance metal extraction; hybrid thermal-chemical routes are trending for improved efficiency. Pre-treatments play a decisive and significant role in upgradation and efficient metal extraction.
-Pre-treatments play a decisive and significant role in upgradation and efficient metal extraction.
-Selective recovery techniques, such as solvent extraction and precipitation, are gaining attention for high-purity product extraction.
-Commercial recycling predominantly uses pyrometallurgy; e-waste is a fraction of the total input.

-Components with precious metals (e.g., capacitors, integrated circuits) are of particular interest.
-Future recycling should focus on eco-friendly methods, separate recycling of base and precious metals, and ensure maximum economic gains.

-An integrated approach for full resource recovery from waste PCBs is recommended.

Article #10 Notes: Micro-copper powders recovered from waste printed circuit boards by electrolysis.

Source Title	Micro-copper powders recovered from waste printed circuit boards by electrolysis.
Source citation (APA Format)	Chu, Y., Chen, M., Chen, S., Wang, B., Fu, K., & Chen, H. (2015). Micro-copper powders recovered from waste printed circuit boards by electrolysis. *Hydrometallurgy, 156*, 152–157. https://doi.org/10.1016/j.hydromet.2015.06.006
Original URL	https://doi.org/10.1016/j.hydromet.2015.06.006
Source type	Journal Article
Keywords	Copper; Recovery; Electrolysis; WPCBs
#Tags	#Waste printed circuit board; #copper recovery; #electrochemistry
Summary of key points + notes (include methodology)	This study developed an efficient and environmental friendly process, directly using the concentrated WPCB metal scraps as anode to obtain micro-copper powder. Factors that affect the electrolysis were examined in detail. An optimal condition was obtained with high efficiency and fine powder products.
Research Question/Problem/ Need	How to directly recover copper from concentrated waste PCB metal scraps?
Important Figures	 **Fig. 7.** SEM photo of copper powders recovered in the cathode (electrolyte, 100 mL; $CuSO_4 \cdot 5H_2O$ concentration, 50 g/L; NaCl concentration, 40 g/L; H_2SO_4 concentration, 118 g/L; current density, 80 mA/cm^2; time, 3 h; temperature, 20 °C).

VOCAB: (w/definition)	SEM: scanning electron microscopy XRD: x-ray diffraction TEM: transmission electron microscopy Electrolysis: Electrolytic cells use an external source of direct current (DC) to drive reactions that would not otherwise be spontaneous. Electrolytic reactions are used purify metals and to plate metals on many types of substrates. Also called electrodeposition.
Cited references to follow up on	Bigum, M., Brogaard, L., & Christensen, T. H. (2012). Metal recovery from high-grade WEEE: A life cycle assessment. *Journal of Hazardous Materials*, *207-208*, 8–14. https://doi.org/10.1016/j.jhazmat.2011.10.001
Follow up Questions	1. Requirement to set-up electrolysis process: what instrument is needed? 2. Can other metals in e-waste be recovered by electrolysis too?

Article notes:

- ➔ WPCBs metal scraps were successfully used as anode to obtain micro-copper powder by electrolysis without pretreatment.
- ➔ Micro copper powders, about 9.35 μm with a purity of 98.12%, were successfully recovered by this process.
- ➔ The effects of $CuSO_4 \cdot 5H_2O$, NaCl and H_2SO_4 concentration, current density and electrolysis time on current efficiency and copper powder size were investigated in detail.
- ➔ The results indicated that current efficiency increased rapidly as the increase of $CuSO_4 \cdot 5H_2O$, H_2SO_4 concentration and current density.
- ➔ Particle size of the recovered copper powders can be controlled by current density and NaCl concentration.
- ➔ The recovered copper powders are dendritic and coated with a layer of dense Cu_2O.
- ➔ Under the optimum conditions (50 g/L $CuSO_4 \cdot 5H_2O$, 40 g/L NaCl, 118 g/L H_2SO_4, 80 mA/cm2 for 3 h), current efficiency was the highest (98.12%) and the particle size was the finest (9.35 μm).
- ➔ the process is effective for copper recovery from concentrated WPCB metal scraps.

Produced copper powders were characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

Article #11 Notes: Hydrometallurgical recovery of silver and gold from waste printed circuit boards and treatment of the wastewater in a biofilm reactor: An integrated pilot application.

Source Title	Hydrometallurgical recovery of silver and gold from waste printed circuit boards and treatment of the wastewater in a biofilm reactor: An integrated pilot application.
Source citation (APA Format)	Dimitrios Vlasopoulos, Panagiota Mendrinou, P. Oustadakis, Pavlina Kousi, Stergiou, A. D., Spyridon-Dionysios Karamoutsos, Artin Hatzikioseyian, P.E. Tsakiridis, E. Remoundaki, & S. Agatzini-Leonardou. (2023). Hydrometallurgical recovery of silver and gold from waste printed circuit boards and treatment of the wastewater in a biofilm reactor: An integrated pilot application. *Journal of Environmental Management, 344*, 118334–118334. https://doi.org/10.1016/j.jenvman.2023.118334
Original URL	https://doi.org/10.1016/j.jenvman.2023.118334
Source type	Journal Article
Keywords	Printed circuit boards; Silver; Gold; Hydrometallurgy; Denitrification
#Tags	Printed circuit board, recycling
Summary of key points + notes (include methodology)	This study developed a multistep hydrometallurgical process for the recovery of gold and silver from waste printed circuit boards (PCBs)and tested the process at pilot scale. Wastewater from the process was treated in a biofile reactor to comply with discharge guidelines.
Research Question/Problem/ Need	How to improve the recovery of silver and gold from waste printed circuit boards and how to treat the waste water to improve sustainability?

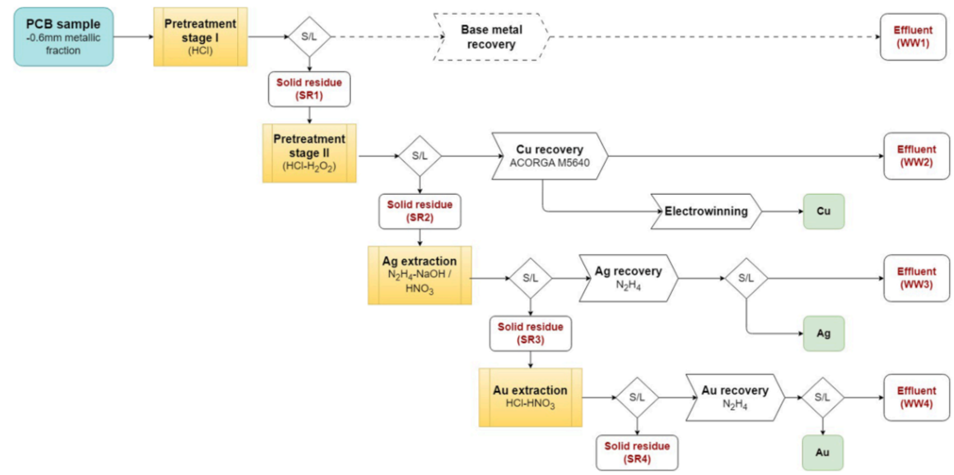
<table>
<tr><td>Important Figures</td><td>

Fig. 1. Hydrometallurgical flowsheet for Ag and Au recovery from waste PCBs.

Hydrometallurgical flowsheet for Ag and Au recovery from waste PCBs.</td></tr>
<tr><td>VOCAB: (w/definition)</td><td>Circular economy: a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. In practice, it implies reducing waste to a minimum.</td></tr>
<tr><td>Cited references to follow up on</td><td>Rocchetti, L., Amato, A., & Beolchini, F. (2018). Printed circuit board recycling: A patent review. Journal of Cleaner Production, 178, 814–832. https://doi.org/10.1016/j.jclepro.2018.01.076</td></tr>
<tr><td>Follow up Questions</td><td>Would it be possible to set-up a biofile reactor? Will need a biolab.</td></tr>
</table>

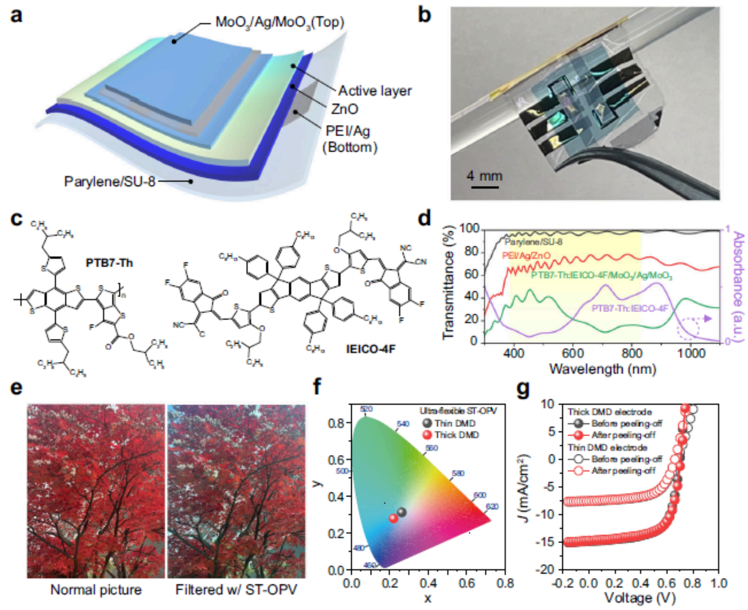
Article notes:

The removal of nitrate and residual metals from wastewater is a priority and in the present work, was addressed via a microbially-mediated process.

- ➔ Extraction of base and precious metals using only two leaching agents: HCl and HNO3.
- ➔ Selective separation and recovery of silver and gold
- ➔ The process comprises four sequential leaching stages; the first two based on HCl, correspond to base metals (e.g. Sn, Cu) removal, while the third is based on HNO3 for Ag leaching and the final on aqua regia for Au leaching.
- ➔ Microbial denitrification of the produced wastewater in presence of metals at ppm level. Using a packed-bed denitrifying biofilm reactor, inoculated with Halomonas denitrificans and operated upflow in fed-batch mode.
- ➔ Wastewater resulting from the process, rich in nitrate (5 g/L) and chloride (50 g/L), was treated by an effective and novel biological denitrification system tolerating metals at ppm level, to comply with zero nitrate and residual metals discharge guidelines.
- ➔ Separation and selective recovery of silver and gold by 83% and 100%, respectively.
- ➔ The overall process requires low reagents and energy input and has zero discharge for liquid effluents.

Article #12 Notes: Ultra-flexible semitransparent organic photovoltaics.

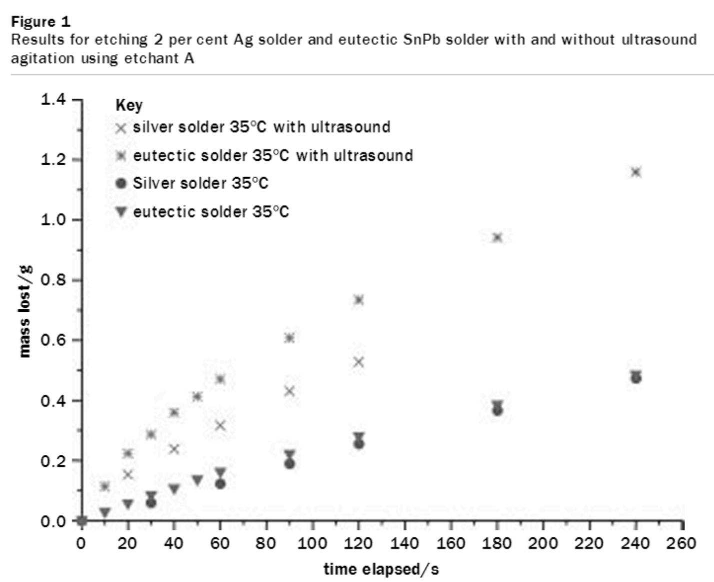
Source Title	Ultra-flexible semitransparent organic photovoltaics
Source citation (APA Format)	Lee, H., Jeong, S., Jae Hyun Kim, Jo, Y., Hyeong Ju Eun, Park, B., Sung Cheol Yoon, Kim, J. H., Lee, S., & Park, S. (2023). Ultra-flexible semitransparent organic photovoltaics. *Npj Flexible Electronics, 7*(1). https://doi.org/10.1038/s41528-023-00260-5
Original URL	https://doi.org/10.1038/s41528-023-00260-5
Source type	Journal Article
Keywords	Organic Photovoltaics (OPVs) Ultrathin Ag Electrodes Semitransparent (ST) Mechanical Durability Power-conversion Efficiency
#Tags	organic photovoltaics, transparent, efficiency
Summary of key points + notes (include methodology)	This study introduced strain-durable ultra-flexible semitransparent OPVs with a thickness below 2 µm. Through optimization, a conformal surface coverage of nanoscale thin metal electrodes (< 10 nm) was achieved, resulting in extremely low flexural rigidity and high strain durability. The study also conducted optical and electrical analyses on ultrathin metal electrodes to show that the devices maintain over 73% of their initial efficiency after 1000 cycles of repetitive compression and release at 66% compressive strain, and the average visible light transmittances remain higher than 30%.
Research Question/Problem/ Need	How to develop ultra-flexible OPVs with transparency and mechanical durability?

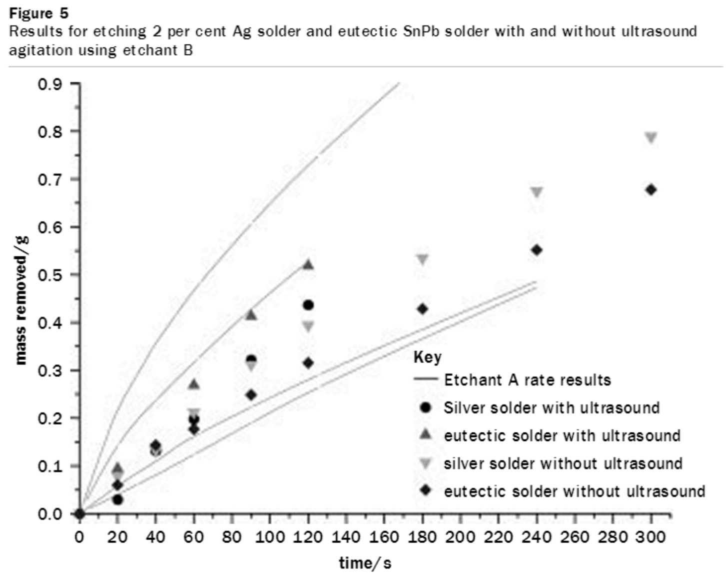
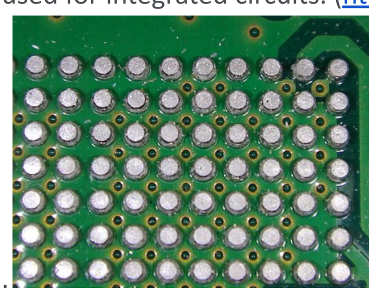
Important Figures	 **Fig. 1 Design of ultra-flexible ST-OPVs.** **a** Schematic of the device structure and (**b**) a photograph of ultra-flexible ST-OPV. **c** Chemical structures of donor polymer, PTB7-Th, and non-fullerene acceptor, IEICO-4F. **d** Absorbance spectra of PTB7-Th:IEICO-4F film (purple) and transmittance spectra of glass/parylene/SU-8 (black), PEI/Ag/ZnO (red), PTB7-Th:IEICIO-4F/MoO3/Ag (8 nm)/ (green). **e** Images captured without obstruction (left) and through parylene (0.5 µm)/SU-8 (0.6 µm)/PEI/Ag (8 nm)/ZnO (50 nm)/PTB7-Th:IEICIO-4F (65 nm)/MoO_3 (5 nm)/Ag (8 nm)/MoO_3 (30 nm)/parylene (1 µm) (right). **f** Color coordinates of ST-OPVs with different thicknesses of DMD electrodes under standard D65 illumination in the CIE 1931 color space. **g** *J–V* characteristics of ultra-flexible ST-OPVs under solar illumination (1000 W/m^2) before and after peeling off from supporting glass. The detailed information regarding the thickness of the metal layer in the D/M/D structure and the transmittance of devices are shown in Fig. S3. Fig. 1: Design of ultra-flexible ST-OPVs. (a) Schematic of the device structure and (b) a photograph of ultra-flexible ST-OPV. (c) Chemical structures of donor polymer, PTB7-Th, and non-fullerene acceptor, IEICO-4F. (d)Absorbance spectra of PTB7-Th:IEICO-4F film (purple) and transmittance spectra of glass/parylene/SU-8 (black), PEI/Ag/ZnO (red), PTB7-Th:IEICIO-4F/MoO3/Ag (8 nm)/ (green). (e) Images captured without obstruction (left) and through parylene (0.5 µm)/SU-8 (0.6 µm)/PEI/Ag (8 nm)/ZnO (50 nm)/PTB7-Th:IEICIO-4F (65 nm)/MoO3 (5 nm)/Ag (8 nm)/MoO3 (30 nm)/parylene (1 µm) (right). (f) Color coordinates of ST-OPVs with different thicknesses of DMD electrodes under standard D65 illumination in the CIE 1931 color space. (g) *J–V* characteristics of ultra-flexible ST-OPVs under solar illumination (1000 W/m2) before and after peeling off from supporting glass.
VOCAB: (w/definition)	PCE: power-conversion efficiency AVT: average visible transmittance ITO: indium tin oxide, a ternary composition of indium, tin and oxygen in varying proportions. Depending on the oxygen content, it can be described as either a ceramic or an alloy, one of the most widely used transparent conducting oxides because of its electrical conductivity and optical transparency
Cited references to follow up on	Hashemi, S. A., Ramakrishna, S., & Aberle, A. G. (2020). Recent progress in flexible–wearable solar cells for self-powered electronic devices. *Energy & Environmental Science*, *13*(3), 685-743.

Follow up Questions	Would the cost-benifit enable large-scale commercial applications?

Article notes:
-Ultrathin Ag bottom electrode and a dielectric-metal-dielectric (DMD) top electrode were utilized for high transmittance and flexibility.
-the highly efficient PTB7-Th:IEICO-4F was used as a photoactive material because it exhibits high PCE with low light absorption in visible light wavelengths (400–550 nm)
-A polymer nucleation layer was introduced to form a continuous thin metal film and obtain highly conductive and transparent bottom electrodes
- Antireflection layers were employed in the top DMD electrode to reduce light reflection and enhance transmittance.
-The optimized ultra-flexible ST-OPV achieved a peak PCE of 6.93% and an AVT of 30.1%.
-These devices showed remarkable mechanical resilience, withstanding strong biaxial tensile strains of about 200% and maintaining over 73% of initial PCE even after 1,000 compression-release cycles.
-DMD films showed high transparency with AVTs up to 78.6% and low resistance.
PEI/Ag/ZnO bottom electrodes achieved AVTs up to 86.4%.
-Both types of electrodes displayed superior mechanical robustness due to their nanoscale thickness, outperforming traditional ITO-based designs.

Article #13 Notes: Novel techniques for electronic component removal

Source Title	Novel techniques for electronic component removal
Source citation (APA Format)	Stennett, A. D., & Whalley, D. C. (1999). Novel techniques for electronic component removal. *Soldering & surface mount technology*, *11*(2), 7-11.
Original URL	https://www.emerald.com/insight/content/doi/10.1108/09540919910265622/full/pdf?title=novel-techniques-for-electronic-component-removal
Source type	Journal article
Keywords	Components, Repair, Rework, Soldering
#Tags	#printed circuit board, #desoldering, #nitric acid
Summary of key points + notes (include methodology)	The article is about testing different ways to remove the soldier from PCBs to release electrical components. This is because, PCBs have electrical components soldered onto them that need to be removed before continuing with any mechanical processes and other subsequent recycling treatment. The researchers evaluated thermal techniques and mechanical methods such as milling and shearing. Then the researchers tested chemical methods, and electrochemical ways of removing solder (desoldering). The most effective way through what they tested was with chemical solutions, Etchant A and B, to remove the soldiering.
Research Question/Problem/ Need	To find a nonthermal technique to enable components to be removed from PCBs without damage to either and with the minimum of operator intervention.
Important Figures	 Figure 1 Results for etching 2 per cent Ag solder and eutectic SnPb solder with and without ultrasound agitation using etchant A

	 Figure 5 Results for etching 2 per cent Ag solder and eutectic SnPb solder with and without ultrasound agitation using etchant B. Comparison with Etchant A rate results are also shown in this figure to show that Etychan A is faster.
VOCAB: (w/definition)	Etchants: Solution used for etching Test Coupon: Standard objects created with the correct dimensions and properties used for testing. Solder: Tin and Lead welding which holds electrical components, “a low-melting alloy, especially one based on lead and tin or (for higher temperatures) on brass or silver, used for joining less fusible metals.” (from Dictionary) Solder Mask: Polymer on the surface of PCBs to protect copper foil BGA:A ball grid array (**BGA**) is a type of surface-mount packaging (a chip carrier) used for integrated circuits. (https://en.wikipedia.org/wiki/Ball_grid_array)  . SIMMs: nine chip single in-line memory modules
Cited references to follow up on	Cited references are not very useful to follow up on. But references citing this article are useful to follow up on since they provide info on technology development in demounting the electric components. Chen, T., Korzenski, M. B., & Jiang, P. (2015). *U.S. Patent No. 9,221,114*.

	Washington, DC: U.S. Patent and Trademark Office. Chen, T., Korzenski, M. B., & Jiang, P. (2017). *U.S. Patent No. 9,649,712*. Washington, DC: U.S. Patent and Trademark Office. Chen, T., Korzenski, M. B., & Jiang, P. (2017). *U.S. Patent No. 9,731,368*. Washington, DC: U.S. Patent and Trademark Office.
Follow up Questions	How to optimize the etchant A for fast etching and less usage of harsh chemicals?

Article notes:

Testing proved that Etchant A was more effective than Etchant B and that sonication would make the process more efficient. Etchant A is nitric acid based and Etchant B is peroxide based.

The nitric acid based stripper has ferric nitrate added and an organic corrosion inhibitor. The ferric nitrate acts to dissolve the tin/copper intermetallics and the purpose of the inhibitor is to slow the etching rate of the copper so as not to damage the PCB tracking (and in this application the component terminations).

Etchant B was an ammonium hydrogen difluoride based etchant, also containing an inhibitor to stop the removal of the copper and activated with 7 per cent by volume of hydrogen peroxide.

During the trials the etchants were agitated either with a magnetic stirrer or ultrasonically.

The etching rate experiments were undertaken using FR4 test coupons covered on both sides with 15mm of copper. To one side of these coupons was applied either eutectic solder or 2 per cent silver solder. The area of the board undergoing the test was approximately 6cm2

The samples were weighed after the solder had been applied and the flux removed. They were then immersed in etchant for an amount of time, quickly washed, dried and reweighed before returning to the etchant solution. From these reduction in mass measurements the etching rate in mm/min was calculated. At the end of each experiment the thickness of the copper plate remaining was also measured and recorded to establish whether the copper had been attacked. In all of the tests the etching of the copper was minimal.

Chemical etching of real components have been carried out on BGAs (one type of PCB) and memory SIMMs (another type of PCB) using etchant A. (no etchant B)

Electrochemical etching was carried out with nine chip single in-line memory modules (SIMMs) and a solution containing tin and lead fluoborate, fluoboric acid, and boric acid. These samples were also examined using an SEM. Clean removal of solder was observed.

Conclusion:

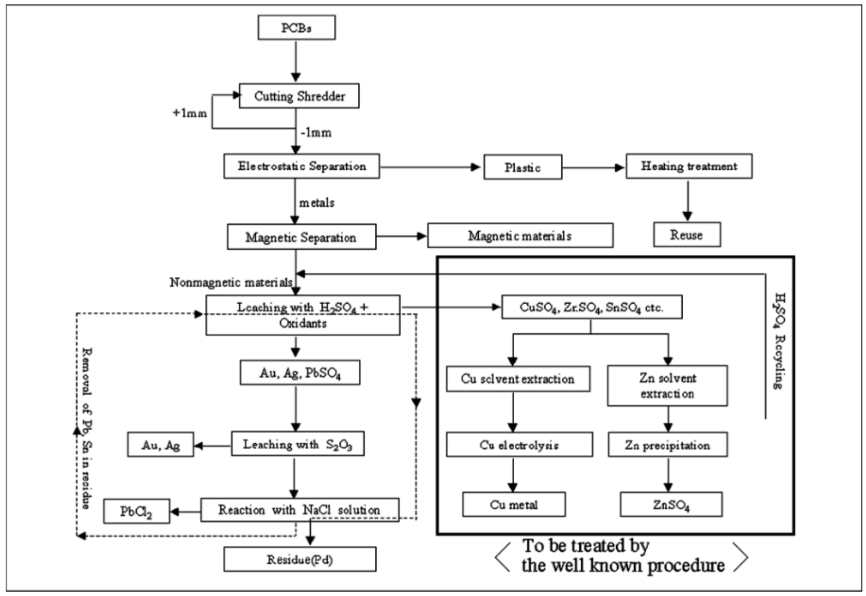
1. Chemical etchant based approaches show promise for the removal of components for recycling as they can be used in bulk situations to remove large quantities of components without significant operator intervention. The process is relatively fast, using off the shelf chemistry, and it is possible that etchants optimized for this application will offer much higher component

removal rates.

2. For the chemical only etchants the application of ultrasound to the etchant bath has been shown to greatly accelerate the etchant rate from approximately 20mm/min to a peak rate of in excess of 100mm/min.
3. The problem of making electrical connections hinders the electrochemical removal of components.

Article #14 Notes: Selective Leaching of Valuable Metals from Waste Printed Circuit Boards

Source Title	Selective Leaching of Valuable Metals from Waste Printed Circuit Boards
Source citation (APA Format)	Oh, C. J., Lee, S. O., Yang, H. S., Ha, T. J., & Kim, M. J. (2003). Selective Leaching of Valuable Metals from Waste Printed Circuit Boards. *Journal of the Air & Waste Management Association*, *53*(7), 897–902. https://doi.org/10.1080/10473289.2003.10466230
Original URL	https://www.tandfonline.com/doi/abs/10.1080/10473289.2003.10466230
Source type	Journal Article
Keywords	Waste printed circuit boards, leaching, metals
#Tags	#printed circuit board, #leaching, #Sulfuric acid
Summary of key points + notes (include methodology)	A procedure to recycle WPCBs was presented in this article. It implemented solely mechanical methods, a novel strategy for recycling e-waste that does not utilize unsustainable heat, expensive, and resource-intensive methods. Initially, e-waste was shredded and then separated into conducting and nonconducting materials through electrostatic separation. The materials were then put through magnetic separation. The non-magnetic materials consisted of many valuable metals, so selective leaching with various solutions was implemented to obtain them. The researchers implemented selective solutions such as sulfuric acid, $(NH_4)_2S_2O_3$ (0.2M), $CuSO_4$ (0.02M), NH_4OH (0.4M), NaCl, and aqua-regia.
Research Question/Problem/ Need	Can a physical pretreatment followed by chemical treatments recover multiple valuable metals?

Important Figures	 **Figure 1.** Flowchart for the recovery of valuable metals from PCB.
VOCAB: (w/definition)	Electrostatic separator: Electrost usually accomplished with a rotor-type separator, which is grounded and positive potential (+), in the electrical field of a large single, negative potential (-) electrode, with the feed particles spilling onto the rotating roll, rapidly developing a surface charge by induction. The particles that are the better conductors acquire the same potential as the rotor (+) and will then be drawn away from it towards the (-) electrode. While the nonconductive particles, less prone to pick up a charge, adhere to the rotor surface until the rotor turns enough for gravity to make the particle fall off.
Cited references to follow up on	Zhang, S., & Forssberg, E. (1999). Intelligent liberation and classification of electronic scrap. *Powder technology*, *105*(1-3), 295-301.
Follow up Questions	What's the estimated operational cost of this process compared to the received value of metals?

Article notes:

1. **Materials**

   PCBs used in the study were analyzed (authors did not specify the exact method, only said "component analysis") as containing the following:

   Metal 30wt%, including Cu 10.9%, Fe 7.7%, Ni 2.5%, Sn 3.9%, Pb 1.5%, Al 1.7%, Zn 1.1% , Au 0.00498%, Ag0.00813%, and Pd 0.002%

   Plastic materials 30wt%

   Metal oxides 40 wt% including 15% silica, 6% alkaline and alkaline earth oxides,6% alumina, and 13% other oxides

2. **Results and discussion**

   a. Electrostatic Separation of Conducting and Nonconducting Materials

      i. By a electrostatic separator

ii. A feed rate of 300 g/hr and electrostatic power settings between 500 and 3000 W were used

iii. Table 1 shows that the efficiency of separation approached a plateau as power settings greater than 1500 W.

Table 1. Separation of conducting and nonconducting materials.

	Electrostatic Power (W)				
	500	1000	1500	2000	3000
Conducting materials (wt %)	5.66	9.45	12	13.35	13.68
Semiconducting materials (wt %)	13.82	13.50	16.23	15.15	15
Nonconducting materials (wt %)	80.52	77.05	72.77	71.50	71.32

b. Magnetic Separation of Magnetic and Nonmagnetic Components

i. A dry magnetic separator

ii. feed rate of 1000 g/hr

iii. field strength ranging from 3000 to 12,000 gauss

iv. at 8000 gauss, nearly all of the magnetic components were separated.

v. 58wt% were nonmagnetic component, which included most of the valuable metals.

c. Chemical Analysis of the Nonmagnetic Material

i. Mostly metal, some semiconductors

ii. The proportions of Au and Ag were 0.227 and 0.697 mg/g, respectively, which indicate major enhancement.

Table 3. Chemical analysis of nonmagnetic material after magnetic separation at 8000 gauss.

	Element									
Assay	Au	Ag	Pd	Cu	Ni	Fe	Zn	Pb	Al	Sn
mg/g	0.23	0.69	0.09	489	1	3.3	10	15	26	31
%	0.02	0.07	0.009	48.9	0.1	0.3	1	1.5	2.6	3.1

d. Leaching of Metals with H_2SO_4

i. Sulfuric acid with H_2O_2.

ii. The H_2SO_4 concentration ranged from 0.25 to 2 M and the H_2O_2 concentration ranged from 0.05 to 0.2 M.

iii. 10 g of sample per L of leaching solution

iv. The optimal condition: 2 M H_2SO_4 and 0.2 M H_2O_2 at 85°C

v. 100% recovery of Cu and Zn within 8 hr,while Fe, Ni, and Al were 95% recovered in 12 hr.

e. Selective Leaching of Au and Ag

i. A leaching solution: $(NH_4)_2S_2O_3$ (0.2M), $CuSO_4$ (0.02M), and NH_4OH (0.4M)

ii. 40°C

   iii. 5g of sample in 1L of solution
   iv. Ag was fully extracted within 24 hr, 95% of the Au being extracted within 48 hr

f. **Selective Leaching of Pb**
   i. The remaining solid material consisted mainly of $PbSO_4$, a small quantity of $SnSO_4$, and Sn
   ii. Leaching solution is NaCl, ranged from 0.5 to 4 M, 2 hr, room temperature
   iii. 20 g sample in 1L of NaCl solution
   iv. 95% of the Pb reacted within 120 min in 2M Nacl

g. **Recovery of Sn**
   i. H_2SO_4 leaching solution (authors did not specify if H_2O_2 was used)
   ii. Resulted in recovery of 98% of the Sn

h. **Remaining Final Residue**
   i. Still contain Pd that was not dissolved in previous steps.
   ii. 30–100% aqua-regia was used at room temperature.
   iii. Most of the Pd was leached by 50% aqua-regia within 3 hr using 10 g solid residue in 1L of solution.

Article #15 Notes: Dismantling of Printed Circuit Boards Enabling Electronic Components Sorting and Their Subsequent Treatment Open Improved Elemental Sustainability Opportunities

Source Title	Dismantling of Printed Circuit Boards Enabling Electronic Components Sorting and Their Subsequent Treatment Open Improved Elemental Sustainability Opportunities
Source citation (APA Format)	Maurice, A. A., Dinh, K. N., Charpentier, N. M., Brambilla, A., & Gabriel, J.-C. P. (2021). Dismantling of Printed Circuit Boards Enabling Electronic Components Sorting and Their Subsequent Treatment Open Improved Elemental Sustainability Opportunities. *Sustainability*, *13*(18), 10357. https://doi.org/10.3390/su131810357
Original URL	https://www.mdpi.com/2071-1050/13/18/10357
Source type	Journal Article, review paper
Keywords	recycling; strategic metals; spectroscopy; X-rays imaging; image recognition; artificial intelligence
#Tags	#printed circuit board, #electronic componets, #sustainability
Summary of key points + notes (include methodology)	This comprehensive review sumerizes the state-of-the-art processes that dismantle and sort ECs, including some unpublished foresight from the authors' laboratory work, which could be implemented in a recycling plant. Conventional recycling involves manual removal of high value electronic components (ECs), followed by raw crushing of WPCBs, to recover main elements (by weight or value). All other elements remain unrecovered and end up highly diluted in post-processing wastes or ashes. To retrieve these elements, it is necessary to enrich the waste streams, which requires a change of paradigm in WPCB treatment: the disassembly of WPCBs combined with the sorting of ECs. This allows ECs to be separated by composition and to drastically increase chemical element concentration, thus making their recovery economically viable. The paper identifies research, business opportunities and associated advanced retrieval methods for those elements that can be recovered, such as refractory metals (Ta, Nb, W, Mo), gallium, or lanthanides, or those, such as the platinum group elements, that can be recovered in a more environmentally friendly way than pyrometallurgy. The paper conducted a thorough literature review and summarized the progress according to dismantling methods, sorting methods and type of metals to be recovered.
Research Question/Problem/ Need	Metal elements such as refractory metals and gallium exist in WPCBs but largely remain unrecovered due to low concentration. There is a strong need to enrich these elements through sorting of ECs to enable cost-effective recycling of them. This review paper summerizes and discusses the current advancements that might be useful in creating such a method.

<table>
<tr><td>Important Figures</td><td>
Table 1. Qualitative comparison of the different dismantling processes (+ cheap, ++ mid-priced, +++ expensive).
<table>
<tr><th>Process</th><th>CAPEX</th><th>OPEX</th><th>Advantages</th><th>Drawbacks</th></tr>
<tr><td>Manual dismantling</td><td>+</td><td>++++</td><td>Easy to implement
Selective disassembling</td><td>Hard manual work
Requires manpower
Slow process
Polluting</td></tr>
<tr><td>Surface cutting knife</td><td>++</td><td>+</td><td>Non-polluting
High disassembly rate</td><td>WPCBs are treated one by one</td></tr>
<tr><td>Crude heating</td><td>++</td><td>+</td><td>Large capacity</td><td>Toxic emissions
Heat damage ECs</td></tr>
<tr><td>Infrared radiators</td><td>++</td><td>+</td><td>High disassembly rate</td><td>Small volumes
Heat damage ECs</td></tr>
<tr><td>Hot air heating</td><td>++</td><td>++</td><td>High disassembly rate
Little maintenance
Non-polluting</td><td>Low accuracy control
Low energy efficiency</td></tr>
<tr><td>Solder bath heating</td><td>++</td><td>+++</td><td>High disassembly rate</td><td>Difficult to automate
Toxic fumes emissions
Dangerous working conditions</td></tr>
<tr><td>Hot fluid heating</td><td>++</td><td>++</td><td>High disassembly rate
High thermal efficiency
High solder recovery rate</td><td>Generating toxic waste fluids and fumes</td></tr>
<tr><td>Heated centrifugation</td><td>++</td><td>++</td><td>High solder recovery rate
Solder elements separation</td><td>High temperature
Heat damage ECs</td></tr>
<tr><td>Solder dissolution</td><td>+</td><td>++</td><td>Selective process</td><td>Requires further treatments
Hazardous chemicals used</td></tr>
<tr><td>Hydrothermal and supercritical fluids treatment</td><td>+++</td><td>++</td><td>Target metals or resin
No toxic product released
Reusable reagents</td><td>Cannot target solder
Requires further dismantling treatments</td></tr>
<tr><td>Epoxy resin treatment</td><td>++</td><td>++</td><td>Recover functional circuits
Chemicals can be recycled</td><td>Need further dismantling process
Hazardous chemicals used</td></tr>
<tr><td>Robotic Dismantling</td><td>+++</td><td>+</td><td>Combined dismantling and sorting</td><td>Low throughput</td></tr>
<tr><td>Fragmentation by high voltage electric pulse crusher</td><td>+++</td><td>++++</td><td>Low manpower
High capacity
Non-polluting</td><td>Low energy efficiency
Expensive initial investment</td></tr>
</table>
</td></tr>
<tr><td>VOCAB: (w/definition)</td><td>Ionic liquids (ILs): compounds completely composed of ions with melting point below 100 °C. It can be considered as a salt in the liquid state at ambient conditions.
Supercritical fluid: a highly compressed fluid that combines the properties of gases and liquids. They are created by increasing temperature and pressure beyond a substance's critical point.
Laser induced breakdown spectroscopy: a rapid chemical analysis technology that uses a short laser pulse to create a micro-plasma on the sample surface. It is used to measure the concentration of major and trace elements in solid, liquid, or air samples, or to record the chemical signature (fingerprint) of a material.</td></tr>
<tr><td>Cited references to follow up on</td><td>Kinoshita, T., Akita, S., Kobayashi, N., Nii, S., Kawaizumi, F., & Takahashi, K. (2003). Metal recovery from non-mounted printed wiring boards via hydrometallurgical processing. Hydrometallurgy, 69(1-3), 73-79.

Mecucci, A., & Scott, K. (2002). Leaching and electrochemical recovery of copper, lead and tin from scrap printed circuit boards. Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology, 77(4), 449-457.

Veit, H. M., Bernardes, A. M., Ferreira, J. Z., Tenório, J. A. S., & de Fraga Malfatti, C. (2006). Recovery of copper from printed circuit boards scraps by mechanical processing and electrometallurgy. Journal of hazardous materials, 137(3), 1704-1709.</td></tr>
<tr><td>Follow up Questions</td><td>What are the differences in nitric acid and sulfuric acid to dismantle ECs?</td></tr>
</table>

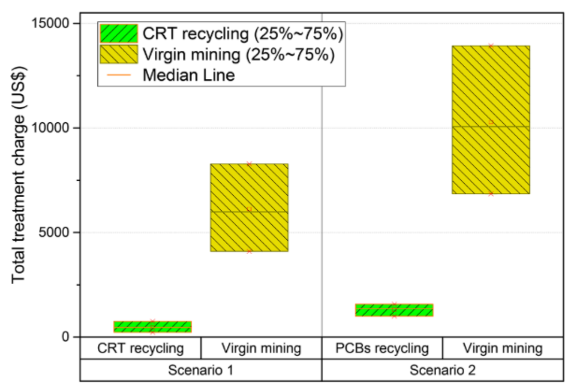
Article notes:

EC dismantling methods include:

1. Mechanical Dismantling
    a. Manual Dismantling
    b. Surface Cutting Knife Dismantling
2. Dismantling via a Heat Treatment
    a. Crude Heating
    b. Infrared Radiators (IR)
    c. Hot Air Heating
    d. Solder Bath Heating
    e. Hot Fluid Heating
    f. Heated Centrifugation
3. Chemical Methods
    a. Solder Dissolution
    b. Hydrothermal and Supercritical Fluids (SCF) Treatment
    c. Dismantling via Epoxy Resin Treatment
4. WPCBs Fragmentation by High Voltage Electric Pulse Crusher

Thermal methods require large capital investment and high energy consumption. In addition, thermal treatment may damage ECs that could be reused.

Article #16 Notes: Urban Mining of E-Waste is Becoming More Cost-Effective ThanVirgin Mining

Source Title	Urban Mining of E-Waste is Becoming More Cost-Effective Than Virgin Mining
Source citation (APA Format)	Zeng, X., Mathews, J. A., & Li, J. (2018). Urban Mining of E-Waste is Becoming More Cost-Effective Than Virgin Mining. *Environmental Science & Technology*, *52*(8), 4835–4841. https://doi.org/10.1021/acs.est.7b04909
Original URL	https://doi.org/10.1021/acs.est.7b04909
Source type	Journal Article
Keywords	E-waste, urban mining, cost-effective, virgin mining
#Tags	#e-waste, #urban mining, #circular economy
Summary of key points + notes (include methodology)	In this paper, the authors used real cost data from e-waste processors in China to varify that that ingots of pure copper and gold could be recovered from e-waste streams at costs that are comparable to those encountered in virgin mining of ores. The results are only confined to the cases of copper and gold extracted and processed from e-waste streams made up of recycled TV sets, but these results indicate a trend and potential if applied across a broader range of e-waste sources and metals extracted. The paper considered the scenario of removing government subsidies and showed that in current stage, government subsidies are necessary incentives for e-waste recycling.
Research Question/Problem/ Need	How does the cost of metal recovery from waste PCBs compare with the cost of metal recovery from virgin mining?
Important Figures	 **Figure 2.** Comparison of total integrated treatment charge for urban mining and virgin mining for same metals yield. Note: Scenario 1 with equivalent yield as CRT recycling, and scenario 2 with equivalent yield as PCBs recycling. Dash area indicates the range of value.
VOCAB: (w/definition)	Urban mining: the process of reclaiming raw materials from waste products sent to landfill.

Cited references to follow up on	Tesfaye, F., Lindberg, D., Hamuyuni, J., Taskinen, P., & Hupa, L. (2017). Improving urban mining practices for optimal recovery of resources from e-waste. *Minerals Engineering*, *111*, 209-221.
Follow up Questions	How does the cost of recovering other metals from PCBs compare with that of virgin mining?

Article notes:

1. **The Total Economics of Urban Mining Versus VirginMining**: The total cost of extracting the basket of metals (withthe same yields as CRT recycling) from virgin ores is US$5,990,thisfigure is dominated (US$5,490, 92%) by the cost of miningthe gold, which can be validated by the previous studies.25,26Inall other cases, the cost of virgin mining is cheaper thanrecycling treatment.
2. **The Economics of Urban Mining Versus Virgin Miningfor Single Metal:**
    a. costs of urban mined copper reducing year by year, toreach levels well below the world market price
    b. the same phenomenon for gold, with even greaterrange (27,000−52,000 US$/kg) of gap between urban miningcost (1,591−8,438 US$/kg) and the market price (36,000−55,000 US$/kg)
    c. If the subsidy is removed, costs of extracting copper from e-waste are not significantly attractive while osts for extracting gold are still well below the world commodity price.

Article #17 Notes: Use of gravity separation in metals concentration from printed circuit board scraps

Source Title	Use of gravity separation in metals concentration from printed circuit board scraps
Source citation (APA Format)	Veit, H. M., Juchneski, N. C. D. F., & Scherer, J. (2014). Use of gravity separation in metals concentration from printed circuit board scraps. *Rem: Revista Escola de Minas*, *67*, 73-79.
Original URL	https://www.scielo.br/j/rem/a/QrD3YSjzxwKKczX9RHgvs6F/?lang=en&format=html
Source type	Journal paper
Keywords	Electronic scrap; metals; gravity separation; printed circuit boards scrap
#Tags	#e-waste; #sustainability; #printed circuit board; #metal
Summary of key points + notes (include methodology)	Recycling of printed circuit boards (PCB) is a complex process, but very important for the recovery of metals of high economic value. Industrial processes for the recovery of metals from PCB are based on pyrometallurgy and hydrometallurgy. In both cases, it is beneficial to carry out a pretreatment that involves the use of mechanical processes. This paper studied the concentration of the metallic fraction of PCB by a Mozley concentrator. The results show that it is possible to recover significant quantities of metals such as copper (concentration 85%), tin (95%), and silver (98%) through the gravity seperation. **Methodology:** 1. generic PCB from various types of equipment collected in a multi-brand service center was used. 2. The printed circuit boards weregrinded in two different ways: a hammer mill for rough grinding (grid = 15mm) and one knife mill to obtain fine particles (grid = 2; 1; 0.5; 0.25 mm). 3. dense medium separation and Mozley concentrator separation were used to create different assays of grinded PCBs 4. induced coupled plasma atomic emission spectrometry (ICP-AES) and flame atomic absorption were used to determine which metals were present.
Research Question/Problem/ Need	How effectively can mechanical processes enrich valuable metals for subsequent refining processes?

Important Figures

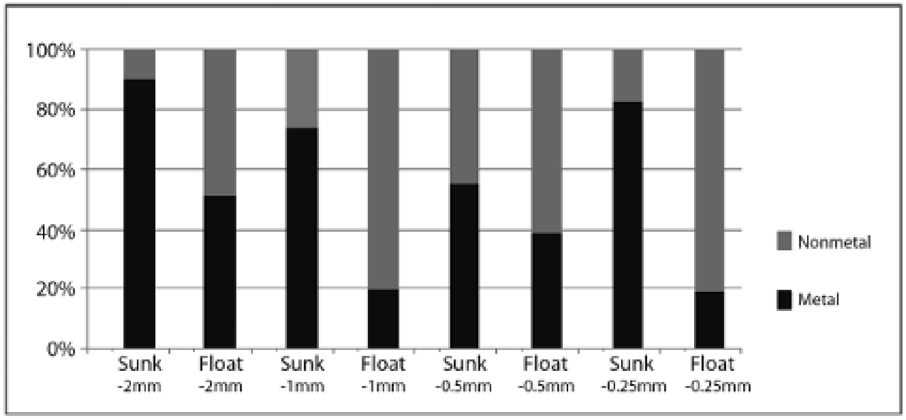


Figure 2
Metals Distribution in the Dense Medium Assay

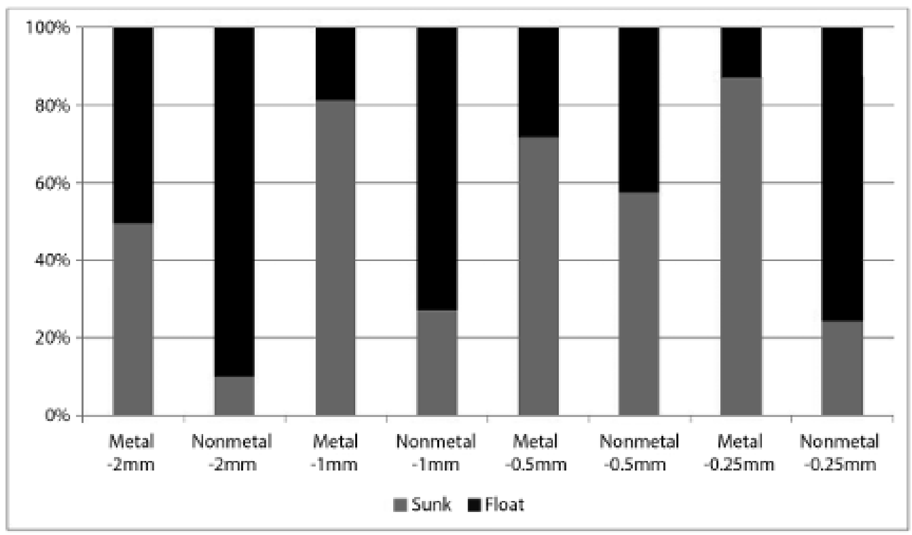
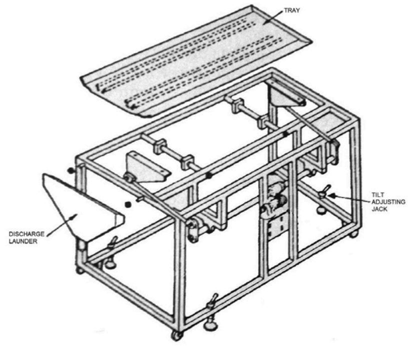


Figure 3
Metals Distribution in Sunk and Float Fractions

VOCAB: (w/definition)

Mozley concentrator: The equipment consists of a flat tray for separating fine particles (10 to 100µm), and a separation V-shaped tray, with a 165 degree angle; it is used for coarse particles (100µm to 2mm) as shown in Figure 1. The parameters that can be varied beyond the tray type are tilt-tray, oscillation frequency, time and flow rate of water.
ICP-AES: induced coupled plasma atomic emission spectrometry

	 Figure 1 Mozley Concentrator (Adapted from Sampaio, 2005)
Cited references to follow up on	WUPPERTAL INSTITUTE, Material Intensity of Materials, Fuels, Transport Services. http:// www.wupperinst.org/uploads/tx_wibeitrag/MIT_2011.pdf, October, 2012
Follow up Questions	How does the environmental impacts and economic costs of secondary metal production compare with that of primary production?

Article notes:

1. dense medium used: 95% tetrabromoethane and 5% acetone with a density of 2.88g/cm³.
2. solid:liquid ratio of 1:10
3. The particle sizes used in the assay were: -2 +1mm, -1+0.25mm, -0.5+0.25mm, and -0.25 mm.
4. Figure 3 (shown previously) show that the fraction with the best separation was -0.25 mm; however, to reach this particle size, much loss of material occurs during the milling process.

Article # 18 Notes: Two-step pre-processing enrichment of waste printed circuit boards: Mechanical milling and physical separation.

Source Title	Two-step pre-processing enrichment of waste printed circuit boards: Mechanical milling and physical separation.
Source citation (APA Format)	Nekouei, R. K., Pahlevani, F., Rajarao, R., Golmohammadzadeh, R., & Sahajwalla, V. (2018). Two-step pre-processing enrichment of waste printed circuit boards: Mechanical milling and physical separation. *Journal of Cleaner Production*, *184*, 1113–1124. https://doi.org/10.1016/j.jclepro.2018.02.250
Original URL	https://doi.org/10.1016/j.jclepro.2018.02.250
Source type	Journal paper
Keywords	E-waste, Waste PCB, Milling, Separation, Enrichment, Bromoform
#Tags	#e-waste; #sustainability; #printed circuit board; #physical separation; #mechanical milling

Summary of key points + notes (include methodology)	- In this study, for the first time, a simple and novel process was proposed to enhance the amount and purity of metallic portion of waste PCBs without using any chemical or thermal process.
	- In each stage, all classified powders were characterized to recognize the composition and metal content present in each classification. This provide valuable information to understand the effect in terms of metal enrichment and separation from polymers after each processing stage.
	- This method allows for a separation process that is efficient and safe without using any chemical or thermal process.
	-
	Method:
	- Mechanical milling
	    - PCBs were cut and then put into a knife mill.
	    - A 2-stage ring mill process helped obtain a fine PCB powder.
	- Physical (gravity) separation
	    - Used bromoform (2.82 g/cm^3) for physical separation.
	    - Added acetone in an 85:15 vol ratio (2.5 g/cm^3) for aluminum.

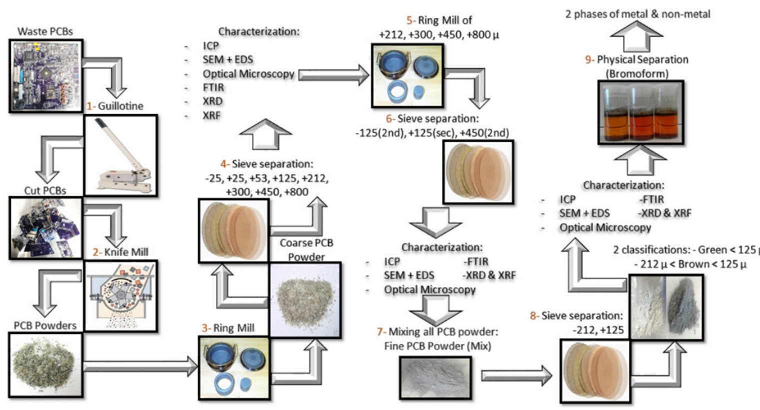
<table>
<tr>
<td>Research Question/Problem/ Need</td>
<td>How do we propose a mechanical-physical separation method for the recovery of metal contents of waste PCBs with no need for further chemical or/and thermal processes?</td>
</tr>
<tr>
<td>Important Figures</td>
<td>


Fig. 1. The flowchart of the process of liberation, beneficiation and enrichment of the metallic and non-metallic components of waste PCBs.
</td>
</tr>
<tr>
<td>VOCAB: (w/definition)</td>
<td>SEM: Scanning electron microscopy. A scanning electron microscope is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons.

FTIR: Fourier transform infrared. Fourier-transform infrared spectroscopy is a technique used to obtain an infrared spectrum of absorption or emission of a solid, liquid, or gas.

X-Ray Fluorescence analysis: the emission of characteristic "secondary" X-rays from a material that has been excited by being bombarded with high-energy X-rays. It is an analytical technique that uses the interaction of X-rays with a material to determine its elemental composition.

TGA: Thermogravimetric analysis or thermal gravimetric analysis is a method of thermal analysis in which the mass of a sample is measured over time as the temperature changes. It is a powerful technique for the measurement of thermal stability of materials including polymers.</td>
</tr>
<tr>
<td>Cited references to follow up on</td>
<td>Evangelopoulos, P., Kantarelis, E., Yang, W., 2015. Investigation of the thermal decomposition of printed circuit boards (PCBs) via thermogravimetric analysis (TGA) and analytical pyrolysis (PyeGC/MS). J. Anal. Appl. Pyrol. 115, 337e343. https://doi.org/10.1016/j.jaap.2015.08.012.

He, J., Duan, C., 2017. Recovery of metallic concentrations from waste printed circuit boards via reverse floatation. Waste Manag. 60, 618e628. https://doi.org/10.1016/j.wasman.2016.11.019</td>
</tr>
</table>

Follow up Questions	- What are other methods of separation? I.e instead of density separation, what if one used a magnetic or electrochemical method? - How do you separate each of the different metal precipitates? Even though Cu is the main component in the precipitates, there are Zn, Fe and other metals in the mixture. - Is calcium considered significant in this study? I noticed it was on the results however it was not present throughout the text prior.

Article notes:

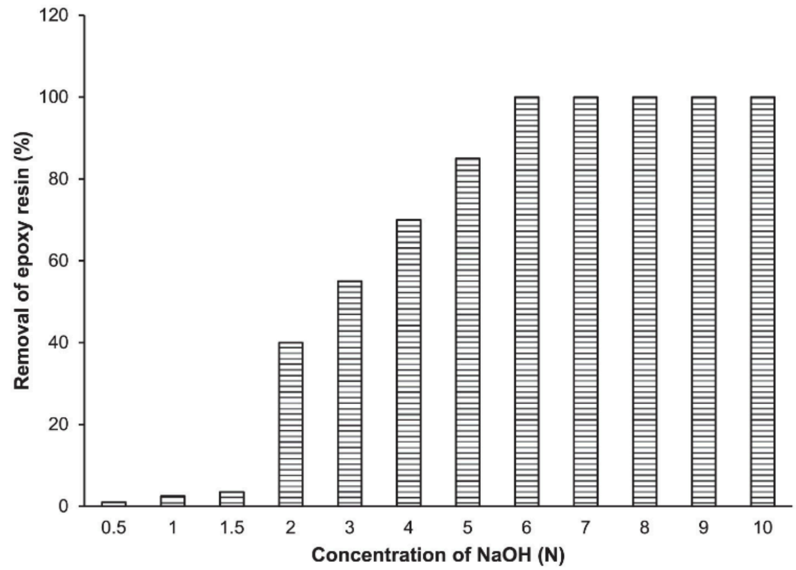
1. Densities: Cu, Pb, Co, Cr, Ni, Fe, Zn, Sn and Al, are 8.9, 11.4, 8.9, 7.2, 8.9, 7.9, 7.1, 7.3 and 2.7 g/cm^3, respectively. Polymers in PCBs are less than 2 g/cm^3

2. Results:

   FTIR: polymers are present in all samples of different stages
   X-ray diffraction analysis: Based on the XRD analysis it can be concluded that the ceramic portion of the mixture is hard to detect which is anticipated to be due to amorphous structure.
   X-Ray Fluorescence analysis: XRF shows that the major ingredients of the ceramic portion are CaO, SiO_2, and Al_2O_3, as glass fibres and ceramic casing for electronic parts.
   ICP analysis: ICP shows that contents of metals are more in "Brown" phase.
   TGA and IR gas analysis:
      a. Weight loss percentage for "Mix", "Brown" and "Green" samples are 26.2, 24.4 and 26.9, respectively, in TGA
      b. IR analysis confirmed the most volatile gases were not simple greenhouse gases such as CO, CO_2 and CH_4. The surface of filter paper was covered by an oily material indicating other gaseous pollutants vaporized on high temperature
   SEM were also used to observe the powder morphology and element distribution.

Article # 19 Notes: A novel method for the removal of epoxy coating from waste printed circuit board.

Source Title	A novel method for the removal of epoxy coating from waste printed circuit board.
Source citation (APA Format)	Senophiyah-Mary, J., Loganath, R., & Meenambal, T. (2018). A novel method for the removal of epoxy coating from waste printed circuit board. *Waste Management & Research*, *36*(7), 645-652.
Original URL	https://journals.sagepub.com/doi/full/10.1177/0734242X18782392
Source type	Journal paper
Keywords	Waste printed circuit board, epoxy coating removal, stripping, bath sonication, optimisation, bioleaching, lye solution
#Tags	#e-waste; #sustainability; #printed circuit board;
Summary of key points + notes (include methodology)	This paper reports a combined process of sonication and solvent stripping in a closed environment for stripping the epoxy coating (solder mask) on waste PCBs. The waste PCBs were cut into approximately 1.5 cm × 1 cm, which weighed approximately 2 g. The e-waste plate was washed and air dried. Sodium hydroxide of various concentrations from 0.5 N to 10 N was tested for soaking time from 4–12 h. Other solvents, such as ethanol, acetone, tween-80, carbinol, benzyl alcohol, and acids like sulphuric acid, nitric acid, hydrochloric acid were also tested for over night. Sonication was also tested. An optimized condition was found.
Research Question/Problem/ Need	What is the optimized recipe to remove solder mask from waste PCBs?

Important Figures	 **Figure 2**. Removal of epoxy coating with various concentrations of NaOH.
VOCAB: (w/definition)	Hydrolysis: hydrolysis is a chemical process in which a molecule of water is added to a substance
Cited references to follow up on	Reinhart TJ (1989) Ultrasonic assisted protective coating removal. In: Google Patents, US4858264A.
Follow up Questions	What's the effect of ultrasonication in solder mask removal?

Article notes:

The usage of 5 N NaOH with a soak time of 8 h and a reaction time of 5 min in a bath sonicator could easily remove the epoxy coating from PCB.

Article #20 Notes: Metals content in printed circuit board waste

Source Title	Metals content in printed circuit board waste.
Source citation (APA Format)	Szałatkiewicz, J. (2014). Metals content in printed circuit board waste. *Pol. J. Environ. Stud*, *23*(6), 2365-2369.
Original URL	https://d1wqtxts1xzle7.cloudfront.net/36855456/Pol.J.Environ.Stud.Vol.23.No.6.2365-2369-libre.pdf?1425481375=&response-content-disposition=inline%3B+filename%3DMetals_Content_in_Printed_Circuit_Board.pdf&Expires=1702338055&Signature=ICzez8IwCRyBIcbIyYrQ-KodHB32qRftB10T3Sj9tSErCmmv5brCn939qCJi~UsCNciNU2PiBhtsiRMhKiFOi7hx3gLZ5f47CnOLEjwg4xQmgAS~lxG5dMWNhgO3QUQ6fmcKGfi5YXzMvmJGZMv9~v2C6BoJ5REhd1THHV4T3zlJUR3NxCYE9clSmmlhYLv4oU8ZhVz7AqoKzjrFflOpHGXIkxz3Pal24ezF5yH8VMT8ODy1mjTofuOlDtMoq0M~AAPk9SuxgU~gTCypMXGtf9qU5-tTAS~wV64NwbucTRIH4jeLbUvVkUyn4cOt7iXn1RJOQb-4SvzNWGmpNff1SA__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA
Source type	Journal paper
Keywords	PCBs, printed circuit boards, WEEE, waste, recovery, recycling, metals
#Tags	#e-waste; #sustainability; #printed circuit board; #metals
Summary of key points + notes (include methodology)	This paper analyzes the metal contents in waste printed circuit boards by summarizing and comparing results found in different references. It provides a good introduction and summary to the content of waste PCBs and their relative amount.
Research Question/Problem/ Need	What are the metal contents in waste PCBs?

Important Figures

Table 1. The content of metals and organic substances present in printed circuit boards from: PC computers (PCB 1 [11], PCB 2 [16], PCB 3 [17]), mobile phones without battery (PCB 4 [18]), mixed (PCB 5 [3]).

PCB 1				PCB 2	PCB 3	PCB 4	PCB 5
Material	Element	Content (%) mass	Overall mass	Content (%) mass	Content (%) mass	Content (%) mass	Content (%) mass
Organic Epoxy resign	C	18.1	31.8%	n/a	24.69	41	26.36
	H	1.8		n/a	1.38		2.8
	N	0.32		n/a	0.85		1
	O Org	6.03		n/a	n/a		15.58
	Br	5.07		n/a	4.94		6.5
	Sb	0.45		1.97	n/a		n/a
Nonmetals Glass fibers	SiO_2/Si	24.7	37.6%	n/a	n/a	n/a	11.3
	Al_2O_3	9.35		n/a	n/a	n/a	n/a
	CaO/Ca	3.36		3.2	1.9	n/a	6.7
	MgO/Mg	0.081		0.096	0.22	n/a	n/a
	BaO/Ba	0.0022		0.16	n/a	n/a	n/a
	NaO/Na	0.09		0.002	n/a	n/a	n/a
	SrO/Sr	0.035		0.02	n/a	n/a	n/a
Metals Solder	Cu	14.6	30.1%	24.69	13.79	13	11.09
	Sn	5.62		2.31	n/a	1	n/a
	Pb	2.96		0.63	n/a	0.6	n/a
Construction Elements	Fe	4.79		0.22	1.97	7	n/a
	Ni	1.65		0.11	0.17	1.5	n/a
	Cr	0.356		0.025	0.003	n/a	n/a
	Mo	0.016		n/a	n/a	n/a	n/a
Connectors	Ag	0.045		0.0242	n/a	0.363	n/a
	Au	0.0205		0.0076	n/a	0.0347	n/a
	Pd	0.022		<0.0027	n/a	0.0151	n/a

VOCAB: (w/definition)

PVC: Polyvinyl Chloride (PVC or Vinyl) is a high-strength thermoplastic material. It is widely used in applications such as pipes, medical devices, and wire & cable insulation.

Cited references to follow up on

Ni M., Xiao H., Chi, Y., Yan J., Bueken A., Jin. Y., Lu S. Combustion and inorganic bromine emsson of waste printed circuit boards in a high temperature furnace. Waste Manage. 32, 568, 2012.

Follow up Questions

What are some of the environmental impacts of pryometallurgical methods?

Article #21 Notes: Aqueous metal recovery techniques from e-scrap: Hydrometallurgy in recycling.

Source Title	Aqueous metal recovery techniques from e-scrap: Hydrometallurgy in recycling.
Source citation (APA Format)	Tuncuk, A., Stazi, V., Akcil, A., Yazici, E. Y., & Deveci, H. (2012). Aqueous metal recovery techniques from e-scrap: Hydrometallurgy in recycling. *Minerals engineering*, *25*(1), 28-37.
Original URL	https://www.sciencedirect.com/science/article/pii/S0892687511003669
Source type	Journal review paper
Keywords	E-scrap, Recycling, Hydrometallurgy, Leaching, Metal recovery
#Tags	#e-waste; #sustainability; #printed circuit board; #metal recovery
Summary of key points + notes (include methodology)	This paper reviews hydrometallurgical processes used for metal recovery from e-waste. Advantages of hydrometallurgical processes included relatively low capital cost,reduced environmental impact (e.g. nohazardousgases/dusts), potential fo rhighmetal recoveries and suitability for small scale applications. The metals are present in native forma nd/or as alloys. An oxidative leaching process is required for the effective extraction of base and precious metals. Typically, a two-stage process based on oxidative acid leaching of base metals followed by leaching of precious metals using cyanide, thiosulfate, thiourea or halide as lixiviant(s) are used for the hydrometallurgical treatment of WEEE. However, the authors pointed out that further research is required to develop new, cost effective and environmentally friendly processes and/or refine existing ones for leaching and, in particular, downstream processes. This is a review paper that surveyed and summarized the metal recovery techniques from e-waste prior to 2012.
Research Question/Problem/ Need	What are the current state-of-the-art technologies for metal recovery from e-waste?

Important Figures

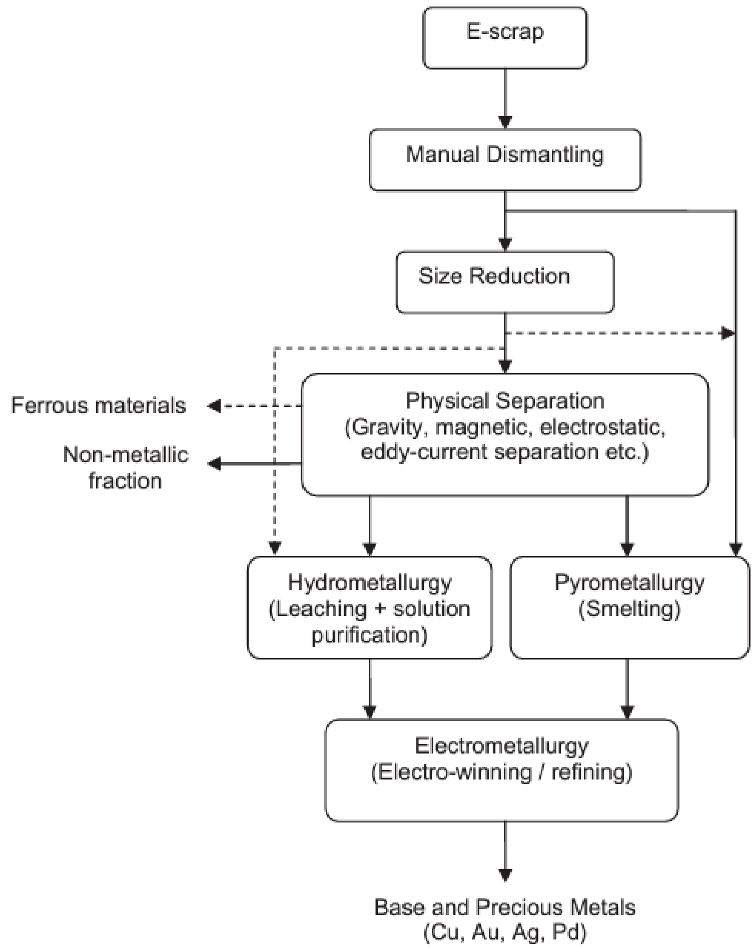


Fig. 1. A schematic flowsheet showing the potential process options for recovery of metals from e-scrap (Adapted from Yazıcı and Deveci, 2009).

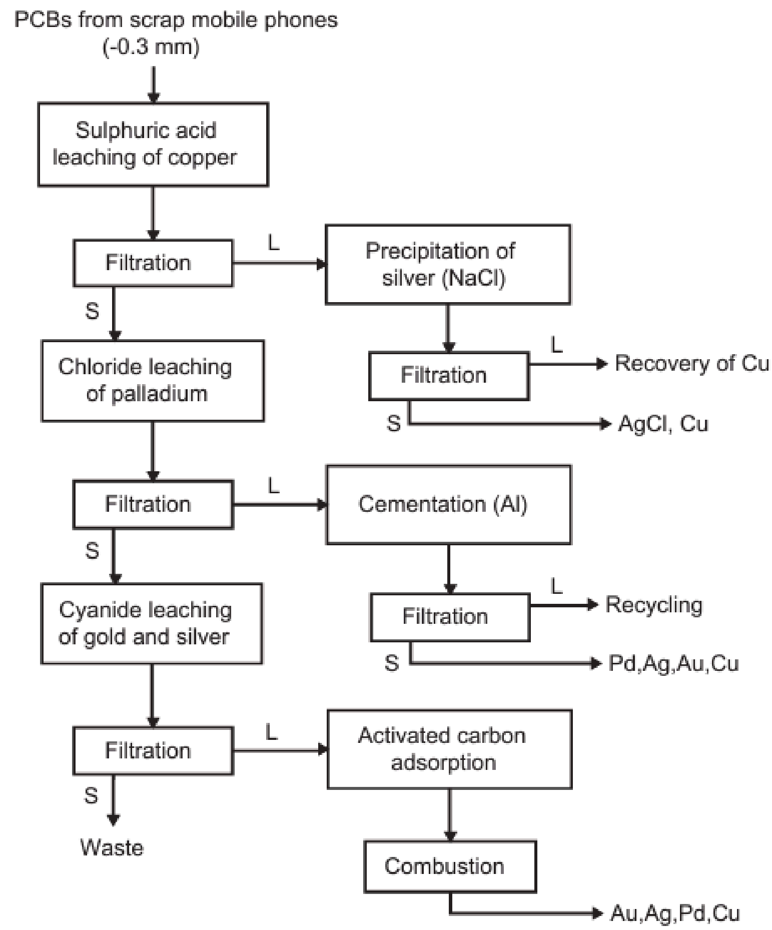


Fig. 5. A process flowsheet proposed for hydrometallurgical extraction of copper and precious metals (Au, Ag and Pd) from PCBs of scrap mobile phones (Quinet et al., 2005).

VOCAB: (w/definition)	Lixiviant: A liquid medium used in hydrometallurgy to selectively extract the desired metal from the ore or mineral. One of the most famous lixiviants is cyanide, which is used in extracting 90% of mined gold.
Cited references to follow up on	Ogunniyi, I.O., Vermaak,M.K.G., 2007. Improving printed circuit board physical processing– an overview. In: Proceedings of European Metallurgical Conference,Dusseldorf,Germany,pp.1645–1656.
Follow up Questions	How to improve the recovery rate of metals by physical separation?

Article notes:

1. Pre-treatment: For the recycling of valuable metals from e-scrap by hydrometallurgic methods, a mechanical pre-treatment step is needed. The different components and devices can be selectively dismantled and separated. Following the removal (and sorting) of components,metal

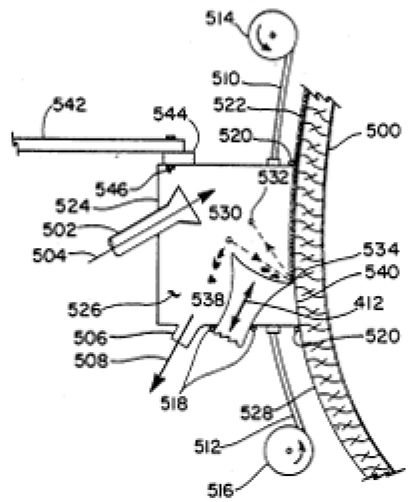
bearing components such as PCB is subjected to size reduction prior to metal recovery process. Shredders and hummer mills are extensively used to fragment, grind, rip or tear the waste.

2. Physical separation processes benefit from low capital and operating costs. One of the important detractions to physical separation processes is the valuable metal losses amounting to 10-35%. The reason for these losses includes insufficient liberation of metals due to the intimate association of valuable metals with plastics, generation of fines (75lm) during size reduction and inefficiency of separation processes for metal recovery from fine fractions.
3. Pyrometallurgical processes: they are energy intensive and high-cost processes with their particular requirement for high grade(rich in copper and precious metals) feed. Halogenated flame retardants used in PCBs, which lead to the formation of dioxins and furans, volatile metals and dust may present environmental problems and, hence, off-gas treatment is prerequisite.
4. Hydrometallurgical processes: Acid leaching in the presence of an oxidant is extensively used for the extraction of copper from printed circuit boards (HCl,H2SO4,HNO3/H2O2,HClO4, NaClO). Mecucci and Scott (2002) achieved high copper and lead extractions (>95%) by nitric acid (HNO3):

$$3Cu^0/Pb^0 + 8HNO_3 \rightarrow 3Cu/Pb(NO_3)_2 + 4H_2O + 2NO \qquad (7)$$

Article (PATENT) 22 Notes: Ultrasonic assisted protective coating removal.

Source Title	Ultrasonic assisted protective coating removal.
Source citation (APA Format)	Reinhart, T. J. (1989). *U.S. Patent No. 4,858,264*. Washington, DC: U.S. Patent and Trademark Office.
Original URL	https://patentimages.storage.googleapis.com/79/c9/2a/e4edc6d33506bc/US4858264.pdf
Source type	US patent
Keywords	Ultrasonic, coating removal, apparatus
#Tags	#coating removal, #untrasonication
Summary of key points + notes (include methodology)	A paint or other protective coating removal arrangement involving the use of ultrasonic frequency mechanical energy applied to the coating by a variety of tool and abrasive substrates in the company of surface preparation agents such as coolant, heating, softening, and/or abrasive agents. The invention is particularly applicable and disclosed in terms of protective coating removal from aircraft, such as is often necessary for replacement or in the reutilization of aircraft with different identification markings. The coating removal arrangement is environmentally and human operator safe in comparison with presently used coating removal arrangements such as abrasive blasting and chemical solvent removal. The invention contemplates both the use of an excited scraping tool and ener gized abrasive particles as a delivery means for the ultrasonic energy. The disclosed ultrasonic energy apparatus has been found to be significantly improved in coating removal ability with respect to previous vibrat ing tool apparatus.
Research Question/Problem/ Need	How can ultrasonic assist the coating removal?

Important Figures	 Illustation of the invention.
VOCAB: (w/definition)	OSHA: Occupational Safety and Health Administration Polymerization: a process of reacting monomer molecules together in a chemical reaction to form polymer chains or three-dimensional networks.
Cited references to follow up on	N/A
Follow up Questions	How can ultrasonication be combined with solvents to remove solder mask from PCBs?

Article notes:

The described invention comprises the bringing together on a coated surface of ultrasonic en ergy agitation of a tool member, in combination with possible solvent or other coating conditioning agents abrasive materials and. Such a combination is a possible alternative to the abrasive blasting and chemical re moval techniques which are currently employed on aircraft. The described invention may, of course, be used with other than aircraft equipment, and may be scaled upward and downward as to energy levels, tool sizes, and utilization times, as is appropriate to the coat ing material and area involved. The frequency of the ultrasonic energy used in the invention may be varied in the range df 20 kHz and upward, including presently available commercial equipment which operates in the 50 kHz range.

Article (PATENT) 23 Notes: Composition for stripping solder and tin from printed circuit boards

Source Title	Composition for stripping solder and tin from printed circuit boards
Source citation (APA Format)	Johnson, I. T., & Fakler, J. T. (2001). *U.S. Patent No. 6,258,294*. Washington, DC: U.S. Patent and Trademark Office.
Original URL	https://patentimages.storage.googleapis.com/9e/82/06/6209d5d4ff7918/US6258294.pdf
Source type	US patent
Keywords	Solder stripping, printed circuit board, additives
#Tags	#e-waste; #printed circuit board; #chemical stripping
Summary of key points + notes (include methodology)	A composition and method for Stripping tin and Solder and tin underlying tin-copper alloy from a printed circuit board is presented. The liquid includes an aqueous Solution of nitric acid in an amount Sufficient to dissolve Solder and tin, a Source of ferric ions in an amount Sufficient to dissolve the tin-copper alloy, and a Source of halide ions in an amount Sufficient to Significantly improve the resistance between printed circuits.
Research Question/Problem/ Need	What is a recipe to effectively remove solder and tin from PCBs?
Important Figures	No drawings included in this patent.
VOCAB: (w/definition)	halide ion: a halogen atom bearing a negative charge. The halide anions are fluoride (F^-), chloride (Cl^-), bromide (Br^-), iodide (I^-) and astatide (At^-).
Cited references to follow up on	N/A
Follow up Questions	The recipe covers wide ranges of concentrations of different components. Can these ranges be narrowed down to an optized recipe?

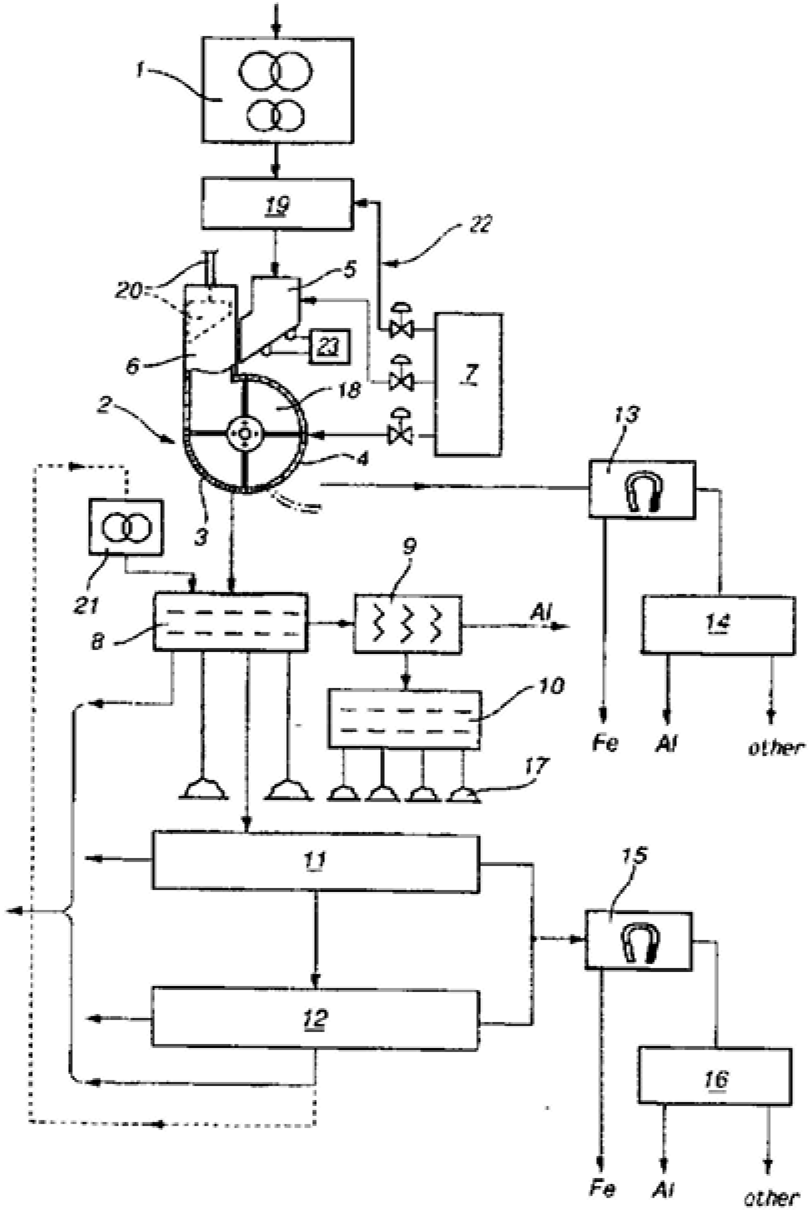
Article notes:

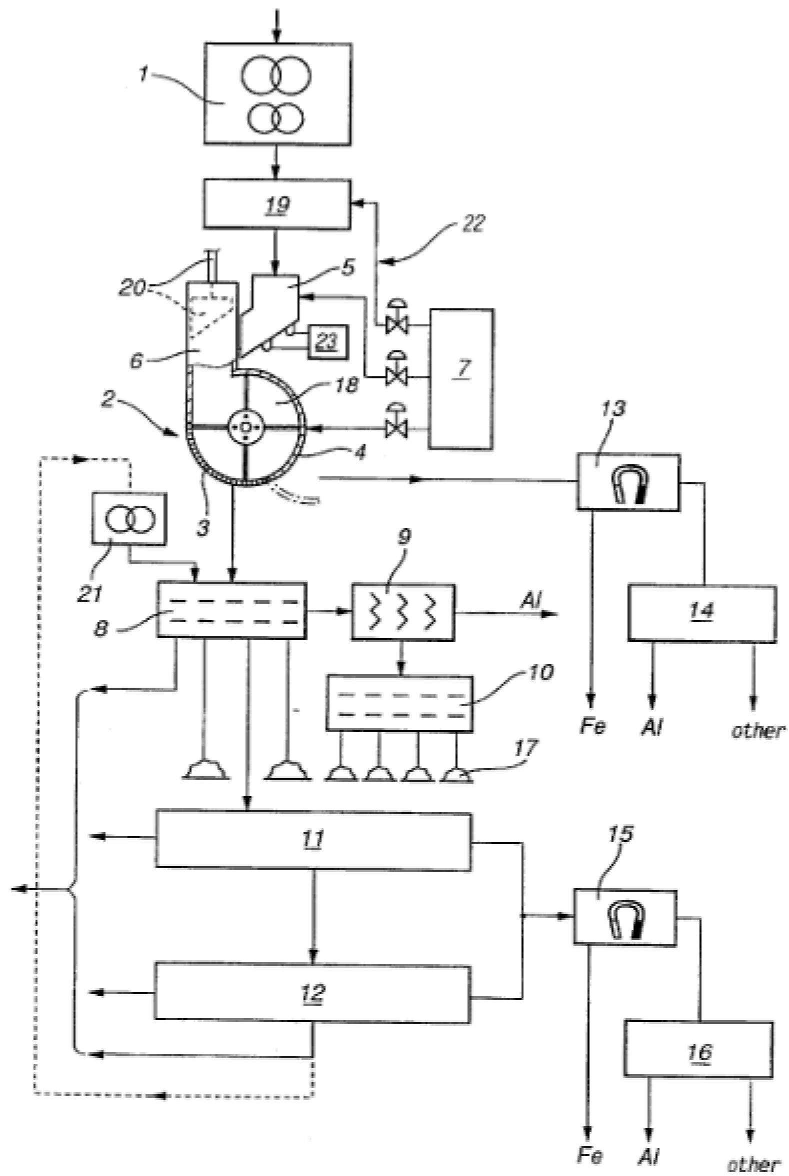
The recipe: the liquid composition of the present invention consists essentially of an aqueous Solution of 5 to 50 percent by volume of 69% by weight nitric acid acqueous solution, 1 to 50 percent by volume of 45% by weight ferric nitrate, 0.1% by weight to saturation of halide ions, and the balance water.

Effects of different components: It is known that nitric acid will dissolve tin or Solder. It is also known that ferric nitrate will dissolve copper and tin-copper alloys. Further, it is known that acidic peroxide fluoride tin and/or Solder StripperS provide improved insulation resistance over nitric acid based tin and/or Solder Strippers. It is not known that the act of combining nitric acid, ferric nitrate, and halide ions in a Single formulation will result in the creation of a nitric acid based Stripping Solution capable of providing enhanced insulation resistance to printed circuits.

Article (PATENT) 24 Notes: Method for recycling waste from printed circuit board assemblies from electrical and electronic devices

Source Title	Method for recycling waste from printed circuit board assemblies from electrical and electronic devices
Source citation (APA Format)	Jakob, R., & Melchiorre, M. (1997). *U.S. Patent No. 5,683,040*. Washington, DC: U.S. Patent and Trademark Office.
Original URL	https://patents.google.com/patent/US5683040A/en
Source type	US patent
Keywords	Printed circuit board, recycling, mechanically comminute, cryogenically embrittle
#Tags	#e-waste; #sustainability; #printed circuit board; #recycling
Summary of key points + notes (include methodology)	After removal of the batteries, mercury switches and PCB-containing capacitors, the printed circuit boards are mechanically precomminuted and the particles are cryogenically embrittled with liquid nitrogen and comminuted in a hammermill. In order to obtain a higher purity of the recovered metal concentrates and, conversely, a lower metal content of the concentrated residue materials as well as less emission during recycling and a simpler process, the cryogenically embrittled particles are selectively comminuted batchwise in a hammermill, wherein the ground material is divided into a fine fraction, emerging from a sieve at the bottom of the grinding chamber, and a coarser metallic fraction, which can be discharged batchwise and from which iron particles can subsequently be magnetically removed. The fine fraction is sorted into several narrow-band size classes with a particle size of about 1:1.6 per size class. Each individual size class of particles can be separately separated with corona-roller separators into residue material particles and metal particles. The latter can then be divided into different metal classes.
Research Question/Problem/ Need	

Important Figures	



schematic flow chart repre senting a preferred embodiment of the present invention.
a two-shaft or four-shaft cutter (1)
a hammermill (2)
the stationary sieve bottom (3)
a discharging shutter (4)
a feeding funnel (S)
a side filling shaft (6)
an insulated reservoir (7)
two different screening machines (8) and (10)
a zigzag separator (9)

	two separating steps (11) and (12) the magnetic separators (13, 15) two electric eddy current separators (14, 16) separate bunkers (17) grinding chamber (18) a cooling apparatus (19) a move able plunger (20) a granulator (21) controllable cooling liquid pipelines (22) a feeding scale (23)
VOCAB: (w/definition)	Comminute: to reduce to minute particles : pulverize. Eddy current seperator: a machine that uses a powerful magnetic field to separate non-ferrous metals from an input waste or ore stream.
Cited references to follow up on	U.S. patent Ser. No. 08/612.287
Follow up Questions	What are the recovery rates of valuable materials by this method? What's the structural optimization of a hammermill w to perform a selective comminution?

Article notes:
This invention presents a method for recycling printed circuit boards from electric or electronic devices comprising the steps of: a) removing, separating and disposing of components containing contaminants from the printed circuit boards, b) mechanically precomminuting the printed circuit boards to obtain precomminuted particles of a size of not more than 30 mm, c) cryogenically embrittling the precomminuted particles by cooling with a liquefied nitrogen to obtain cryogenically embrittled particles, d) comminuting the cryogenically embrittled particles in a hammermill to obtain fragments of a particle size of less than about 4 mm., e) separating the fragments into ferrous metals, nonferrous metals and residues by sieving, electrostatic separation, magnetic separation and eddy current separation.

A greater purity of the recovered metal concentrates can be achieved because of the improved material disintegration. Due to the high purity, higher profits can be achieved for recovered iron and non-ferrous metals. Moreover, due to the small proportion of residue materials, the emission of pol lutants (dioxins and furans) is minimized during the smelt ing of the metals.