Metal Recovery from E-Waste Using Flash Joule Heating and Super Critical Fluid Extraction

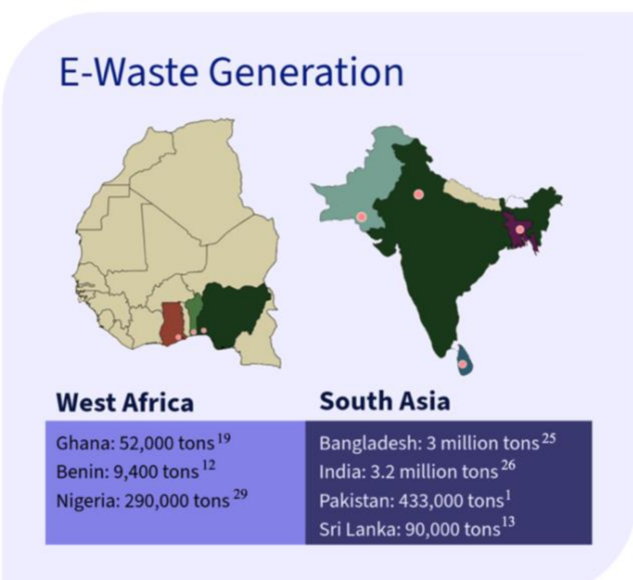
Emily Jones, State University of New York, United States of America; and Kshirajaa Ramesh, State University of New York, United States of America

Supporting Lecturer: Jamie Shinn (jeshinn@esf.edu).

Key Messages

- E-waste is a rampant problem for select South Asian and African countries, which are burdened not only with managing internally generated e-waste, but also legal and illegal imports.
- Current technologies for e-waste recycling and metal recovery from e-waste require significant energy and resources to operate, producing hazardous byproducts, with negative environmental and health impacts.
- Flash Joule Heating (FJH) and Supercritical Fluid Extraction (SCFE) are two emerging technologies innovating the process of metal recovery from e-waste. They are more resource efficient and produce fewer hazardous materials than current technologies.
- For successful implementation of FJH and SCFE, policies must promote improved data quality, support private investments and the cost recovery of new infrastructure, and ensure the informal sector is not adversely impacted.

When electronics come to the end of their useful life, they become electronic waste (e-waste). This e-waste is often dumped in large landfills even while still containing unrecovered and potentially valuable metals. In 2019, 53.6 million metric tons (Mt) of e-waste was disposed of globally and by 2030, e-waste generation is projected to reach 74.7 million Mt.[11] The UN estimates that the annual value of e-waste generated globally is over $62.5 billion.[28] Meanwhile, the pressure to mine for metals for new electronics (e.g., clean energy technologies) increases, even as we continue to landfill e-waste containing recoverable metals.[15] Valuable materials such as rare earth, precious and base metals contained in existing e-waste showcase opportunities for wealth generation with the development of new, resource efficient recovery processes.



Illustrating the Landscape

Rising income and the concomitant increase in demand for new electronics result in high rates of e-waste generation in both developed and developing economies.[12] Yet a significant portion of e-waste from developed countries is exported to developing countries, despite prohibitions under the Basel Convention. E-waste that is not for reuse or repair cannot be transported across borders unless all countries involved give their prior and informed consent.[4] However, the repair loophole allows developed countries to cheaply export their e-waste to developing countries. An estimated 209,000 tons of e-waste from the UK were shipped to developing countries 2019.[10] Yet, due to the inherent lack of transparency in illegal exports, this number is also unreliable.

Once the legal and illegal shipments of e-waste arrive to a port city in Africa or Asia, they are transported to an e-waste collection site, often located near major cities (e.g., Accra, Lagos, Dhaka, Karachi, New Delhi, Colombo).[23,24,25,27,28,32] These sites can span dozens of acres with tens of thousands of tons of e-waste and support a robust informal recycling sector. The labor-intensive, low-paid, and unregulated work of collecting, sorting, and dismantling e-waste is done by workers with little access to safety equipment. Components containing the most valuable materials are then exported to international markets for final recovery, leaving behind a large percentage of e-waste.[12,17] This leaves these countries with much of the environmental and public health risk with little economic reward.

Recovery of Valuable Materials

TrTraditional techniques for e-waste recycling include pyrometallurgical (uses heat to separate extract materials) and hydrometallurgical (uses strong solvents to recover materials) processes. Both these technologies

are resource intensive and can generate environmental pollutants as a byproduct of their operations.[2,13,33] Two emerging technologies are currently in development that improve upon traditional techniques: Flash Joule Heating (FJH) and Supercritical Fluid Extraction (SCFE).

Flash Joule Heating (FJH) uses a high voltage capacitor bank to raise the temperature quickly and efficiently to vaporize valuable e-waste materials. These materials are then condensed back into their original forms for reuse in new electronics.[9]

Supercritical Fluid Extraction (SCFE) is a process by which a solvent is heated and pressurized beyond its critical point, making it supercritical, and giving it the capability to act as a leaching agent in the extraction and recovery of materials from e-waste.[3]

Table. Technical Advantages and Limitations of FJH and SCFE

	Flash Joule Heating	Supercritical Fluid Extraction
Advantages	Quicker and more resource efficient material recovery process[a]	Quicker and more resource efficient material recovery process[a] [22,30]
	More energy efficient, lower energy cost[a] [9]	More energy efficient, lower energy cost[2,22,30]
	Simultaneous extraction and concentration of multiple valuable materials[a] [8]	Simultaneous extraction and concentration of multiple valuable materials[a] [23]
	Enables extraction of materials previously too costly to extract because of low concentrations[a] [6]	Enables extraction of materials previously too costly to extract because of low concentrations[a] [33]
	Conversion of plastic waste into graphene (a significant input for electronics)[9]	Recovery of materials from plastic components of e-waste[22]
	Extracted metals have fewer impurities[a] [6]	No toxic waste byproducts produced[3,22,30]
Limitations	Validated at lab scale only for e-waste material recovery;[7] Univeral Matter will open a demonstration plant at the end of 2023[29]	Validated in at lab scale only for e-waste material recovery, commercialized successfully for other industrial applications[b] [3,33]
	Requires same manual collection and sorting of e-waste in pre-process steps[a]	Requires same manual collection and sorting of e-waste in pre-process steps[a] [21]
	Rice University, Texas owns intellectual property rights for FJH material recovery process	

[a] Compared to hydrometallurgical and pyrometallurgical processes.

[b] Potentially facilitating the transition to industrial scale for easte recovery processes.

Benefits of Implementation of FJH and SCFE

Generating wealth from waste: SCFE can be used to recover and enrich base, precious, and rare metals (see Annex 1) from e-waste at recovery rates of between 93% and 99%.[3,16,33] FJH has a recovery rate of 80-100% for precious metals such as gold and silver.[8] Formalizing these e-waste technologies can then support the creation of new business and safe employment opportunities, particularly in developing economies.[12] One study estimated first year revenue of an SCFE plant recovering material from magnets would be between 17 and 65 million USD.[3]

Reducing demand for traditional mining: The percentage of extractable critical rare earth elements found in e-waste is 2 to 3 times greater than those found in the highest concentrated ores.[9] The harmful effects of mining operations are not evenly distributed across populations as mines are typically located in rural sites in developing countries.[5] Efficient and profitable material recovery from e-waste will reduce the demand for minerals from traditional mines, thereby reducing their unevenly distributed environmental and human health risks.

Detoxification of e-waste: Along with metal, glass, and ceramic components, e-waste contains organic materials (i.e. plastic polymers, flame retardants, and PCBs) that become hazardous to environmental and human health if discarded in a landfill or incinerated. SCFE can detoxify these while FJH can reduce the heavy metals present with the same metal recovery process.[8,16,17]

Challenges to Implementation

Initial investment costs: Initial investments will be required to develop a formal e-waste processing on processing site using either of the proposed technologies. One analysis focused on Canada found that a 4000 L capacity SCFE processing site would initially cost 5.3 million USD, but would begin making profit within half a year.[3]

Uncertainty of Scaling Up: More research is needed on the industrial scalability of SCFE and FJH, including feasibility and pilot studies in local contexts. While some cost-benefit analyses exist,[3] they are not context-specific to developing countries and are based on well-researched, but theoretical scenarios. A cost benefit analysis of SCFE specific to India is expected in 2024.[21]

Conclusion

Recovering valuable metals from e-waste is imperative if we are going to transition to green energy in a sustainable and just manner. In order to be equitable, e-waste recycling technologies have to achieve material recovery without further endangering environmental or public health, especially in countries where e-waste is an acute problem. These technologies can be essential components of meeting the United Nation Sustainable Development Goals of promoting healthy lives and well-being (SDG 3), decent work and economic growth (SDG 8), responsible consumption and production (SDG 12) and especially that of climate action (SDG 13).

A West African Case Study: Ghana

While Ghana generates approximately 50,000 tons of e-waste annually, the amount of e-waste imported from North America and Europe is about three times that number.[32] Most of this e-waste is gathered at the Agbogbloshie site in Accra. That waste is manually dismantled by informal recyclers to collect valuable metals or burned to separate waste from desirable materials; this dismantling creates adverse environmental and public health outcomes.

To regulate e-waste management, Ghana passed the Hazardous and Electronic Waste Control and Management Act in 2016 and established Technical Guidelines on Environmentally Sound E-waste Management in 2018.[14] While a lack of awareness by stakeholders and informal recyclers has created gaps in implementation of these initiatives,[19] they indicate a willingness to shift e-waste recycling processes if there are perceived economic benefits or understanding of adverse environmental impacts.

The informal recycling sector in Ghana is critical to the country's economy. A 2010 study found that this sector generates $105-$268 million annually to the Ghanian economy and employs at least 200,000 people.[20] Building FJH or SCFE recovery sites near high-volume sites of e-waste, such as Agbogbloshie, will not necessitate the creation of new collection paths. Additionally, existing labor sources can be formalized thereby sustaining livelihoods and improving safety.[31]

Policy Recommendations: preparing for e-waste recovery infrastructure

Funding Research: National governments should allocate funding to research universities investigating the development and implementation of e-waste recovery technologies to advance the efficiency and scalability of the technologies within their country's context.

Facilitating Exchange of Information: Multilateral organizations, such as the United Nations, should facilitate the exchange of knowledge through the development of educational exchange programs for researchers and engineers. Programs should focus on sharing best practices for e-waste management and latest developments in e-waste recovery technologies. The program should also connect the researchers and engineers with policy makers to ensure that policies will support the development and implementation of e-waste recovery technologies.

Improving the Quality of Data to Understand Scale and Material Needs: E-waste exporting countries should enforce stricter adherence to the Basel Convention Treaty to enable the accurate tracking of the quantity and quality of e-waste shipments. To do so, national governments should fund adequate technical, financial and labor capacity to ensure compliance and minimize illegal shipments. Destination countries should build institutional capacity to track imports and locally generated e-waste to understand the scale and logistical requirements to right size e-waste recovery sites.

Facilitating Investment in Infrastructure: Although they require high initial investments, e-waste recovery facilities can begin generating profits within their first year of operation. To offset the high upfront cost required for implementation, tax incentives and concessions should be offered by national governments to private investors to encourage initial investment.

Prioritizing Permitting to Facilitate Growth of E-Waste Recovery: National policies must prioritize efficient permitting for formalized e-waste management operations to reduce barriers for implementation and improve investor support for the construction of new recovery sites. However, efficiency of permitting requirements should not compromise environmental and human health protections.

Integrating the Informal Sector: National and local labor and trade policies should build-in protections for the informal sector to ensure livelihoods are not harmed by the transition to formalized e-waste recovery operations. Policies should ensure informal recyclers and material resellers are formally incorporated into resale operations of recovered materials.

Protecting workers: Policymakers at national and local levels should also implement regulations to protect workers from health hazards associated with e-waste management, including but not limited to personal protective equipment (PPE) and proper ventilation of sorting facilities. Public education and free or low-cost provision of PPE is critical to the success of such policies.

Distributing Wealth Generated from Waste: National trade policies should mandate companies with new e-waste recovery operations to enter benefit sharing agreements or similar contracts with local communities. Benefit sharing agreements aim to reduce conflict between industry and community, thereby ensuring continued stability for all parties. Agreements may include stipulations requiring monetary payments to the community, skill development for workers, and the development of community infrastructure. However, national policies should ensure local governments are administratively and monetarily equipped to implement and enforce such agreements.

References

1. Armughan, M., & Zafar, S. (2022). Analyzing the effects of e-waste on human health and environment: A study of Pakistan. Pakistan Institute of Development Economics . https://pide.org.pk/research/analyzing-the-effects-of-e-waste-on-human-health-and-environment-a-study-of-pakistan/
2. Azimi, G. (2022). Recycling of lithium, cobalt, nickel, and manganese from end-of-life lithium-ion battery of an electric vehicle using supercritical carbon dioxide. Resources, Conservation and Recycling, 187, 106628. https://doi.org/10.1016/j.resconrec.2022.106628
3. Azimi, G., Sauber, M. E., & Zhang, J. (2023). Technoeconomic analysis of supercritical fluid extraction process for recycling rare earth elements from neodymium iron boron magnets and fluorescent lamp phosphors. Journal of Cleaner Production, 422, 138526. https://doi.org/10.1016/j.jclepro.2023.138526
4. Basel Convention: Where are WEee in Africa? (2012). Basel Convention E-Waste Africa Programme.http://www.basel.int/Portals/4/Basel%20Convention/docs/pub/WhereAreWeeInAfrica_ExecSummary_en.pdf
5. Bell, R.G. (2017). Protecting the environment during and after resource extraction, WIDER Working Paper, No. 2017/164, ISBN 978-92-9256-390-5, The United Nations University World Institute for Development Economics Research (UNU-WIDER), Helsinki, https://doi.org/10.35188/UNU-WIDER/2017/390-5
6. Chen, W., Chen, J., Bets, K. V., Salvatierra, R. V., Wyss, K. M., Gao, G., Choi, C. H., Deng, B., Wang, X., Li, J. T., Kittrell, C., La, N., Eddy, L., Scotland, P., Cheng, Y., Xu, S., Li, B., Tomson, M. B., Han, Y., Tour, J. M. (2023). Battery metal recycling by flash Joule heating. Science Advances, 9(39), eadh5131. https://doi.org/10.1126/sciadv.adh5131
7. Chen W, Cheng Y, Chen J, Bets K, Salvatierra R, Ge C. (2023). Nondestructive flash cathode recycling. ChemRxiv. Cambridge: Cambridge Open Engage.
8. Deng, B., Luong, D. X., Wang, Z., Kittrell, C., McHugh, E. A., & Tour, J. M. (2021). Urban mining by flash Joule heating. Nature Communications, 12(1), 5794. https://doi.org/10.1038/s41467-021-26038-9
9. Deng, B., Wang, X., Luong, D. X., Carter, R. A., Wang, Z., Tomson, M. B., & Tour, J. M. (2022). Rare earth elements from waste. Science Advances, 8(6), eabm3132. https://doi.org/10.1126/sciadv.abm3132
10. Environmental Audit Committee. (2020). Electronic Waste and the Circular Economy. UK Parliament. https://publications.parliament.uk/pa/cm5801/cmselect/cmenvaud/220/22002.htm
11. Forti V., Baldé C.P., Kuehr R., Bel G. The Global E-waste Monitor 2020: Quantities, flows and the circular economy

potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam.

12. Gunarathne, N., De Alwis, A., & Alahakoon, Y. (2020). Challenges facing sustainable urban mining in the e-waste recycling industry in Sri Lanka. Journal of Cleaner Production, 251, 119641. https://doi.org/10.1016/j.jclepro.2019.119641

13. Hocking, M. (2017). "Hydrometallurgy - an Overview | ScienceDirect Topics." Minerals Engineering. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/hydrometallurgy.

14. Kansuk, Stephen (2023). Shaping sustainable paths for e-waste management in Ghana. UNDP. Retrieved November 29, 2023, from https://www.undp.org/ghana/blog/shaping-sustainable-paths-e-waste-management-ghana

15. Klinger, J. M. (2017). Rare Earth Frontiers: From Terrestrial Subsoils to Lunar Landscapes. Cornell University Press. http://www.jstor.org/stable/10.7591/j.ctt1w0dd6d

16. Li, K., & Xu, Z. (2019). A review of current progress of supercritical fluid technologies for e-waste treatment. Journal of Cleaner Production, 227, 794–809. https://doi.org/10.1016/j.jclepro.2019.04.104

17. Liu, K., Zhang, Z., & Zhang, F.-S. (2016). Direct extraction of palladium and silver from waste printed circuit boards powder by supercritical fluids oxidation-extraction process. Journal of Hazardous Materials, 318, 216–223. https://doi.org/10.1016/j.jhazmat.2016.07.005

18. Nigeria turns the tide on electronic waste. (2019, June 19). UN Environment Programme. Retrieved November 23, 2023, from https://www.unep.org/news-and-stories/press-release/nigeria-turns-tide-electronic-waste

19. Owusu-Twum, M. Y., Kumi-Amoah, G., Heve, W. K., Lente, I., Owusu, S. A., Larbi, L., & Amfo-Otu, R. (2022). Electronic waste control and management in Ghana: A critical assessment of the law, perceptions and practices. Waste Management & Research: The Journal for a Sustainable Circular Economy, 40(12), 1794–1802. https://doi.org/10.1177/0734242X221103939

20. Prakash, S., Manhart, A., Amoyaw-Osei, Y., & Agyekum, O. O. (2010). Socio-economic assessment and feasibility study on sustainable e-waste management in Ghana. Öko-Institut eV in cooperation with Ghana Environmental Protection Agency (EPA) & Green Advocacy Ghana, Ministry of Housing, Spatial Planning and the Environment, VROM-Inspectorate. http://ressourcenfieber.org/publications/reports/2010-105-en.pdf

21. Preetam A. (2023, November 20). Personal communication [Personal interview].

22. Preetam, A., Jadhao, P. R., Naik, S. N., Pant, K. K., & Kumar, V. (2023). Supercritical fluid technology - an eco-friendly approach for resource recovery from e-waste and plastic waste: A review. Separation and Purification Technology, 304, 122314. https://doi.org/10.1016/j.seppur.2022.122314

23. Priyashantha, A. K. H., Pratheesh, N., & Pretheeba, P. (2022). E-waste scenario in South-Asia: An emerging risk to environment and public health. Environmental Analysis, Health and Toxicology, 37(3), e2022022. https://doi.org/10.5620/eaht.2022022

24. Rodrigo, Malaka. (2020, December 9). Sri Lanka to the U.K.: Here's your waste back. And there's more to come. Mongabay Environmental News. https://news.mongabay.com/2020/12/sri-lanka-to-the-u-k-heres-your-waste-back-and-theres-more-to-come/

25. Roy, H., Islam, Md. S., Haque, S., & Riyad, M. H. (2022). Electronic waste management scenario in Bangladesh: Policies, recommendations, and case study at Dhaka and Chittagong for a sustainable solution. Sustainable Technology and Entrepreneurship, 1(3), 100025. https://doi.org/10.1016/j.stae.2022.100025

26. Sengupta, D., Ilankoon, I. M. S. K., Dean Kang, K., & Nan Chong, M. (2022). Circular economy and household e-waste management in India: Integration of formal and informal sectors. Minerals Engineering, 184, 107661. https://doi.org/10.1016/j.mineng.2022.107661

27. Toxics Link. (2019). Informal E-Waste Recycling in Delhi. Toxics Link. https://toxicslink.org/wp-content/uploads/2022/08/Informal%20E-waste.pdf

28. UN report: Time to seize opportunity, tackle challenge of e-waste. (2019, January 24). UN Environment Programme. Retrieved November 11, 2023, from https://www.unep.org/news-and-stories/press-release/un-report-time-seize-opportunity-tackle-challenge-e-waste

29. Universal Matter. (2023, July 18). About us - universal matter. Retrieved November 20, 2023, from https://www.universalmatter.com/about-us/

30. Xavier, L. H., Ottoni, M., & Abreu, L. P. P. (2023). A comprehensive review of urban mining and the value recovery from e-waste materials. Resources, Conservation and Recycling, 190, 106840. https://doi.org/10.1016/j.resconrec.2022.106840

31. Xavier, L. H., Ottoni, M., & Lepawsky, J. (2021). Circular economy and e-waste management in the Americas: Brazilian and Canadian frameworks. Journal of Cleaner Production, 297, 126570. https://doi.org/10.1016/j.jclepro.2021.126570

32. Yeung, Peter (2019). The Toxic Effects of Electronic Waste in Accra, Ghana. Bloomberg.Com.

https://www.bloomberg.com/news/articles/2019-05-29/the-rich-world-s-electronic-waste-dumped-in-ghana

33. Zhang, J., & Azimi, G. (2022). Recycling of lithium, cobalt, nickel, and manganese from end-of-life lithium-ion battery of an electric vehicle using supercritical carbon dioxide. Resources, Conservation and Recycling, 187, 106628. https://doi.org/10.1016/j.resconrec.2022.106628

Annex

Table. Category Breakdown of Major Metal Components in E-Waste (non-exhaustive)

Metal Type	Major e-waste components
Base Metals[a]	Li (lithium), Co (cobalt), Ni (nickel), Mn (manganese), Cu (copper), Fe (Iron), Al (Aluminum)
Precious Metals[b]	Au (silver), Ag (gold), and Pd (palladium)
Rare Earth Metals[c]	Nd (neodymium), Y (yttrium), Tb (terbium), Pr (Praseodymium), Eu (europium)

Sources:[2,16,17]

[a] Base metal – A common metal of relatively low value.

[b] Precious metal – A relatively uncommon metal of high economic value.

[c] Rare Earth Metal – Rare earth metals are a set of seventeen metallic elements. These include the fifteen lanthanides on the periodic table.