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Sustainable Circuits: Evaluating the Economic and Environmental Implications of Recycling Methods for Technology Products

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Abstract

The growing severity of the climate crisis has led many technology companies to pursue sustainability, which has often been done through the recycling of materials. However, the material that is recycled often varies as companies choose to recycle either plastic or metal. With such variation, firms are faced with a pressing issue on which recycling method to pursue, so that they can ensure a shift towards sustainability while retaining profitability. Thus, the aim of this paper was to compare the environmental and economic consequences of plastic and metal recycling for technology products to determine the situations in which each would be most logical. The methods for this paper entailed qualitative research and environmental accounting, which have determined that metal recycling, in terms of fixed and marginal costs, is cheaper than plastic recycling and is overall more sustainable. However, plastic recycling may lead to greater consumer satisfaction. Recycling metal is most logical for companies who value environmental impact and smaller companies who cannot afford plastic recycling. Plastic recycling is most logical for companies who want to promote their brand and gain more customer loyalty. As a result of these factors, plastic recycling remains popular despite metal recycling's many benefits. Further adoption of metal recycling can be encouraged through more public discourse, investment in newer recycling technologies, and stronger advertisements for metal recycling. Metal recycling can also be encouraged through carbon legislation, such as carbon taxes or tax deductions on sustainable practices. Overall, this research demonstrates the need for further action to promote metal recycling.

Keywords: Sustainability, Plastic recycling, Metal recycling, Environmental accounting, Environmental consequences, Fixed costs, Marginal costs

1. Introduction

With the rise of climate change, eco design has become a prominent method for gearing national economies towards sustainability. Eco design is a process that keeps products in use for as long as possible through constant refurbishing, remanufacturing, and reuse. The chief goal of eco design is to minimize resource requirements and environmental impacts (Mendoza et al., 2017).

Eco design is based on the idea of sustainability. Sustainability is a product or process's ability to operate during its life with little environmental consequences (Horani, 2023). Sustainability encompasses three areas, known as the three factors of sustainability: the environment, the economy, and social considerations. Eco design focuses on applying these factors to product design to generate the least possible environmental consequences throughout the product's life cycle while maintaining product quality. Eco design specifically considers a product's life cycle, marketing, usage, recyclability, and reusability to design a product that meets the factors of sustainability.

Employing eco design within technology products is important due to the overwhelming presence of e-waste, which is waste from end-of-life electronic devices (Perkins et al., 2014). Figure 1 shows that only 20% of e-waste is recycled in the United States, with the remaining 80% going to landfills or being unreported. E-waste contains harmful substances such as acids, toxic fumes, and mercury, all of which pose serious health risks to the circulatory system, nervous system, reproductive systems, lungs, growth rates, and cognitive development. By implementing eco design within technology products in a cost-effective yet efficient manner, the amount of e-waste in landfills can be reduced, benefiting the environment and global public health. For technology companies, one of the largest ways in which eco design is accomplished is through recycling.

Several technology companies have attempted to employ eco design through recycling various materials. Fairphone, a Dutch phone company, implements eco design by using recycled metals and polycarbonate parts from older devices ("How recyclable is the Fairphone 2?" 2017, Hobson et al., 2018). More specifically, Fairphone uses recycled copper, tin, and plastic within their phones ("Fair Materials", n.d.). However, Fairphone phones remain circular at the end of their life cycles as well; approximately 60% of phones are recycled and processed to harvest their valuable materials, which are later used to manufacture more phones ("Recycle your old phone(s)", n.d.). To harvest such materials, Fairphone uses several recycling methods, the main ones being smelting, dismantling, and shredding ("Fair Materials 101 – A guide to the materials in your phone", 2021). Smelting involves melting the entire phone and separating its parts to harvest each of its constituent elements in base form. Dismantling involves separating the parts of the phone and placing them through very specific recovery processes. For example, a lithium battery would go to a specific furnace to be smelted, allowing the lithium and cobalt within to be harvested. Lastly, shredding involves removing the battery and feeding the rest of the phone through a cutting mill to separate its parts. Each part is then placed in its appropriate processing line.

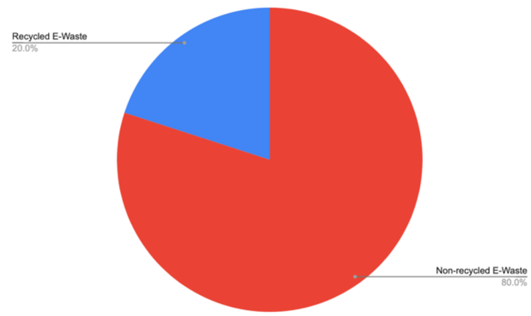

Figure 1. Most e-waste that is produced is not recycled. (Perkins et al., 2014)

However, Fairphone is not the only technology company to implement eco design within its products. In fact, several laptop companies have attempted to do this as well. Rather than manufacturing virgin plastic, these companies use plastic waste or plastic from previous computers to outfit new laptops. Figure 2 illustrates the companies who have done this and the composition of recycled plastic within their products. Acer has attempted to use the Acer Aspire Vero, made of 40% post-consumer recycled plastic, to include eco design within its products ("Aspire Vero", n.d.). Logitech has done something similar with the Logitech Brio 300 Webcam, which is made of 48% post-consumer recycled plastic ("Brio 300", n.d.). Lenovo has also attempted to implement eco design by creating environmentally friendly ThinkPads, which contain post-consumer recycled plastic ("Environmentally Conscious Product Design", n.d.). Lastly, other technology companies have tried to create products with eco design in the past, such as the PowerMate Eco, which was a computer made of non-toxic materials, few chemicals, and 100% recyclable NuCycle Plastic ("NEC Brings First Ecological 'All-in-One' Desktop Computer to U.S. Market", 2002). All of these technology products aim to fulfill eco design's chief goal of reducing resource requirements and environmental impacts.

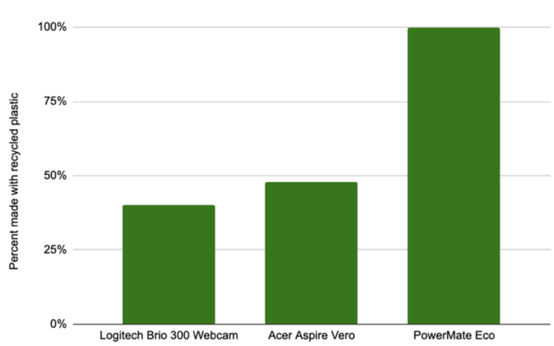

Figure 2. Each laptop company focuses on recycling plastic, but in different amounts.

However, while Fairphone and the laptop companies attempt to implement eco design in their products, they do so in different ways. Fairphone implements eco design by recycling metals, while the laptop companies do the same by recycling plastic. Although metal recycling has been shown to be a very sustainable option ("National Overview: Facts and Figures on Materials, Wastes and Recycling", n.d.), the overwhelming popularity of plastic recycling and the profits it brings cannot be overlooked (Ruokamo et al., 2022). Furthermore, 60% of companies now have sustainability targets, demonstrating its importance in the corporate sphere (Unruh et al., 2016). Amidst this

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immense shift towards sustainability, firms must consider which recycling method can better meet their goals while still allowing them to remain profitable. Thus, the goal of this paper is to analyze the economic and environmental consequences for metal and plastic recycling within technology products to establish when it is more logical for technology companies to recycle plastics or metals.

2. Methods

The objective behind this research strategy was to generate a summary table that compares the environmental and economic costs of different recycling strategies. The main methods for producing the table below consist of qualitative research and environmental accounting. Obtaining the statistics included within Table 1 entailed reviewing and evaluating research papers, journals, and government websites. The main sites that were used to search for these resources include ScienceDirect, Research Gate, the Environmental Protection Agency, and Google Scholars. The search process originally began with keywords such as 'circular economy' and 'sustainability'. However, as the search grew more specific, recycling-specific keywords began to be used more often, such as 'metal recycling costs' and 'plastic recycling environmental impacts'. As more general information on both recycling methods was obtained, such as costs and carbon footprint, more specific keywords were used to obtain more specific statistics, such as 'consumer preferences for recycled plastic'. When necessary, the estimates of cost and environmental impact were converted into the desired units, which are tons and KJ/ton. Some cost figures were also averaged if the sources that were used presented a wide range of data.

3. Results

This section discusses the numbers that were found using the above search process, which relate to the environmental impact and economic viability of both metal and plastic recycling.

3.1 Plastic Recycling

Plastic recycling is one of the chief recycling methods to achieve eco-design. Plastic recycling has three techniques: mechanical, pyrolysis, and gasification. Mechanical recycling involves standard recycling measures, such as grinding and granulating ("Science & Tech Spotlight: Advanced Plastic Recycling", 2021). Pyrolysis and gasification involve heating plastic to convert it into energy sources, like liquid oil and syngas ("Science & Tech Spotlight: Advanced Plastic Recycling", 2021). These techniques are known as chemical recycling methods.

Costs between these methods vary. Generally, the cost of mechanically recycling one ton of plastic ranges from \$2,000 to \$857,000, depending on the method being used (Thomas, 2022). These figures were obtained through a thorough survey of other review papers conducted by Nikiema and Asiedu (2022), who converted from other currencies, including euros and rupees, into USD (Nikiema & Asiedu, 2022). Major technologies used in plastic recycling include granulators, washers, dryers, pyrolysis reactors and gasifiers, again depending on the chosen method. These processes are much more expensive than producing one ton of virgin plastic, which is \$1,200 (Crawford & Martin, 2020). This figure was obtained through a thorough review of *Plastics Engineering* by Crawford and Martin, who computed the overall cost of plastic by accounting for raw material costs and fabrication costs. Fabrication costs include the costs for labor and power. Fixed costs for the recycling technologies used vary amongst the three methods as well, ranging from \$2,185,028 - \$61,705,766 depending on the chosen method (Lase et al., 2023, Ghodrat et al., 2019, Biomass Combined Heat and Power Catalog of Technologies", 2015). These figures were derived from a thorough review of plastic recycling literature. The examined sources used data from equipment suppliers and published estimates to calculate costs related to chief areas like transportation, equipment, and production, which they then aggregated to obtain the figures above.

For each ton of plastic recycled, recycling processes save 1.99 to 2.13 tons of carbon dioxide compared to producing virgin plastic, depending on whether mechanical or chemical recycling was used (Jeswani et al., 2021). However, mechanical recycling often creates lower quality plastics through a process known as downcycling, restricting its use to lower quality products ("Science & Tech Spotlight: Advanced Plastic Recycling", 2021). The

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products of chemical recycling, such as syngas, biochar, and bio-oil, can be used as fuel for commercial purposes, providing an environmentally friendly alternative to fossil fuels (Yue et al., 2016). Lastly, plastic recycling saves 38,373,915 kilojoules per ton of plastic recycled ("Life cycle impacts for postconsumer recycled resins: PET, HDPE, and PP", 2018).

3.2 Metal Recycling

Metal recycling is an alternative method that technology companies can use to further implement eco design. Unlike plastic recycling, there is only one method for metal recycling, which involves shredding, melting, purifying, and sorting metals into their pure, base forms ("How recyclable is the Fairphone 2?", 2017).

The major technologies involved in this recycling process include shredders, furnaces, and electrolysis, which are much less complex than the machinery required for chemical plastic recycling. The average cost of recycling one ton of metal is $200 ("Cost to Recycle Metal", 2017). This figure was derived from Desert Metal Recycling, who computed an average of the expenses required for processing a ton of metal. These include transportation costs, sorting costs, and smelting costs. Furthermore, recycling metal is much cheaper compared to the cost of mining one ton of virgin metal, which is approximately $4,000 (Zeng et al., 2022). This figure is an average of different virgin mining costs for common metals, namely aluminum and copper. Fixed costs for metal recycling machinery range from $50,000 to $500,000 (Sheykin, 2023). This figure was derived from FinModelsLab, who computed an average of the different costs for specialized recycling equipment. These include balers, shredders, a weighing system, and granulators. The range in cost depends on factors such as the size and location of the recycling facility, the specific equipment needed, and local regulations (Sheykin, 2023).

For each ton of metal recycled, the metal recycling process saves 3.34 tons of carbon dioxide compared to mining virgin metal ("National Overview: Facts and Figures on Materials, Wastes and Recycling", n.d.). Metal recycling saves about 58,200,437 kilojoules per ton of metal recycled (Nizami et al., 2017). Lastly, metals do not experience downcycling when recycled, but instead retain their quality throughout the recycling process. As a result, they can be used for higher quality products alongside virgin metals, giving metal recycling more flexibility for its uses.

Table 1. Summary statistics of metal and plastic recycling

	Metal	Plastic
Carbon emissions saved (per ton recycled)	3.344 tons CO_2 equivalent	2.13 tons CO_2 equivalent (chemical recycling) 1.99 tons CO_2 equivalent (mechanical recycling)
Energy saved (KJ/ton)	58,200,437	38,373,915
Marginal cost of producing a ton (new)	$4,000 (virgin mining)	$1,200
Marginal cost of recycling a ton	$200 (average)	$2,000-$10,000 (mechanical) $857,000 (pyrolysis) $385,000 (gasification)
Fixed technological cost	$50,000 - $500,000	$2,642,012 - $3,380,299 (mechanical) $3,630,357 (pyrolysis) $4,476,700 - $61,705,766 (gasification)
Trading prices (ton)	$2,231 (Al); $2,099 (Pb) $8,065 (Cu); $17,783 (Ni) $2,466 (Zn); $23,786 (Sn)	$2,168

4. Discussion

To analyze the economic and environmental implications of plastic and metal recycling, this section focuses on the business cases for each choice. The plausible conditions of each choice are analyzed, and these choices are evaluated within the practical realities of the recycling industry. Table 2 illustrates the two axes of comparison that were used: the material and its condition. As a result, there were six choices that were analyzed: recycled metal vs.

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recycled plastic, new metal vs. new plastic, new metal vs. recycled plastic, new plastic vs. recycled metal, new metal vs. recycled metal, and new plastic vs. recycled plastic.

4.1 Business Cases

Table 2. Axes of comparison

	Recycled	Newly Produced
Metal	Recycled metal	Newly produced metal
Plastic	Recycled plastic	Newly produced plastic

The first choice compares recycled metal with recycled plastic. There are numerous conditions where metal recycling is more feasible than plastic recycling. For example, smaller companies who may be unable to afford the high costs of plastic recycling may be more drawn to metal recycling due to its lower marginal and fixed costs. Additionally, companies may choose to recycle metal if they want to maintain product quality. Unlike mechanical recycling methods, which diminish the quality of plastics, metals retain their quality throughout the recycling process (Thomas, 2022, "Science & Tech Spotlight: Advanced Plastic Recycling", 2021). Lastly, due to metal recycling's more positive environmental impacts, a company may choose to recycle metal if it greatly values its sustainability goals and environmental footprint. However, plastic recycling may be more feasible if a company wants greater appeal towards consumers. A study conducted by Ruokamo et al. shows that the use of recycled plastics positively affected the purchase decisions of 86% of consumers, and 93% of consumers were satisfied with products that include recycled plastics (Ruokamo et al., 2022). This is largely due to the perceived reduction in carbon that surrounds plastic recycling (Ruokamo et al., 2022). Ruokamo et al.'s results imply that the use of recycled plastics positively impacts consumer sentiment, so companies who want to improve their branding and appeal to consumers could use plastic recycling to do so.

The second choice concerns the use of newly produced metal compared to newly produced plastic. If a company is interested in saving more money in the short term and maintaining product quality through metal recycling processes, then they may use newly produced metal to avoid fixed costs. However, if a company wants to spend less on present marginal costs, then they may choose to use newly produced plastic since it is cheaper to produce plastic than mine metal.

The third choice compares newly produced metal with recycled plastic. A company may choose to use newly produced metal if it is looking for lower overall expenses, which may benefit smaller companies who cannot afford plastic recycling. On the other hand, plastic recycling methods may be more feasible if a company values their environmental goals and impact, since mining releases carbon emissions and toxic compounds into the environment ("Environmental Risks of Mining.", 2016). Additionally, using recycled plastic will appeal more to consumers as it is perceived to be more environmentally friendly (Ruokamo et al., 2022).

The fourth choice compares newly produced plastic with recycled metal. Companies may choose to use newly produced plastic if they wish to be more cost-effective. By using newly produced plastic, companies must only worry about the marginal cost to produce new plastic and can avoid the larger fixed costs for recycling technologies. On the other hand, companies may choose to use recycled metal if they value environmental and humanitarian impact. Unlike metal recycling, plastic production uses fossil fuels and releases toxic chemicals, which negatively impacts the ecosystem and human health (Hogan & Steinbach, 2019).

The fifth choice compares newly produced metals with recycled metal. Companies may choose to use newly produced metals if their products include many radioactive metals, which cannot be recycled ("Radioactive Material in Scrap Metal", n.d.). However, since technology products usually do not contain such materials, there is little to no reason for technology companies to use virgin metals over recycled metals (Wheeler, 2018).

The sixth and final choice compares virgin plastic with recycled plastic. A company may choose to use virgin plastic if a company is looking for cheaper marginal costs. Companies may also choose to use virgin plastics if they want to maintain product quality but cannot afford chemical recycling processes. However, a company may choose to use recycled plastic if it wishes to boost consumer attitudes towards its products or fulfill its sustainability goals (Ruokamo et al., 2022).

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4.2 Limitations of the Recycling Industry

These recycling methods are also analyzed within the practical realities of the recycling industry. Compared to plastic recycling, it would appear that metal recycling better enables a shift towards sustainability while maintaining profitability. As stated in Table 1, metal recycling saves 56-68% more carbon; 34% more kilojoules of energy, which depletes less natural resources and lowers GHG emissions; and costs substantially less in terms of fixed and marginal costs (Jeswani et al., 2021, "National Overview: Facts and Figures on Materials, Wastes and Recycling", n.d., Nizami et al., 2017, "Life cycle impacts for postconsumer recycled resins: PET, HDPE, and PP", 2018, "Saving Energy Improves Americans' Health and the Environment", n.d.). Therefore, metal recycling would supposedly allow companies to become more sustainable while retaining profitability, seemingly making it the more optimal recycling method.

Yet, despite its many benefits, numerous limitations exist within the recycling industry that hinder its widespread use. One of the chief obstacles is consumer misinformation. As Ruokamo's study indicates, consumers derive much satisfaction from PCR products (Ruokamo et al., 2022). Although plastic recycling is appealing because of its environmental benefits, it is not the most circular or environmentally friendly option. However, the overwhelming popularity and satisfaction surrounding plastic recycling prevents consumers from realizing the needed improvements of current plastic recycling methods.

Secondly, purifying metals can be cumbersome. Many recyclable metals contain impurities that cannot be recycled with metal recycling processes, such as plastic and rubber ("[FAQ] The Challenges Facing the Metal Recycling Industry", 2024). As a result, separating these impurities from the metals can often be time consuming, making the entire process inefficient and cost intensive. While there have been some advances in separation technology, specifically related to the use of x-rays and laser spectroscopies, these methods are very new and far from being widely implemented in metal recycling plants (Loibl & Espinoza, 2021). As a result, the separation barrier is a lasting one that firms will have to deal with now and in the future (Loibl & Espinoza, 2021).

Additionally, metal recycling is contingent on infrastructure. If the infrastructure in a certain area is old or inefficient, such as those in the third world or more rural areas, it would become more difficult for companies to gather and process recyclable metals, leading to an increase in transportation costs, delays in output, and overall inefficiency ("[FAQ] The Challenges Facing the Metal Recycling Industry", 2024).

Lastly, one of the chief obstacles to metal recycling is the lack of accountability towards companies. Currently, the United States lacks a national carbon tax (Kotchen, 2023). Because of a lack of legislation, companies have no incentive to invest in sustainability or shift to more sustainable technologies because they are not held accountable and do not internalize the social cost that they place on the environment. The effect of these obstacles is best reflected in the projected growth rates of the global metal and plastic recycling markets. Figure 3 shows that the metal recycling market was valued at \$2.5 billion in 2022 and is predicted to increase to a value of \$4.37 billion by 2032, growing at a compound annual growth rate (CAGR) of 5.8% ("Recycled Metal Market", 2023). However, the plastic recycling market was valued at \$44.94 billion and is predicted to increase to a value of \$104.09 by 2032, growing at a CAGR of 9.3% ("Recycled Plastic Market", 2023).

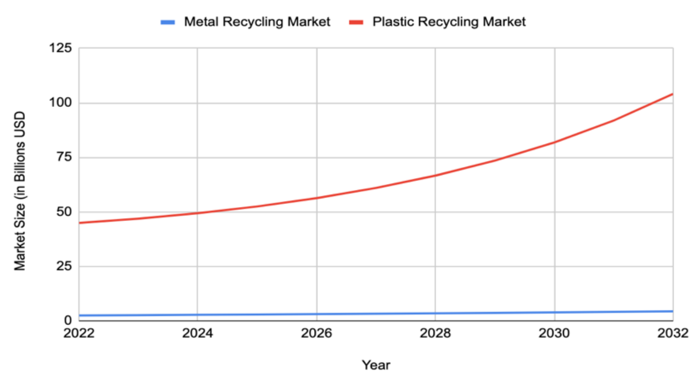

Figure 3. Growth rates of plastic and metal recycling markets are compared. The plastic recycling market is expected to grow much more rapidly than the metal recycling market, with a CAGR of 9.3% compared to 5.8%. (Modified from sources: Precedence Research, *Recycled Metal Market*, 2023, *Recycled Plastic Market*, 2023)

However, some action can be taken encourage a shift to metal recycling technologies. First, efforts to inform consumers about the reality of plastic recycling can be undertaken. Rather than only discussing the benefits of plastic

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recycling or the idea that it is the most sustainable practice, the drawbacks and shortcomings of plastic recycling should also be discussed more publicly. The environmental and financial consequences of metal recycling can also be discussed more openly to increase consumer awareness of metal recycling technologies. In addition, development of newer separation technologies, which can come from the investment of companies, may increase the efficiency of metal recycling, expediting the process and reducing costs. For instance, studies show that vacuum distillation is an extremely effective method to separate and recover metals, with recovery efficiencies of 95.65%, 99.28%, and 99.12% for Cu, Ag, and Au, respectively (Zha et al., 2019). Yet, Gaustad et al.'s survey of impurity removing technologies indicates that distillation techniques for the recycling industry are still in the research and development phase, demonstrating the need for further investment to bring such effective technologies to the market (Gaustad et al., 2011). Lastly, more action can be taken to encourage companies to invest in more sustainable technologies. For example, carbon taxes can be instituted on a national level to hold companies accountable for the damages that they impart on the environment, encouraging them to shift towards more sustainable practices like metal recycling. Tax deductions on sustainable practices, like metal recycling, can also be considered to incentivize companies to adopt more sustainable business models.

5. Conclusion

To conclude this paper, actionable recommendations for companies looking to transition to metal recycling are discussed. First, companies should acquire the physical capital required for metal recycling spaces, namely land. This ensures that companies have the available space to begin recycling their products. Next, companies should acquire the technological capital needed for metal recycling processes. This includes washers, granulators, and shredders, to name a few. As these machines can cost several hundreds of thousands of dollars depending on the size of the recycling facility, companies should evaluate whether or not they have adequate capital for such expenses. Next, companies should devise a system for collecting scrap metal. If infrastructure in the surrounding area is stable, then companies could use trucks or other similar transportation systems to collect and deliver recyclable metals. Furthermore, companies should heavily promote their metal recycling initiatives and its benefits through social media and other advertisement platforms. Such exposure opens the floor to further discussion of metal recycling amongst consumers, bringing its added benefits to their attention. As a result, interest and favorability towards metal recycling may grow, combating the overwhelming public interest in plastic recycling and leading to more purchases for the company's recycled products, which in turn will allow it to remain profitable. Lastly, if companies have the required capital, then they can also invest in newer metal recycling technologies. Current recycling technologies can, at times, be inefficient and cost-intensive, so investing in newer technologies like vacuum distillation can eliminate the logistical and financial liabilities that come with current technologies, further solidifying the profitability of the firm. Overall, further legal, technological, and economic action must be taken to promote metal recycling and more sustainable practices as a whole.

References

Aspire vero. (n.d.). Acer. https://www.acer.com/us-en/laptops/aspire/aspire-vero.

Biomass combined heat and power catalog of technologies. (n.d.). www.epa.gov/sites/default/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_v.1.1.pdf.

Brio 300. (n.d.). LogiTech. https://www.logitech.com/en-us/products/webcams/brio-300-webcam.960-001441.html

CASS. "[FAQ] The Challenges Facing the Metal Recycling Industry," September 2024. https://www.cass-usa.com/news/faq-the-challenges-facing-the-metal-recycling-industry.

Cost to recycle metal. (n.d.). Desert Metal Recycling. Retrieved October 27, 2023, from https://recycletucson.com/cost-recycle-metal/#:~:text=Non%2Dferrous%20metals%20such%20as,a%20ton%20of%20scrap%20metal.

Crawford, R., and Martin, P.J. (2019). *Plastics Engineering*. Elsevier. https://books.google.com/books/about/Plastics_Engineering.html?id=xGjLDwAAQBAJ

Environmentally conscious product design. (n.d.). Lenovo. https://www.lenovo.com/medias/GreenPaper-ThinkPad-Design-for Environment.pdf?context=bWFzdGVyfHNvY2lhbF9yZXNwb25zaWJpbGl0eXw0ODk5MzJ8YXBwbGljYXRpb24vcGRmfHNvY2lhbF9yZXNwb25zaWJpbGl0eS9oNjAvaDA5LzkzMjkxMzI3OTc5ODIucGRmfDQxY2QyMzUyMjU4NzdiMzE4MDYzNDFjZDkyZDUxMDc1MGZlYmMzNjBiYjE3YTIzYTNmYWZhZGRlMWMzZTA3MjA.

Environmental risks of mining. (2016). Massachusetts Institute of Technology. Retrieved March 8, 2024, from https://web.mit.edu/12.000/www/m2016/finalwebsite/problems/mining.html#:~:text=It%20involves%20large%2Dscale%20movements,metals%2C%20it%20becomes%20a%20contaminant.

Fair materials. (n.d.). Fairphone. https://www.fairphone.com/en/impact/fair-materials/.

Fair materials 101 – A guide to the materials in your phone. (2021, January 17). *Fairphone*. https://www.fairphone.com/en/2021/01/17/fair-materials/amp/.

Gaustad, G. G., Olivetti, E. A., and Kirchain, R. E. "Improving Aluminum Recycling: A Survey of Sorting and Impurity Removal Technologies." *Resources Conservation and Recycling* 58 (2012): 79–87. https://api.semanticscholar.org/CorpusID:110022928.

Ghodrat, M., et al. (2019). Economic feasibility of energy recovery from waste plastic using pyrolysis technology: An Australian perspective. *International Journal of Environmental Science and Technology*, *16*(7), 3721–3734. https://doi.org/10.1007/s13762-019-02293-8

Hobson, K., et al. (2018). Systems of practice and the Circular Economy: Transforming mobile phone product service systems. *Environmental Innovation and Societal Transitions*, *26*, 147–157. https://doi.org/10.1016/j.eist.2017.04.002.

Hogan, A., & Steinbach, A. (2019, April 17). *A polymer problem: How plastic production and consumption is polluting our oceans*. The Georgetown Environmental Law Review. https://www.law.georgetown.edu/environmental-law-review/blog/a-polymer-problem-how-plastic-production-and-consumption-is-polluting-our-oceans/.

Horani, L. (2023). Sustainable design concepts and their definitions: An inductive content-analysis-based literature review. *Technological Sustainability*, *2*. https://doi.org/10.1108/TECHS-10-2022-0041.

How recyclable is the fairphone 2? (2017, February 27). *Fairphone*. https://www.fairphone.com/en/2017/02/27/recyclable-fairphone-2/amp/.

Jeswani, H., et al. (2021). Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. *Science of The Total Environment*, *769*, 144483. https://doi.org/10.1016/j.scitotenv.2020.144483.

Kotchen, M. (2023, November 1). *Are we ready for a global carbon tax?* Yale School of the Environment. Retrieved March 8, 2024, from https://environment.yale.edu/news/article/are-we-ready-global-carbon-tax#:~:text=The%20U.S%2C%20currently%20does%20not,have%20cap%20and%20trade%20programs.

Lase, I. S., et al. (2023). Method to Develop Potential Business Cases of Plastic Recycling from Urban Areas: A Case Study on Nonhousehold End-Use Plastic Film Waste in Belgium. *ACS Sustainable Chemistry & Engineering*, *11*(34), 12677–12694. https://doi.org/10.1021/acssuschemeng.3c02748.

Life cycle impacts for postconsumerrecycled resins: PET, hdpe, AND PP. (2018, December). Association of Plastic Recyclers. https://plasticsrecycling.org/images/library/2018-APR-LCI-report.pdf.

Loibl, A., and Tercero Espinoza, L. A. "Current Challenges in Copper Recycling: Aligning Insights from Material Flow Analysis with Technological Research Developments and Industry Issues in Europe and North America." *Resources, Conservation and Recycling* 169 (June 1, 2021): 105462. https://doi.org/10.1016/j.resconrec.2021.105462.

Mendoza, J. M. F., et al (2017). Integrating Backcasting and Eco-Design for the Circular Economy: The BECE Framework. *Journal of Industrial Ecology*, *21*(3), 526–544. https://doi.org/10.1111/jiec.12590.

National overview: Facts and figures on materials, wastes and recycling. (n.d.). Environmental Protection Agency. Retrieved October 24, 2023, from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials#recycling.

Nikiema, J., and Asiedu, Z. "A Review of the Cost and Effectiveness of Solutions to Address Plastic Pollution." *Environmental Science and Pollution Research* 29, no. 17 (April 1, 2022): 24547–73. https://doi.org/10.1007/s11356-021-18038-5.

NEC brings first ecological 'all-in-one' desktop computer to U.S. market. (2002, August 6). Digital Journal. https://www.digitaljournal.com/tech-science/nec-brings-first-ecological-all-in-one-desktop-computer-to-u-s-market/article/34589.

Nizami, A.-S., et al. (2017). Energy, Economic and Environmental Savings by Waste Recycling: A Case Study of Madinah City. *Proceedings of the 9th International Conference on Applied Energy*, *142*, 910–915. https://doi.org/10.1016/j.egypro.2017.12.146.

Perkins, D. N., et al. (2014). E-Waste: A Global Hazard. *Annals of Global Health*, *80*(4), 286–295. https://doi.org/10.1016/j.aogh.2014.10.001.

Radioactive material in scrap metal. (n.d.). https://www.epa.gov/radtown/radioactive-material-scrap-metal#:~:text=Radioactive%20materials%20should%20not%20be,yards%20and%20scrap%20metal%20yards.

Recycled metal market (By metal type: Ferrous and non-ferrous; By end user: Construction, transport & automotive, industrial machinery, electronics, defense, packaging, military, consumer goods, and others) - global industry analysis, size, share, growth, trends, regional outlook, and forecast 2023 - 2032. (2023, November). Precedence Research. Retrieved March 1, 2024, from https://www.precedenceresearch.com/recycled-metal-market.

Recycled plastic market (By source: Plastic bottles, plastic films, polymer foam, and others; By product: Polyethylene, polyethylene terephthalate, polypropylene, polyvinyl chloride, polystyrene, and others; By application: Packaging, building & construction, textiles, electronics, automotive, and others) – global industry analysis, size, share, growth, trends, regional outlook, and forecast 2023 – 2032. (2023, June). Precedence Research. Retrieved March 1, 2024, from https://www.precedenceresearch.com/recycled-plastic-market.

Recycle your old phone(s). (n.d.). Fairphone. https://shop.fairphone.com/recycle.

Ruokamo, E., Räisänen, M., & Kauppi, S. (2022). Consumer preferences for recycled plastics: Observations from a citizen survey. *Journal of Cleaner Production*, *379*, 134720. https://doi.org/10.1016/j.jclepro.2022.134720.

Saving energy improves Americans' health and the environment. (n.d.). American Council for an Energy-Efficient Economy. https://www.aceee.org/sites/default/files/ee-improves-environment.pdf.

Science & tech spotlight: Advanced plastic recycling. (2021, September 14). Gao. https://www.gao.gov/products/gao-21-105317.

Sheykin, H. (2023, August 19). *How much does it cost to open a metal recycling business: Unveiling the CAPEX and starting costs*. FinModelsLab. https://finmodelslab.com/blogs/startup-costs/metal-recycling-startup-costs

The circular economy in detail. (n.d.). Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/the-circular-economy-in-detail-deep-dive.

Vol. 2025 (2) 121 – 130
ISSN 2688-3651 [online]

Thomas, D. (2022). Cost-Effective environmental sustainability. *NIST*. Retrieved October 25, 2023, from https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.100-48-upd1.pdf.

Unruh, G., et al. "Investing For a Sustainable Future." *MIT Sloan Management Review*, May 11, 2016. https://sloanreview.mit.edu/projects/investing-for-a-sustainable-future/.

Wheeler, A. (n.d.). *What raw materials are used to make hardware in computing devices?* Engineering. Retrieved October 11, 2023, from https://www.engineering.com/story/what-raw-materials-are-used-to-make-hardware-in-computing-devices.

Yue, Y., et al. (2016). Characteristics and potential values of bio-oil, syngas and biochar derived from Salsola collina Pall. In a fixed bed slow pyrolysis system. *Bioresource Technology*, *220*, 378–383. https://doi.org/10.1016/j.biortech.2016.08.028.

Zeng, X., et al. (2022a). Comparing the costs and benefits of virgin and urban mining. *Journal of Management Science and Engineering*, *7*(1), 98–106. https://doi.org/10.1016/j.jmse.2021.05.002.

Zha, G. et al. "New Vacuum Distillation Technology for Separating and Recovering Valuable Metals from a High Value-Added Waste." *Separation and Purification Technology* 209 (January 31, 2019): 863–69. https://doi.org/10.1016/j.seppur.2018.09.038.