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. Thus, this paper aims 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. My methods for this paper entail qualitative research and environmental accounting. Through my methods, I 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. In a socially optimal setting, the most prevalent recycling method would be metal recycling due to its low costs and larger environmental impact.

Introduction

As more time passes, the effects of climate change are rapidly worsening. With more extreme weather, the loss of glaciers, and the rising of the ocean at previously unprecedented levels, the effects of climate change are more palpable than ever before. As a result, many companies, consumers, and governments have begun to focus on sustainability. Sustainability is known as a product or process's ability to operate while producing little environmental consequences (1). The increasing focus on sustainability has led to a rise in eco design, or ecological design. Eco design focuses on designing environmentally friendly products that meet the requirements of sustainability described above (1). Within the technology industry, companies have been applying eco design to their products by recycling various materials, specifically plastic or metal (2-9). Choosing which material to recycle is an important decision for companies to make as both materials have their respective benefits and drawbacks. Thus, this paper focuses on the economic and environmental implications of recycling plastic or metal within technology products in order to determine when it would be most logical for companies to use each strategy.

Plastic recycling costs vary greatly as there are several methods for recycling plastic. Generally, recycling one ton of plastic can range from $2,000 to $857,000, much more expensive than the $200 it costs to recycle one ton of metal (10-11). Fixed costs for plastic recycling technologies are much larger than the same costs for metal recycling as well (12-15). Lastly, metal recycling saves nearly 2 tons more carbon emissions per ton recycled as compared to plastic, and it also saves about 20 million more kilojoules per ton recycled compared to plastic recycling methods (16-19). The methods I used to obtain these statistics consist of environmental accounting, which was done to format all statistics in tons or kilojoules per ton, and extensive qualitative research, which was carried out through qualitative evaluations of research papers, journals, and government websites.

There are four separate methods that technology companies can use to manufacture their products: recycled metal, recycled plastic, newly produced metal, and newly produced plastic. Each eco design strategy has conditions under which they make the most sense, and I evaluated these conditions by analyzing the business cases for each one. Recycled plastic could potentially offer greater customer loyalty since recycled plastic greatly increases consumer satisfaction of products (20). Recycled metal offers cheaper marginal and fixed costs compared to most recycling methods and has the largest environmental benefits out of the four methods (10-22). Using newly produced plastic offers relatively cheap production costs and avoids any fixed technology costs (21). Lastly, newly produced metal avoids fixed technology costs and is more beneficial for products with non recyclable metals (22).

However, I further examined these four methods in a socially optimal setting, which is one in which all companies can afford any recycling method or technology and all companies internalize the social cost that they place on the environment. Within a socially optimal setting, the most prevalent method would be metal recycling. Metal recycling has the cheapest marginal costs and is the most sustainable, and, unlike other recycling methods, it also maintains product quality (11-20). Thus, because of these economic and environmental benefits, metal recycling would be most apparent in a socially optimal setting.

Lastly, I further discussed the implications and further research that could be done regarding my findings. I conjectured that metal recycling, due to its low costs and large environmental impact, could be a better recycling alternative for other industries as well, some of which could be the toy and automobile industries. Metal recycling could also become the mainstream recycling method because of the conditions above. Further research could center on how to encourage more metal recycling, how to better inform consumers about its benefits, and more affordable and effective plastic recycling methods.

Literature Review

With the rise of climate change, the circular economy has become a prominent framework on how to gear national economies towards a more sustainable path. The circular economy is a regenerative economic model that is similar to a cycle, one in which goods are constantly reused rather than made anew (23). The circular economy has three objectives: eliminating waste, circulating products and materials, and regenerating nature. The circular economy favors processes that save energy, labor, and greenhouse gas emissions, among others. On the product side, the circular economy aims to use eco design; 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 (24). One of the largest ways in which eco design is accomplished is through recycling.

Eco design is built upon the idea of sustainability. Sustainability is a product or process's ability to operate during its life with little environmental consequences (1). Sustainability encompasses three areas, known as the three factors of sustainability: the environment, the economy, and social considerations. Eco design focuses on applying the three factors of sustainability to product design in order to generate the least possible amount of environmental consequences throughout the product's life cycle, all while maintaining product quality. Eco design specifically takes into account a product's life cycle, marketing, usage, recyclability, and reusability in order to design a product that meets the goals outlined by sustainability.

Eco design has several requirements and tools that are needed in order for it to function. First, eco design requires tools that combine guidance, information, and education (25). Designing products in a sustainable manner is a new and growing field, so designers need ample information and education in order to carry out this process in the correct manner. Several eco design tools already exist, such as the LiDS wheel and the EcoReDesign Programme, but these tools often lack the guidance and information that designers need to carry out eco design (26-27). Secondly, eco design also requires specific information regarding environmental product design, such as materials to use and construction techniques, rather than general environmental facts. Similar to the need for tools, this is because eco design is a new and unfamiliar field to many product designers. Lastly, eco design requires ample time. Contemporary eco design processes often require a full day to plan out environmental designs, even with the use of eco design tools. Although the inputs for eco design are very demanding, they can be alleviated through tools like the 'Information/Inspiration' tool outlined by Vicky Lofthouse (25). The 'Information/Inspiration' is an eco design tool prototype that provides specific information regarding sustainable design, such as information on materials. Through 'Information/Inspiration', product designers receive more guidance and information on how to carry out eco design, possibly reducing the many demands that come with it.

Eco design can also be broken down into three central aspects: the design and development of products, reducing the environmental impact of products, and the product's life cycle (28). The design and development aspect requires a shift away from the throwaway mindset and towards a mindset that promotes a sustainable business model. In order to create such a shift, there must be company specific design principles, new information sources, and extensive education and training due to the novelty of eco design. The design and development stage also requires closing the loop, or cutting down on resources and waste. This can be done by using renewable energy and materials and designing products specifically for durability, modularity, recyclability, disassembly, remanufacturing, and reuse. In order to reduce the environmental impact of products, the environmental impacts during a product's early stages, such as when it is being produced, must be limited. Focusing on limiting the environmental consequences of these stages has shown to be the most effective way to curb a product's environmental implications. Lastly, focusing on the life cycle of a product entails analyzing its environmental consequences from cradle to grave, or from when it is produced to when it is no longer usable. The environmental impacts that a product will have throughout its life can be quantified through tools like the Life Cycle Assessment, which gives insight into the environmental damages that a product will produce based on how it is designed (28).

Other research has examined the role of eco design for various products. For example, Joan Mendoza conducted a case study in order to determine the circularity of a vacuum cleaner (24). Like this research, this paper examines the role of eco design within the creation of products and how effective they are in terms of eco design. By disassembling a vacuum cleaner into its constituent parts and examining each part separately, Mendoza and her colleagues concluded that vacuum cleaners are not circular due to their low use of recycled materials and their inability to reuse many of their parts. Such examination was done through the Backcasting and Eco Design for the Circular Economy (BECE) framework; a guideline that helps people analyze certain products and conclude whether or not they are circular (24). While both this paper and Mendoza's work examine the role of eco design in products, there are several differences. Mendoza's paper aims to determine whether or not a product is circular, while this research examines technology products already deemed to be circular. Moreover, while Mendoza's paper focuses on the presence or absence of eco design in a product, this research compares the different types of eco design present within technology products in order to examine each method's benefits and drawbacks.

Employing eco design within technology products is important due to the overwhelming presence of e-waste. E-waste is defined as waste from end-of-life electronic devices (29). 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 those exposed. As a result, e-waste is known to negatively affect 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 that ends up in landfills can be reduced, thus benefiting the environment and global public health.

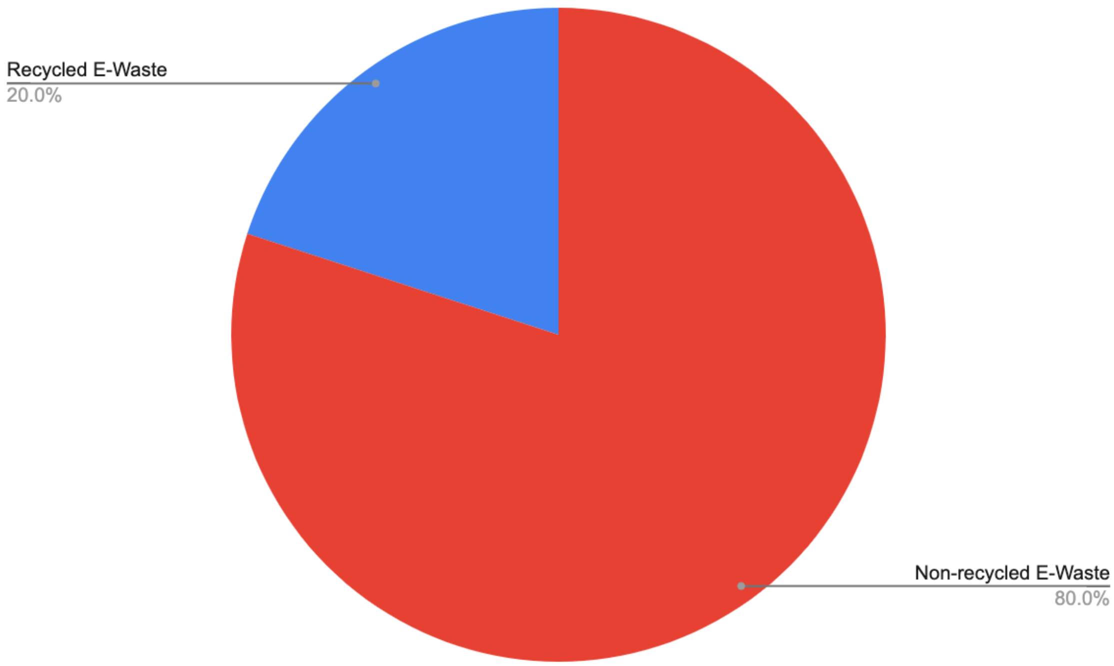

Figure 1. Most e-waste that is produced is not recycled.

Several technology companies have attempted to employ eco design through recycling various materials. For example, Fairphone, a Dutch phone company, implements eco design within its phone during the production and end of life stages (3). Fairphone's phones have eco design in that they are made out of recycled polycarbonate parts and materials from older devices (30). More specifically, Fairphone uses recycled copper, tin, and plastic within their phones (4). This follows the goal of eco design to reduce resource requirements. However, Fairphone phones remain circular at the end of their life cycles as well. Approximately 60% of phones are recycled and processed in order to harvest their valuable materials, such as gold (5). These materials are later used to create more phones. In order to harvest such materials, Fairphone uses several recycling methods. For example, the Fairphone 2 has three recyclable routes: Smelting, Dismantling, and Shredding (3). Smelting involves smelting the entire phone and separating each of its parts in order to harvest each of its constituent elements in base form. Unfortunately, smelting has the lowest percentage of materials recovered by weight and a poor range of recovered materials, making it the least circular recycling method. 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. This method has the highest percentage of materials recovered by weight and the largest range of recovered materials, making it the most circular recycling method. 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. While this method has a high percentage of materials recovered by weight, it has a limited range of recovered materials, making it an intermediately circular recycling method.

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 choose to 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. For example, Acer has attempted to use the Acer Aspire Vero, which is made of 40% post consumer recycled plastic, as a way to include eco design within its products (6). Logitech has done something similar with the Logitech Brio 300 Webcam, which is made of 48% post consumer recycled plastic (7). Lenovo has also attempted to implement eco design by creating environmentally friendly ThinkPads, which contain post consumer recycled plastic (8). 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 (9). All of these technology products aim to fulfill eco design's chief goal of reducing resource requirements and environmental impacts.

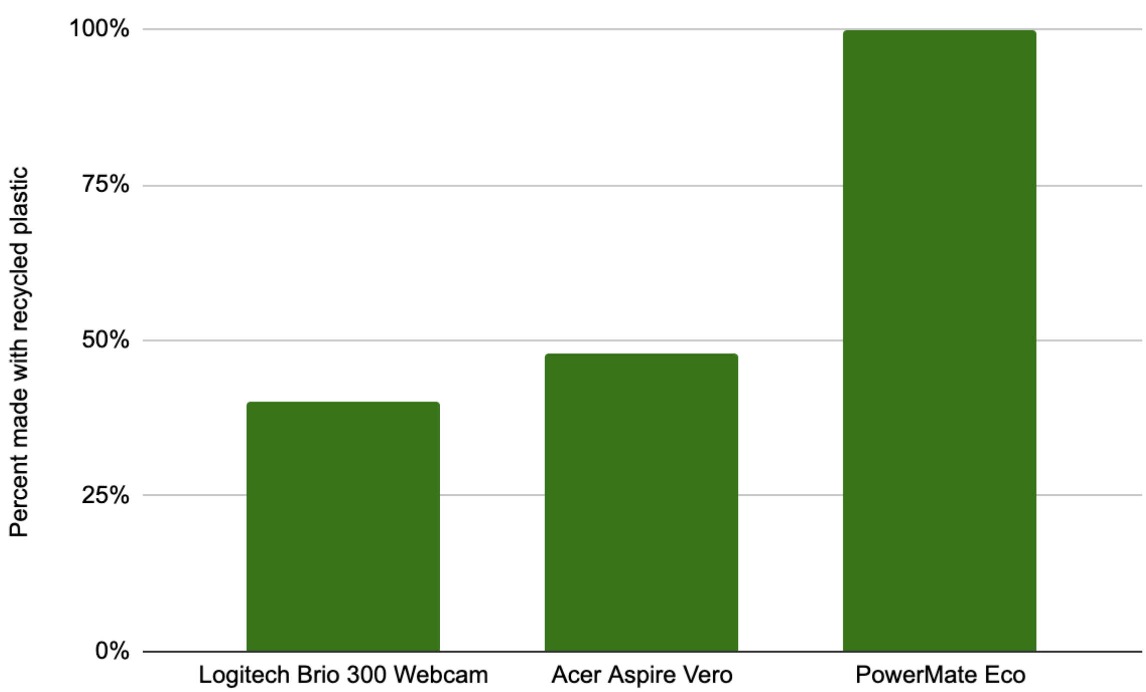

Figure 2. Each laptop company focuses on recycling plastic, but in different amounts.

Although both Fairphone and the laptop companies implement eco design, they do so in different ways. Fairphone implements eco design by recycling metals, while the laptop companies do the same by recycling plastic. Although the impacts of recycling metal are quite profound (17), the overwhelming popularity of plastic recycling cannot be overlooked (20). Thus, the goal of this paper is to analyze the economic and environmental consequences for metal and plastic recycling within technology products in order to establish when it is more logical for technology companies to recycle plastics or metals.

Background

With the rapid onset and effects of climate change, reducing carbon emissions has become increasingly important. Such a shift towards a more sustainable mindset has influenced many companies to make the decision to adopt more sustainable policies. Whether this be through their products or processes, numerous companies have shifted towards a greener model in order to oppose the rising threat of climate change and appeal to more consumers, many of whom are becoming more aware of the threats that climate change poses. Specifically in the technology industry, companies have shifted towards a more sustainable model through the way they create their products, which often includes the recycling of materials (2-9). However, device and hardware manufacturers have chosen to recycle different materials, the main ones being plastic or metal. Recycling metal or plastic is an important decision for companies to make as they both have their respective economic and environmental implications. Thus, with the shift towards a more sustainable mindset, deciding which material to recycle has become paramount for technology companies in order to ensure that they contribute to the circular economy while remaining economically viable.

Plastic recycling has become one of the most popular recycling methods to date due to the sheer number of global plastics. Plastic recycling has three methods: mechanical, pyrolysis, and gasification. Mechanical recycling involves more standard recycling measures, such as grinding, granulating, washing, and sorting (31). Pyrolysis involves heating plastic waste at high temperatures in order to convert it into energy sources, such as liquid oil (31). Gasification involves heating plastic at high temperatures in order to convert it into syngas, which can then be used as a form of energy (31). Both gasification and pyrolysis are known as chemical recycling methods.

Costs between these three methods vary. Generally, the cost of recycling one ton of plastic with mechanical methods ranges from $2,000 to $10,000 (10). The major technologies used for such processes include granulators, washers, and dryers. Pyrolysis and gasification are much more expensive. Using pyrolysis to recycle one ton of plastics costs $857,000, while using gasification to recycle one ton of plastics costs $385,000 (10). Such high prices are due to the more complicated nature of these methods, which often require the use and maintenance of more advanced machinery. Major technologies used for pyrolysis include pyrolysis reactors and gas pipes, while the major technology for gasification is a gasifier. Such costs are much more expensive than the cost of producing one ton of virgin plastic, which is $1,200 (21). Fixed costs pertaining to the different technologies used vary amongst the three methods as well. The costs to purchase and install mechanical recycling machinery ranges from $2,185,028 - $2,804,392 (13). Fixed costs for pyrolysis machinery costs $3,630,537 (14). Fixed costs for gasification range from $4,476,700 to $61,705,766, depending on how much plastic waste the plant receives (15). Lastly, one ton of plastic is traded at around $2,168 (32).

For each ton of plastic recycled, the mechanical recycling process saves 1.99 tons of carbon dioxide as compared to producing virgin plastic (16). For each ton of plastic recycled, chemical recycling processes save about 2.13 tons of carbon dioxide as compared to virgin plastics (16). Mechanical methods of recycling often do not preserve the quality of plastics, but instead create lower quality plastics through a process known as downcycling (31). Thus, companies use recycled plastics for lower quality products, or they mix it with virgin plastic to give it more value and implement it within higher quality goods. Virgin plastics, on the other hand, are typically used in higher quality goods since they are not downcycled and have not undergone the recycling process. The products of gasification and pyrolysis, such as syngas, biochar, and bio-oil, can be used as fuel for commercial purposes, providing an environmentally friendly alternative to fossil fuels (33). For technology companies, recycled plastics from mechanical recycling processes would be used for the external areas of the product, such as the case. Recycled plastics from chemical methods of recycling could be used by companies as fuel or raw materials. Lastly, plastic recycling saves about 38,373,915 kilojoules per ton of plastic recycled (19).

Metal recycling is an alternative method that technology companies can use to further implement eco design within their products. Metal recycling involves shredding, melting, purifying, and sorting metals into their pure, base forms (3). The major technologies involved in this recycling process include shredders, furnaces, and electrolysis.The average cost of recycling one ton of metal is $200 (11). This is much cheaper compared to the cost of mining one ton of virgin metal, which ranges from $2,500 to $5,500 (34). Fixed costs pertaining to the recycling machinery ranges from $50,000 to $200,000 (12). Different metals are traded at different prices. For one ton of each metal, aluminum is traded at $2,231, lead is traded at $2,099, copper is traded at $8,065, nickel is traded at $17,783, zinc is traded at $2,466, and tin is traded at $23,786 (35). Such variation in prices can be attributed to the amount of energy and money used to produce each type of metal. Lastly, for each ton of metal recycled, the metal recycling process saves 3.34 tons of carbon dioxide as compared to harvesting virgin metal (17). Metal recycling also saves about 58,200,437 kilojoules per ton of metal recycled (18). Metals often retain their quality throughout the recycling process, so they can be used for the same styles of products as those of virgin metal. For technology companies, recycled metals could be used for wires, circuit boards, and batteries, all while maintaining the same quality as its predecessor.

Methodology

The objective behind my research strategy was to generate a summary table that compares the environmental and economic costs of different recycling strategies. My main methods for producing the table below consist of qualitative research and environmental accounting. I reviewed and evaluated various research papers, journals, and government websites in order to obtain the statistics included within Table 1. The main sites that I used to search for these resources include ScienceDirect, Research Gate, the Environmental Protection Agency, and Google Scholars. I originally began my search process by using keywords such as ‘circular economy’ and ‘sustainability’. However, as my search grew more specific, I began to use keywords related to recycling, such as ‘metal recycling costs’ and ‘plastic recycling environmental impacts’. As I gained more general information on both recycling methods, such as costs and carbon footprint, I began to use more specific keywords in order to obtain more specific statistics, such as ‘consumer preferences for recycled plastic’. When necessary, I converted these estimates of cost and environmental impact into my desired units, which are tons and KJ/ton.

	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)	$2,500-$5,500 (mining)	$1,220
Marginal cost of recycling a ton	$200 (average)	$2000-$10000 (mechanical) $857000 (pyrolysis) $385000 (gasification)
Fixed technological cost	$50,000 - $200,000	$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 (Lead) $8,065 (Cu) $17,783 (Ni) $2,466 (Zn) $23,786 (Sn)	$2,168

Table 1. Metal and plastic recycling metrics are compared. Metal recycling is overall cheaper and has a larger environmental impact than plastic recycling methods.

Analysis

The purpose of this paper is to analyze the economic and environmental implications of plastic and metal recycling in order to determine when it is most logical for companies to use each choice. To do this, I will be focusing on the business cases for each choice. I will be analyzing under what conditions each choice is plausible, and I will also focus on these choices as they pertain to a "socially optimal" environment. Table 2 illustrates the two axes of comparison that I will be focusing on: the material and its condition. As a result, there are six choices in particular that I will be analyzing: recycled metal vs. 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.

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

Table 2. Axes of comparison used to compare different recycling choices.

The first choice concerns the use of recycled metal compared to recycled plastic. There are numerous conditions under which metal recycling is more feasible as opposed to 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 methods for plastic recycling, which diminishes the quality of plastic through downcycling (31), metals retain their quality throughout the recycling process (10). This would allow companies to produce more products of the same quality as its predecessor. Lastly, due to metal recycling's greater environmental impacts pertaining to carbon emissions and energy saved, a company may choose to recycle metal if it greatly values its environmental impact. On the other hand, plastic recycling methods may be more feasible if a company wants greater appeal towards consumers. A study 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 (20). Such attractiveness is largely due to the use of recycled plastic and the perceived reduction in carbon and materials. The 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 potentially use plastic recycling as a way 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 Table 1 shows that it is cheaper to produce plastic than mine metal.

The third choice concerns the use of newly produced metal compared to recycled plastic. A company may choose to use newly produced metal if it is looking for the cheaper option. Table 1 shows that mining expenses are much lower than the fixed and marginal costs associated with plastic recycling, so using newly produced metal is the more cost-effective option and may benefit smaller companies who cannot afford the large expenses of plastic recycling. On the other hand, plastic recycling methods may be more feasible if a company cares about their environmental impact. Plastic recycling benefits the environment by reducing carbon emissions and saving energy, but mining releases carbon emissions and toxic compounds into the environment (36). Additionally, using recycled plastic will appeal more to consumers as it is perceived to be more environmentally friendly, raising consumer satisfaction rates and overall satisfaction with the product. Thus, if a company is concerned with appealing to consumers and promoting its brand, then they can use plastic recycling to do so rather than newly produced metals.

The fourth choice concerns the use of newly produced plastic compared to recycled metal. Companies may choose to use newly produced plastic if they are looking for the cheaper option. By using newly produced plastic, companies only have to worry about the marginal cost to produce new plastic and can avoid the much larger fixed costs for metal recycling technologies. On the other hand, companies may choose to use recycled metal if they care about environmental impact. Table 1 shows that metal recycling significantly reduces carbon emissions and saves a lot of energy, but plastic production requires the use of fossil fuels and releases toxic chemicals, which may impact human health (37). Thus, choosing which strategy to use ultimately comes down to how much a company values its environmental impact and finances.

The fifth choice concerns the use of newly produced metals compared to recycled metal. Companies may choose to use newly produced metals if their products include many radioactive metals, which cannot be recycled (22). However, since technology products usually do not contain such materials, there is little to no reason for technology companies to use newly produced metals over recycled metals (38). On the other hand, there are numerous reasons as to why a company may use recycled metals. A company may choose to use recycled metals if it wants cheaper marginal costs for metals and cares about its environmental impact. Table 1 shows that the marginal costs to produce new metal are much larger, and metal extraction processes like mining are much more harmful for the environment as compared to metal recycling methods.

The sixth and final choice concerns the use of newly produced plastic compared to recycled plastic. A company may choose to use newly produced plastic if a company is looking for cheaper marginal costs. Companies may also choose to use newly produced plastics if they want to maintain product quality but cannot afford the costs associated with chemical recycling processes. Mainstream recycling methods, such as mechanical recycling, often produce lower quality plastic through a process known as downcycling, so if a company wants products of the same quality, then mechanical recycling methods may not be the most viable option (31). However, a company may choose to use recycled plastic if a company values its environmental impact, which plastic recycling methods greatly improve. Additionally, recycled plastics within products boosts consumer sentiment, so a company may choose to use recycled plastics if it wants to improve consumer satisfaction with its products (20).

These recycling methods will also be analyzed within the context of a socially optimal world. A socially optimal world is one where all companies can afford any recycling technology, and all companies and consumers make decisions where they internalize the costs they impose on the environment such that they are held accountable for externalities. Within the context of a socially optimal world, plastic and metal recycling technologies would be available to all companies. Both the fixed and marginal costs would be feasible for all companies regardless of magnitude since all companies would be able to afford whichever method they choose. Such recycling methods may also come with incentives, such as tax deductions, in order to motivate companies to further invest in sustainable spending. Consistently choosing to use environmentally harmful practices rather than these recycling methods could also come with higher taxes in order to incentivize companies to invest in sustainability and hold them accountable for the social cost that they impart on the environment.

Within the context of a socially optimal world, there would be more metal recycling as opposed to plastic recycling. Firstly, metal recycling saves more carbon emissions compared to plastic recycling. According to Table 1, metal recycling saves 3.34 tons of carbon for each ton of metal recycled, while plastic recycling only saves 1.99 to 2.13 tons for each ton of plastic recycled (16-17). Therefore, metal recycling is much more environmentally efficient because it saves between 56% to 68% more carbon for the same amount of material recycled. Secondly, metal recycling saves more energy. Table 1 also shows that for each ton of metal that is recycled, metal recycling methods save 58,200,437 kilojoules (KJ) per ton, while plastic recycling methods only save 38,373,915 KJ per ton, leading to less usage of natural resources and lower GHG emissions (18-19, 39). Therefore, metal recycling is much more beneficial from an energy standpoint as it conserves 34% more kilojoules per ton for each ton of material recycled, further increasing metal recycling's positive environmental impact. Thirdly, metal recycling is much cheaper than plastic recycling. According to Table 1, the fixed costs associated with metal recycling can range from $50,000 to $200,000, but fixed costs for plastic recycling can range from $2,642,012 to $61,705,766 depending on the method being used

(12-15). Similarly, Table 1 shows that marginal costs to recycle one ton of metal have an average of $200, while the marginal costs to recycle one ton of plastic range from $2,000 to $857,000 depending on the method (10-11). Therefore, because metal recycling's fixed and marginal costs are vastly cheaper than the same costs for plastic recycling, it is ultimately the most financially logical choice and the one that would be best geared to help companies maintain a profit. Lastly, metal recycling maintains product quality. When metals are recycled, they often undergo smelting or shredding processes, none of which downgrade the quality of the material. Plastic recycling, on the other hand, often produces lower quality plastic through a process known as downcycling (31). Downcycling is especially prevalent within mechanical recycling, which is the most popular recycling method for plastics. Therefore, metal recycling would allow companies to remain circular while still producing high quality products, making it the more efficient recycling method overall.

However, several obstacles exist that prevent this more widespread use of metal recycling. Firstly, one of the main obstacles is consumer misinformation. Plastic recycling methods are overwhelmingly popular, and consumers derive much satisfaction from PCR products. In fact, 93% of consumers who bought products with recycled plastic were satisfied with the product, and the existence of recycled plastic within these products positively affected the purchase decisions of 86% of consumers (20). Although plastic recycling is appealing because of its environmental benefits, it is not the most circular or environmentally friendly option; however, the overwhelming popularity of plastic recycling prevents consumers from realizing the drawbacks, flaws, and needed improvements of current plastic recycling methods. Secondly, another main obstacle to more metal recycling is the lack of accountability towards companies. Currently, the United States does not have a carbon tax on the national level (40). Because of a lack of vehicles like carbon taxes, 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% (41). However, the plastic recycling market was valued at $44.94 billion and is predicted to increase to a value of $104.09 billion by 2032, growing at a CAGR of 9.3% (42).

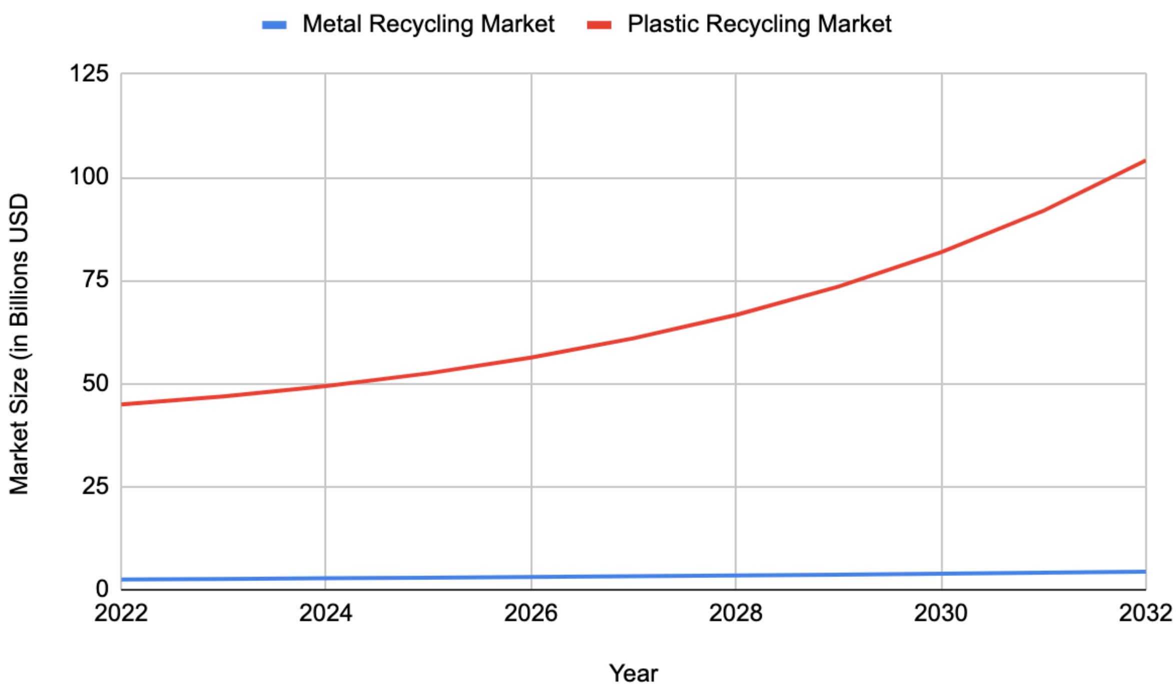

Figure 3. Growth rates of plastic and metal recycling markets are compared. The plastic recycling market is expected to grow much more rapidly than the metal recycling market, with a CAGR of 9.3% compared to 5.8%.

However, action can be taken to encourage a shift to metal recycling technologies. First, efforts to inform consumers about the reality of plastic recycling can be undertaken. Rather than pushing the false narrative that plastic recycling is the most sustainable form of recycling, the drawbacks and shortcomings of plastic recycling should also be discussed more publicly. In addition, the environmental and financial consequences of metal recycling can be discussed more openly so as to increase consumer awareness of metal recycling technologies. Second, 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 so as 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 in order to incentivize companies to move towards more sustainable business models.

Discussion

To conclude, I will discuss the implications of my research concerning metal and plastic recycling, and I will also discuss further research that could be undertaken on this topic. The main implication of my research is that metal recycling is more effective than plastic recycling for technology companies, which could mean that it is a more effective alternative for other industries as well. Some examples of such industries include the toy industry and the automobile industry, both of which have products that contain plastic and metal and may subsequently be faced with the choice between plastic or metal recycling. Another implication of my research is the larger role that metal recycling could play in the future. Given its enormous economic and environmental benefits, I believe that metal recycling could become the mainstream method of recycling. However, this shift towards metal recycling would have to be more encouraged through the right policies and discussed more openly amongst consumers in order to more effectively inform them on this topic. Some examples of policies that could encourage such a shift are tax benefits for products with recycled metal and a national carbon tax.

Further research can also be done to further the findings of this research. First, further research can be done to investigate effective ways to encourage more metal recycling. A shift towards a more widespread use of metal recycling is certainly possible, but the use of metal recycling first has to be encouraged. Therefore, by researching various methods that can encourage the use of metal recycling, such as government policies, we can ensure that metal recycling grows in popularity and becomes more widespread. As mentioned above, national carbon taxes and tax benefits for products with recycled metal could help further this process. Second, further research can also be done to investigate more effective ways to inform consumers of the benefits of metal recycling. One of the main obstacles to the more widespread use of metal recycling is the consumer misinformation surrounding plastic recycling. However, by investigating more active measures to inform consumers of metal recycling, we can ensure that metal recycling is fully realized for its potential and that it can grow in popularity. One measure that can be used to inform consumers is instituting more multi-material recycling bins, so as to inform consumers that plastic is not the only material that can be recycled. Lastly, further research could also look into more affordable and effective methods for plastic recycling. While plastic recycling may not be as effective as metal recycling, it is still important since some products are only made out of plastic, such as plastic water bottles. Therefore, more effective methods of plastic recycling could be researched so as to ensure that, when they are used, plastic recycling processes function at optimal efficiency. Although limitations may have arisen from using some open websites, this research demonstrates the larger benefits of metal recycling as opposed to plastic recycling.

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