Electronic waste recycling: Understanding the ecosystem and opportunities for improvement

by

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Abstract

With the growth of the smartphone industry a commensurate growth in the volume of electronic waste has occurred. Electronic waste is any electronic or electrical device that has reached the end of its useful life and has been disposed of by a consumer. The volume of this waste stream is the fastest growing waste stream globally and has begun to impact the developing world disproportionately as these regions are often at the receiving end of an endless stream of hazardous waste components. The industries that handle electronic waste must be thought of as a System of Systems or ecosystem if real improvement is to be made.

The ecosystem can be decomposed into three major systems: collection, which collects electronic waste from consumers and introduces it to the recycling process; pre-processing, which turns electronic waste into discrete material streams for ultimate recycling; and end-processing, which turns individual material streams into raw materials with market value.

Improving the overall recycling ecosystem is a critical component of making global industrialization sustainable. This improvement must address both the individual challenges facing each component system in the ecosystem as well as the broader challenges that span the whole ecosystem. The three component systems of the ecosystem face economic, social, environmental, and technological challenges. As a result, the available solution space is broad and varied.

However, from an ecosystem perspective, the greatest challenges exist at system interfaces and the greatest opportunity exists in improving these interfaces. In so doing, improved communication between systems and stakeholders will drive the overall improvement of the ecosystem. This communication should generate a uniform set of requirements for how the system should operate. In turn, measuring success in the ecosystem and meeting the requirements requires alignment of goals for each system with those of the broader ecosystem. Finally, a fourth member of the ecosystem—the device manufacturers—must play a crucial role in facilitating this interface management; in this sense, manufacturers have the opportunity to become the *de facto* architects of this evolving system. As architects, manufacturers could exert more power to realize the changes required while also guiding the ecosystem to more sustainable ground.

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Chapter 1

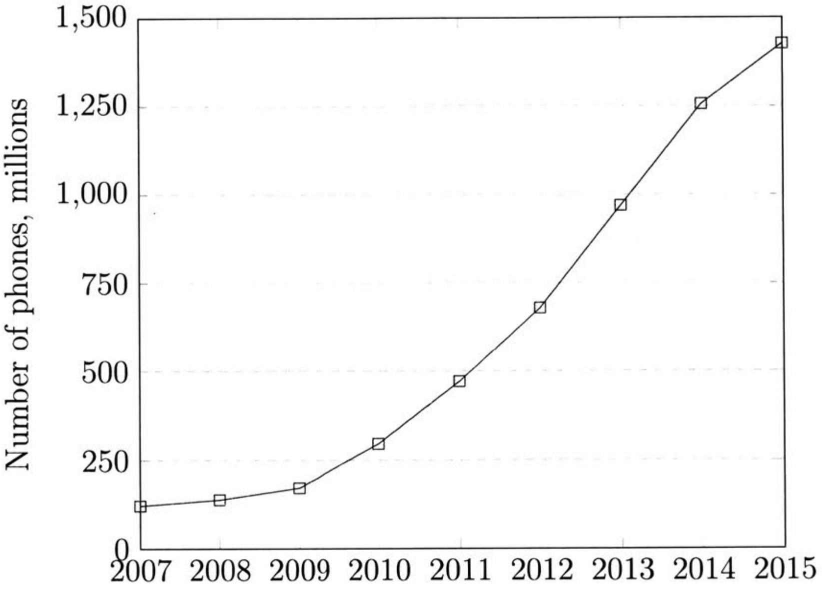
Introduction

For many years there has been an increasingly ardent push towards "sustainability" in all aspects of modern life. This effort has manifested mainly in developed countries in the actions taken by citizens, corporations, and governments. The developing world is also beginning to make strides towards implementing "sustainable" solutions for their growth. Of course, as is usually the case, "sustainability" writ large is a term thrown around relatively carelessly with governments touting it as their pledge to reform or clean up the environment, with companies using it as a way to promote themselves, and with individuals arguing they are acting altruistically in the interests of society as a whole.

The modern formal definition of "sustainability" can be traced to the Brundtland Report published by the United Nations World Commission on Environment and Development in 1987. [1] In this work, sustainable development was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Taking this as the framework against which one can evaluate particular efforts, it becomes possible to tease out just how "sustainable" things really are.

While the world is looking to grow more sustainably and responsibly, it is growing nonetheless. In parallel with this growth the world is becoming more and more connected—largely driven by the devices most people carry around in their pockets: cell phones and smart phones. The explosive growth of smart phones (a mobile phone that is capable of performing multiple functions above and beyond placing calls) since 2007 has fostered immense networks of people across the world via the internet and cellular networks.

Figure 1-1: Global smartphone growth [2]



As people hunger for greater connection and companies hunger for greater profits, the economy has been pumped full of these devices. As shown in Figure 1-1 the massive influx of smart phones has flooded the market with small, portable electronic devices. However, these devices are highly transient. While they are relatively robust and long-lasting, the typical lifetime of a smart phone today is on the order of 1–3 years, and it is decreasing. [3, 4, 5] Producers of smart phones are eager to introduce new features on thinner, lighter, more powerful devices that quickly make the previous generation of devices obsolete. The question, then, is what happens to these obsolete devices? These devices represent a literal mountain of physical resources as well as real financial value. Where do they go? What happens to them? Is that part of their lifecycle "sustainable" as in keeping with this omnipresent goal to make life more compatible with the natural environment? This thesis intends to explore these questions by examining the lifecycle of smartphones after their primary owners have disposed of them. This focus is particularly pertinent for a few reasons: smartphones represent one of the fastest growing segments of electronic waste; these devices are ubiquitous with nearly 2.6 billion users projected in 2017 [2]; and they contain a vast array of materials whose production stems entirely from non-renewable resources. This work will frame this problem as a study of the System of Systems (or "SoS") that involves many stakeholders and subsystems, all who play a role in taking a device declared "waste" and figuring out what to do with it. This waste is more accurately described as electronic waste.

1.1 What is electronic waste?

Electronic waste is "obsolete equipment that is dependent on electric currents or electromagnetic fields to work properly and equipment for the generation, transfer, and measurement of such current." [6] Peeling apart this rather technical definition from the European Union, electronic waste (e-waste or waste electrical and electronic equipment, WEEE) is any electrical device that no longer functions and has reached its end-of-life (EOL). More and more, though, many researchers have begun to include devices that are no longer "trendy" in the definition of WEEE because they have been made obsolete by newer generations of devices; these devices may work perfectly well, but their primary owner has discarded them in favor of a newer device. This, then, means that defining a device as WEEE is as much a decision of the primary owner and the changing condition of the product market as it is result of the how the actual device is performing. These dynamics will play a role in how to manage the consumer-side of the SoS.

There are many subclasses of WEEE. Because most modern household appliances have some sort of electric components, they can be classified as WEEE. Likewise, personal and commercial information technology equipment can be classified as WEEE. Even within personal electronic devices, one can parse the definition of WEEE further: personal computers, laptops, mobile phones, notebooks and tablets, and wearables. As a class of waste, WEEE generation is growing rapidly. However, this thesis will focus specifically on smart phones in the United States. Smart phones occupy a unique place in American society with 90% of Americans owning a cell phone, and 64% of Americans owning a smart phone. [7] Furthermore, producers of smart phones have repeatedly reported growing sales of smart phones indicating continual influx of devices into the economy. [8] The other side to this profits-are-high-and-sales-are-growing coin, though, is that the smart phones already in the economy have to be going somewhere. To this point, some reports indicate that consumers—those who are buying the new smart phones—are becoming more aware of how their behavior is affecting the "sustainability" of their habits. [9] Society may be at a tipping point where people begin to care very deeply about what happens to their WEEE and EOL devices. After all, relatively recently consumers have expressed concern about the sustainability of their food sources, clothing choices, and buildings. It seems to be only a matter of time before these sentiments are extended to their personal electronics; in fact, a recent poll found that 86% of Americans would be willing to pay 10% more for electronic products if they knew they were made from recycled materials. [10]

1.2 What is the scale of electronic waste?

Consumers have every right to be concerned about what happens to their EOL devices. It is estimated that WEEE is the fastest growing segment of "waste" globally, growing at a compound annual growth rate of 3–5%. [11] There are varying estimates about how large this waste stream is, but some believe as much as 27–45 million tonnes of WEEE are disposed of each year globally, with roughly 20% of that coming from the United States. [6] It is estimated that smart phone WEEE will grow from 2014 levels of 19,000 tonnes to over 39,000 tonnes in 2020—a 105% increase. Beyond the tonnage of waste generated, there is an inherent value to WEEE that cannot be underestimated. The value of WEEE cell phones in the European Union is expected to reach €746 million in 2020, with the WEEE industry as a whole worth €2.15–3.67 billion by that period. [11] In the United States, the WEEE handling industry—principally scrap handlers—employed 7,000 people while taking in $700 million in revenue in 2003, and over 35,000 people in 2011 while making over $5 billion. [4, 12]

The value of WEEE is principally driven by the value of refurbished and resold devices and the metal contents of the WEEE devices themselves. In cell phones, for example, over 80% of the intrinsic value of the device comes from less than 20% of the weight of the equipment; gold accounts for 56% of the value, palladium 15%, platinum and cobalt 7%, silver 5%, and plastics and copper 3%. [11, 13, 14] But all told these elements are present in minute fractions—their high value per unit mass drives the overall value of the device.

1.2.1 The fate of electronic waste

With all of this value trapped in WEEE it is important to understand where most of it ends up—both historically and today. Unfortunately the narrative most often repeated in the literature and the news shows that in stark contrast to the noble goals of "sustainability," the overwhelming majority of WEEE has wound up in landfills historically. It has been estimated that as much as 80% of all WEEE ultimately makes its way to a landfill. [6, 15] While there are some indications that this trend is improving in recent years two facts remain: the landfilled waste is still in the landfill, and, unless dramatic efforts are made, the situation is unlikely to improve soon. Worse still, of the 20% of WEEE that is not landfilled, a majority of that (as much as 50-80%) is shipped to developing countries like China and India where it is processed cheaply but at great detriment to human and environmental health (these data will be discussed—and disputed—below). [4, 16, 17]

Once overseas, the impact of WEEE is striking. WEEE is picked over by hand in many developing countries to recover the small amounts of metal values. The remaining plastics are then often burned in open pits, leading to serious health and environmental repercussions. [16] These practices have led to toxic levels of lead, copper, and zinc in the soil and water supply of these communities. [18] Even in developed countries, the impacts of the WEEE are felt in landfills; WEEE contributes 70% of the cadmium and mercury found in US landfills. [6] Taken together, the fate of most WEEE is certainly far from ideal.

1.2.2 The environmental impact of electronic waste

As discussed above, WEEE contains a variety of metals, many of which can be toxic if released into the environment. Additionally, many of the plastics used in electronic devices (particularly older devices) contain brominated flame retardants (BFR) and polyvinyl chlorides (PVC) that form dioxins when burned. [19] Dioxins are powerful carcinogens that require additional treatment in established industrial operations. However, beyond the health hazards associated with the release of toxic metals or harmful gases, WEEE poses other environmental risks that can easily be mitigated. The main risk stems from the commodity values contained in the WEEE devices themselves.

By landfilling or otherwise disposing of WEEE devices, millions of tons of metal values are lost from the economy each year. In turn, generating new metals and materials from virgin sources (namely, mines and petroleum products) requires massive amounts of energy and real harm done to the environment. This is, perhaps, the greatest impact WEEE (and all forms of waste) has. Unfortunately, it is also the most obscured from public view. Due to long supply chains that separate the end customer from the primary producer it is often very difficult to see how the choice to throw something in a landfill can require the movement of hundreds of tons of earth to mine fresh sources of metal to replace the metal lost in WEEE. The only real solution to combat these impacts is recycling.

1.3 Recycling of electronic waste

Recycling of WEEE is of ultimate importance because it has the potential to offset a majority of the health, social, and environmental impacts associated with WEEE and their disposal. More recently, recycling of WEEE is being framed in the context of "urban mining" wherein the devices are considered deposits of highly enriched metals ripe for recovery, reprocessing, and reintroduction into the supply chain. [20] This paradigm is part of a larger vision for a "circular economy" that seeks to realize "zero waste" by perpetual reuse of materials through innovative recycling technologies, control of primary consumption, and rational and effective waste management policies. In essence, the circular economy seeks to maintain products in a usable state for longer while also using more secondary materials in the production cycle. WEEE is critical to this vision because it contains such a high fraction of many of the metals used in everyday life. A smart phone in the circular economy would be originally manufactured from recycled metals and materials and, when its useful life has ended, would be demanufactured and recycled entirely into a new device of equal or greater value. This is also referred to as "closed loop" manufacturing. [21]

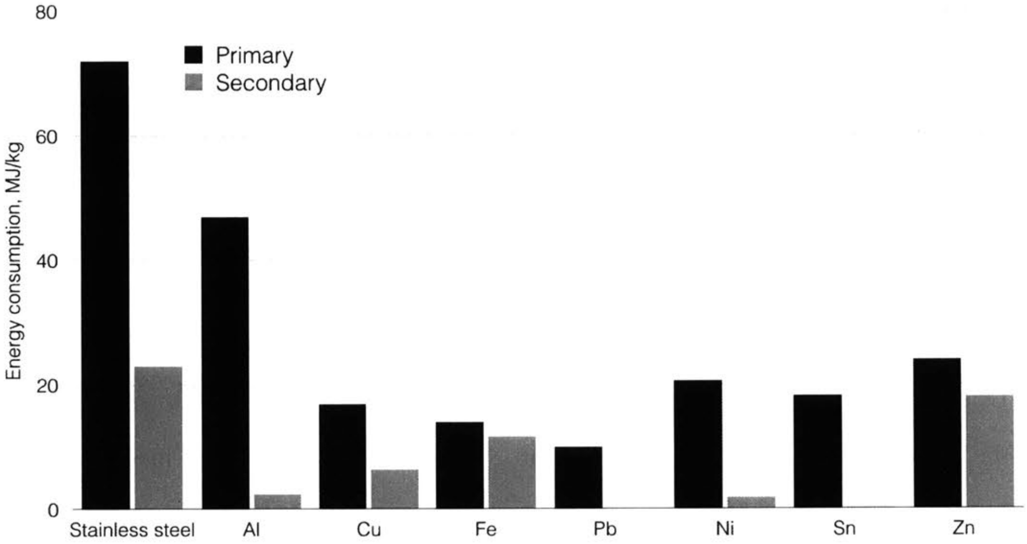
Recycling of WEEE, therefore, is also part of the conversation around sustainability. All of the critical components in modern electronics are fashioned from non-renewable materials. By definition, society does not have an inexhaustible source for this materials. (While it is unlikely that society will run out of many, if any, of these materials within the next few generations, a responsible society will seek to find solutions to this problem before the problem arises.) As Jay and Gerard outlined in their overview of what sustainability means in a modern context, recycling can be framed as a critical component to enabling implementation of sustainable strategies at all levels of the economy and society. [22] One of the most important benefits of using recycled materials (*i.e.* closing the loop to some extent) is the mitigation of environmental impacts associated with the production of new products from virgin materials. [6, 21, 23]

The beauty of metals is that they can essentially be recycled endlessly. To some extent, once a metal is incorporated into a certain use-case it is unlikely to be recycled into other use-cases. For example, many of the alloying elements in steels will never be isolated from scrap steel for recycling to other, potentially purer, applications. Instead, those alloying elements will remain in steel when the scrap steel that contains them is recycled. In general, though, metals can see endless use and reuse cycles as long as they are recycled appropriately. [24] To this end, it is important to understand the value-cycle of recycling: metals can be recycled to the same value applications, higher value applications (so-called "upcycling"), or lower value applications (so-called "down-cycling"). Every time a tonne metal is recycled that is a tonne of metal that does not have to be produced from primary sources. And because of process inefficiencies and the nature of ores that host metals, one tonne of recycled metal can actually offset the use of tens, hundreds, or even thousands of tonnes of raw materials.

Figure 1-2 shows how the energy associated with the production of virgin metals (*i.e.* metals from their ores) exceeds the energy associated with the production of secondary metals from scrap and recycled sources. The energy associated with steel production, for example, can be nearly 70% less [25]; it can be up to 90% less for aluminum. Similar trends are seen in comparing the carbon intensity of primary production processes compared to secondary production processes. [26] This large difference is driven in part by the fact that the metals found in WEEE are already highly refined and therefore require minimal reprocessing, avoiding many of the energy intensive steps associated with primary production. Additionally the concentration of metals in WEEE is often orders of magnitude higher than the concentrations of those metals in their natural ores. [4] It should be noted that some of the difference between the energy consumption associated with primary and secondary metal production can look artificially high due to the way in which the energy share in a process is allocated between final products. [27] However, these differences are fairly minor relative to the highly refined nature of scrap and the high concentrations of metals in scrap products.

As illustrated when framing the enormity of the challenge around WEEE, it is clear that implementation of recycling strategies is an uphill battle. With only approximately 20% of all WEEE entering the recycling pipeline (and even less than that actually being recycled entirely), the circular economy and closed loop manufacturing are far from realization. However, much of the basic infrastructure is in place. Additionally, society is beginning to push for these initiatives. Within the last few decades, since recycling was first made mainstream in the late twentieth century, American society has pushed for organic and local farming, hybrid and electric vehicles, high efficiency appliances, socially and environmentally responsible business practices, and many more initiatives reflective of a more sustainability-minded public. It is likely only a matter of time before the same consumer who cares about where

Figure 1-2: Energy consumption associated with production of primary versus secondary metals [26]



his beef was raised cares about the materials that went into manufacturing his smart phone (see, for example, the Fairphone). To this end, a 2014 Harris poll found that 86% of Americans wished manufacturers designed products for easier recycling. [10] This sentiment seems to suggest that, at least at a conceptual level, people are beginning to see the importance of recycling and how it can be part of a more sustainable society. Therefore, the time has come for a concerted effort to improve recycling of WEEE so that society can realize a circular economy and lessen its impact on the environment.

1.4 Legislative action taken to date

Before outlining some of the reasons that recycling is not taking place at higher rates, and the types of business strategies and government policies that could improve the effectiveness of WEEE recycling, it is important to understand the legislative landscape in the United States as it exists today. Unfortunately, the United States is woefully behind the European Union in implementing far reaching legislation to regulate WEEE and its industries. The European Union has implemented Directive 2002/92/EC and the RoHS Directive 2002/95/EC to restrict the use of hazardous substances in electronic devices, Directive 2002/96/EC to promote collection and recycling, and EuP Directive 2005/32/EC to set frameworks for eco-design. [6, 28] A critical component to the efforts of the European Union has been to create Extended Producer Responsibility (EPR) programs (covered under Directive 2002/96/EC) that make the producers of electronic devices ultimately responsible for their recycling at EOL. As a result of these programs, producers have been encouraged to improve overall collection of EOL devices and to make their recycling easier through eco-friendly design (Design for Environment, Design for Recycling, Design for Demanufacturing, etc.). [29] Through these legislative actions, the European Union has seen steady improvements in recycling metrics and has served as the model that other countries (including Japan, Canada, South Korea, and Taiwan) have followed when they have sought to implement their own strategies.

Many American companies have followed the direction of the European Union under the realization that since they compete in a global market it is best to comply with (or exceed the compliance standards of) the strictest regulations available. Greenpeace publishes a report that outlines the efforts of electronics companies to come into compliance. [30] It is encouraging to see that many companies have made great strides at eliminating materials banned under the RoHS Directive along with taking steps to "green" their operations.

Some authors have highlighted American legislation (or lack thereof) as being the lynchpin to realizing improved domestic recycling rates. [28] In the United States WEEE regulation is essentially a patchwork of laws implemented at the state level regulating various segments of the WEEE industry. For example, cathode ray tubes were banned from landfills in Massachusetts in 2000, California in 2001, and later in Maine and Minnesota. [4] California enacted its own EPR program titled the "California Electronics Waste Recycling Act" in 2003 wherein manufacturers had to collect 90% of the number of devices they sold or pay a fee. California also has an "advanced recovery fee," that requires a manufacturer to pay a few dollars to the state for each product sold, in what is essentially a tax on the size of electronics products covered by the program. [31]) The income from this fee is then used to incentivize higher recycling rates (on a per pound basis) of recyclers in the state. At the time that California's original law was implemented the collection rate was estimated to be around 9%. [4] At present twenty-five states and the District of Columbia has some sort of WEEE law. At the federal level, the only major legislation that has been enacted concerns lead-containing devices and the disposal of cathode ray tubes. [32] These laws were all passed between 2003 and 2014. The majority of the laws passed at the state level established EPR-type programs to increase the recycling rates of WEEE. The Electronics Recycling Coordination Clearinghouse maintains a useful list and plain-English description of the laws currently in effect and under review across the United States. [32] However, lack of federal leadership has lead to disjointed and inconsistent regulation nationally.

Of course, one can argue whether the lack of political guidance and government oversight is a boon or hinderance to the WEEE industry. There are many instances where regulation has encouraged positive, sustainable behavior. However, there are also many instances where it has stifled innovation. Therefore, the regulatory environment in the United States must be judged for what it is with the understanding of the global context within which it exists. Whether or not federal oversight is needed is as much a political question as it is a policy one.

1.5 Goals for this thesis

Bearing in mind the current condition of the WEEE and WEEE recycling industries in the United States, this thesis will examine these industries as a System of Systems (SoS) in a broader recycling ecosystem. In so doing, this work will develop a more complete understanding of the flow of WEEE through the economy and how it interacts with major stakeholders. The ecosystem will be decomposed into architectural components to outline the challenges facing each component system and how these challenges could become opportunities. As previously stated, this thesis will focus specifically on the management of EOL smartphones. These devices represent a rapidly growing segment of the WEEE stream and they are ubiquitous in all of the developed and most of the developing worlds. The shear volume of EOL smartphones represents a literal mountain of materials that, if recovered, could be a major step towards developing more sustainable options for industry. Finally, because they are small and have relatively short lifespans, the management of EOL smartphones is much more difficult that other larger types of WEEE. While this work will focus on smartphones, the conclusions drawn here could be abstracted to apply more generally to the WEEE recycling industries at large; "smartphones" could be replaced with "WEEE" fairly simply in the following analysis.

This work will first develop a more complete understanding of the component systems in the ecosystem in Chapter 2. Chapter 3 will quantify the flow of WEEE in the United States. A more nuanced understanding of stakeholder value and the challenges facing each system will be outlined in Chapters 4 through 6. Chapters 7 and 8 will provide a more holistic view of the ecosystem to identify intersystem opportunities to implementing an improved recycling industry.

Ultimately, this thesis seeks to guide the WEEE recycling industry to more sustainable ground in the hopes of one day realizing its potential as part of a circular economy.

Chapter 2

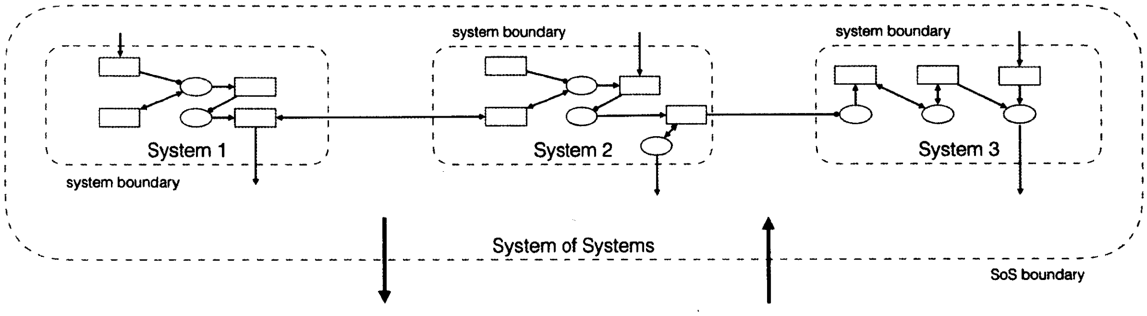
Electronic waste recycling as an ecosystem

2.1 Ecosystems and Systems of Systems

A system, in the setting of systems thinking, is a "set of entities and their relationships, whose functionality is greater than the sum of their individual parts." [33] This definition can be parsed to illustrate that a system is really two things: it is made up of, is comprised of, or contains things (forms and functions); and the interrelations of forms and functions yield processes that, taken together, yield something greater, or different from, the individual forms and functions. Extending this definition out of abstraction, it is fairly easy to frame any engineering problem, be it social, technical, or economic, as a system.

An ecosystem, then, or a "System of Systems (SoS)," is a collection of systems. [34] An engineering ecosystem is a group of systems that interact with each other in such a way as to deliver even greater functionality. A key characteristic of an ecosystem is that each individual component system is a system in its own right: it can (and sometimes does) exist on its own, decomposing it would yield levels of hierarchy in form and function, and its component forms and functions yield greater value than they would on their own. The ecosystem, then, creates an opportunity for different systems to interact in such a way that through their interaction they can create new value (Fig. 2-1). In the complex world of today, the majority of systems are actually ecosystems: individual systems working closely together to deliver value to stakeholders and beneficiaries. Viewed through this lens, the recycling system to handle WEEE is an ecosystem. As will be illustrated in more detail below, the manner in which WEEE is collected, pre-processed, and ultimately end-processed all to mitigate environmental harm, return value to stakeholders, and close the loop on supply chains is a delicate interaction between individual systems that accomplish a limited subset of the goals of the overall system. Each component system would exist on its own; but the greater value is realized when interactions occur across component system boundaries in such a way that operands (*i.e.* WEEE components or material streams) are passed from one stakeholder in one system to another in another component system who performs different functions via different processes.

Figure 2-1: Generic System of Systems



Of course, the relevant question is "why is it useful to think of WEEE recycling as an ecosystem?" Where is the value in framing such a social, technical, and economical challenge in the vernacular of Systems of Systems thinking? The benefit lies in the tools of systems thinking: principally, system architecture, system engineering, and system project management. Instead of viewing the WEEE recycling ecosystem as a tangled mess of companies, consumers, and EOL devices, system thinking challenges the viewer to decompose the interactions of component systems for deeper analysis. System thinking empowers the practitioner to understand existing systems and imagine the outcomes that might arise from changes to the existing system. [33] Furthermore, a systems thinking approach to understanding WEEE recycling can help manage much of the complexity (and apparent complexity) that emerges from the different stakeholders and interactions between component systems.

Thus, the first step in understanding the WEEE recycling ecosystem is to decompose the ecosystem into its component systems. As already alluded to above, WEEE recycling occurs in three main stages: collection, pre-processing, and end-processing. [4, 6, 17, 35, 36] In general terms, each stage exists as an independent system. In some cases the individual systems share stakeholders, needs, goals, and operands. But for the purposes of this analysis, each stage of WEEE recycling will be considered a component system to the larger ecosystem. After decomposing the ecosystem into its component systems a stakeholder value network will reframe this analysis in terms of how different entities derive value from the current state.

2.1.1 Collection

Collection is the first step in the EOL supply chain for WEEE. (While the goal of any business system is to generate profit, the analysis presented here will examine the functional goals of the recycling ecosystem as to how they generate profits.) The ultimate goal of this system, which can be presented in the "to-by-using" framework [33], is

to	move EOL devices from the hands of consumers to the hands of qualified recyclers
by	facilitating easy collection services
using	the infrastructure systems of various system stakeholders.

The real fuzziness of this goal arises from the *using* clause. There are essentially five methods to perform collection: curbside pickup (like normal municipal waste services in most communities), dedicated collection sites, retailer-organized pick-up, one-off collection events, and pre-paid postage services. [6] With this list, it is clear that there are many different potential stakeholders involved. Curbside pickup would be operated by municipal governments. Dedicated collection sites could be operated by any number of entities (municipalities, retailers, producers, non-governmental organizations, etc.). Retailer-organized pick-up services could be operated by electronics wholesalers (*e.g.* producers as in the EPR model) or by retailers (*e.g.* Best Buy, Target, or Walmart). One-off events could be operated by any number of government or private organizations. Finally, pre-paid postage services could be operated under the EPR model and thus run by device producers or by other organizations.

In the context of smart phones, collection typically involves an individual consumer giving his or her device to a collection agency (through one of the five different models outlined above). In this sense, collection is a social challenge because it involves controlling consumer behavior and affecting consumer choices. A component to the goal of the collection system is convincing consumers to actually turn in WEEE for recycling. As will be described in more detail below, collection is the single most difficult part of the entire EOL supply chain. Collection is plagued by high logistics costs, regulatory uncertainty and burden, and competing interests from different stakeholders. Of course, the real goal of the collection system is to generate a profit. So one goals of the ecosystem architect must be to ensure that a profit can be generated while also ensuring that consumers do not simply throw their WEEE in the trash where it eventually ends up in a landfill. But if collection services do not interface delicately with the pre-processing system, the collection system can simply become a conduit to landfills in its own right.

It is worth arguing that the collection system is truly a component system to the recycling ecosystem. Principally, the collection system could exist on its own; it is a complete system capable of existing without the broader recycling ecosystem. However, its functionality is greatly improved in the presence of it parent ecosystem. As is shown in a stakeholder analysis, the entities that are part of the collection system can generate value without stakeholders who interface with the pre-processing system. However, that value is improved through this interaction. In the absence of the ecosystem, "collectors" can create financial value by refurbishing WEEE devices to second-hand users; they can also create value by bundling WEEE and selling to landfills wholesale who value a waste stream that is free of toxic or hazardous materials. Social value is also created as consumers feel that they have "done their part" by giving their devices to someone claiming to "do the right thing." All of these effects though are amplified to greater value if the next step in the supply chain is pre-processing.

2.1.2 Pre-processing

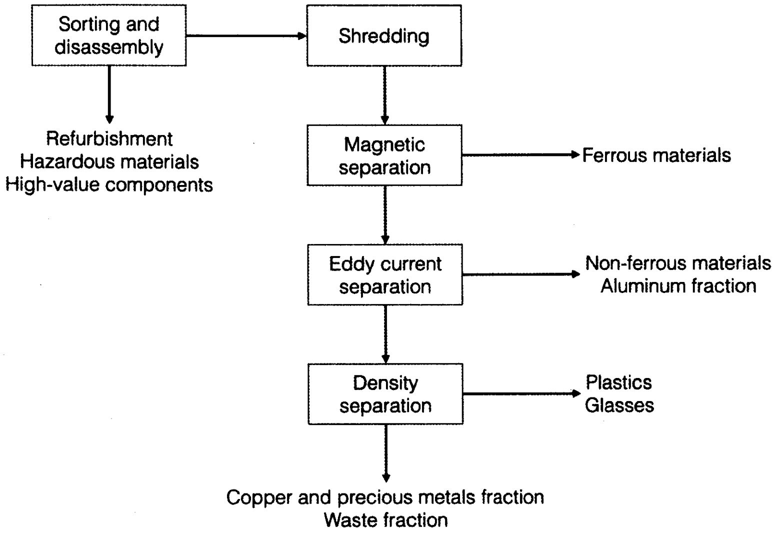
Pre-processing is the second step in the EOL supply chain. Whereas collection was largely a social challenge, pre-processsing is a technical challenge. The goal of this system is

to generate maximum value from WEEE
by identifying and isolating subcomponents of WEEE for some sort of further processing
using demanufacturing and refurbishing techniques.

Pre-processing is the stage wherein WEEE smart phones stop looking like smart phones. It is essentially a six step process. [6] The challenge, though, lies is performing these functions at minimal cost so as to still yield profit during pre-processing. The main drivers of revenue in this system are the ability to sell refurbished devices and the ability to sell high value scrap to end-processing. Any reduction in quality (or purity) of either one of these streams significantly hinders profitability. Therein lies the technical challenge.

In the first step, WEEE smart phones are sorted; those devices that are still functional (but perhaps no longer "trendy") are identified for refurbishment or harvesting of still functional components (*e.g.* batteries, computer chips, and logic boards). During sorting the major hazardous components are removed. In smart phones, this involves removing the battery without starting a fire. Though most smart phone manufacturers have already phased out these materials, this can also involve removing components known to be high in lead or heavy metals; in the past this might have

Figure 2-2: The pre-processing system flow sheet



involved soldered components, screens, or batteries. Additionally, components that are known to have high intrinsic value (due to their high precious metals content) are isolated before shredding to minimize losses during downstream processing. [14]

In the second step, the remaining material is shredded. This is performed mainly to facilitate easier separation of different components by their chemical or physical properties and to liberate small components. The trade-off during shredding is that while it will make downstream processing easier it also has the potential to inflict significant losses. It has been estimated that as much as 50% of the precious metals content in WEEE can be lost during shredding operations. [14] These materials are typically lost to dusting (and thus the environment), or to other material streams from which the precious metals cannot be recovered due to incomplete liberation during shredding (this will be discussed below). This is the primary motivation for removing as much of the precious metals-bearing content and components before shredding. In some cases, because smart phones are known to be relatively high in precious metals, they skip the shredding and many other downstream steps entirely, passing directly to end-processing.

After shredding, the stream undergoes several separation steps that seek to take advantage of the different properties of the component materials to isolate homogenous streams for dedicated, material-specific end-processing. Typically the material undergoes a magnetic separation to remove ferrous components that can be further processed by steel producers. Next, eddy current separation is used, primarily to remove non-ferrous metals (namely aluminum) that can be processed by other metal producing operations. Next, a density separation is performed either by air classification—an energy intensive but relatively "clean" process—or by dense media—a simple but "dirty" operation—to separate different plastic fractions and glass fractions from a copper and precious metals fraction. To some extent, sorting has been automated through the use of magnets and scanning technologies. However, especially where labor is cheap, a significant fraction of the sorting work involves manual labor.

Finally, the last step involves sourcing destinations for the different streams generated in the sorting steps. Often this involves disposal of a significant fraction of material in landfills if a taker cannot be identified. However, for fractions that can be sold to end-processors, the next step involves recovery of materials into resalable "secondary" materials.

Just as with the collection system, the pre-processing system could exist on its own. It also generates refurbished devices that could drive the profitability of its business. Additionally, it generates relatively homogenous output streams that are useful to other stakehoders as feed material for their operations. The majority of "recycling" companies one finds on the internet are actually pre-processors: they will take WEEE, perform some level of demanufacturing and sorting and route these materials to other entities. These operations turn a tidy profit for the pre-processors. In this sense, though, they are part of the larger ecosystem. It can be misleading to the average consumer who thinks "I gave my old cell phone to a recycler, that's good enough, right?" In reality, though, it is critical to question what the pre-processor does with the homogenous output streams they generate. The best option, from a sustainability point-of-view, is that the pre-processor routes these materials to an end-processor who is equipped to handle these materials responsibly and efficiently. Otherwise the pre-processor functioning as a recycler is simply spending energy (and thus polluting) before dumping material in either resource sinks that do not maximize reuse or, worse still, in landfills.

2.1.3 End-processing

End-processing is the final step in the EOL supply chain and the point at which the loop has the potential be closed. In this sense, end-processing is the stage at which WEEE can be turned into material that can be reintegrated with the supply chain. The outputs of end-processing are typically identified as "secondary" materials to differentiate them from "primary" materials that are generated from virgin sources (*i.e.* raw materials like ore or petroleum products). [23] The goal of end-processing is

to	generate high purity, homogeneous output streams for integration into value-added products
by	liberating materials of value from host materials
using	metallurgical extraction techniques.

At the crux of this goal is the *using* statement: the only methods available at scale today to generate usable secondary materials from WEEE are metallurgical techniques. As a result, there are only a handful of organizations performing true end-processing at any appreciable scale. This significantly limits the flexibility of this system to adapt to challenges presented by newer generations of smart phones.

Metallurgical processing techniques can be abstracted into two categories: hydrometallurgy and pyrometallurgy. The former techniques involve low temperature, water-based processes. Currently only a small subset of WEEE is processed using hydrometallurgical techniques and is largely inconsequential. However, many have argued that hydrometallurgy represents the best future state of WEEE processing as hydrometallurgy has the potential to have lower environmental impact than pyrometallurgical techniques. [35, 36] At present, though, hydrometallurgical techniques are usually too expensive for large scale deployment do to the extremely slow chemical kinetics and complex purification processes required. Pyrometallurgical techniques involve high temperature treatment of materials to produce high purity streams of individual metals or alloys. These processes are the traditional methods to produce metals from ores.

The most consequential pyrometallurgical process in WEEE end-processing is the copper smelting process. As already discussed, the major value drivers in WEEE are the precious metals and copper content. These metals are most effectively recovered from WEEE streams through copper pyrometallurgy. The other streams generated during pre-processing—namely, plastics, aluminum, and ferrous fractions—are relatively inconsequential from a value perspective. However, their treatment will be discussed briefly below. During copper-based processing of WEEE, the copper- and precious metals-bearing fractions of WEEE are mixed with virgin ore and/or other copper scrap for refining. Copper pyrometallurgy is a multistep process targeted at liberating copper from sulfide ores. [14, 37]

In the first step copper sulfide ores are smelted to produce a copper matte. This copper matte is then refined to copper oxide or blister copper. This material is then deoxidized through fire refining to produce anode copper. These processes are performed at high temperatures wherein the copper is melted to a liquid state and reduced to metallic copper while successively upgrading its purity from *ca.* 20–30% to *ca.* 99–99.5%. WEEE materials can be added to the copper refining process at any point in the flow sheet. However, in most cases, WEEE that is particularly high in precious metals is added at the final step during fire refining (performed in an anode furnace) to minimize potential losses of precious metals. During copper refining the precious metals are soluble in the copper phase and thus follow the copper metal through the process. The other metals that might be contained in the WEEE (*e.g.* iron and aluminum) report to the slag and are typically lost for processing. In some cases the slag is further processed in a lead smelting furnace to capture residual precious metals and special metals (*e.g.* indium, selenium and tin).

After fire refining, the copper anodes contain essentially all of the precious metal contents of the feed. The anodes are electrolytically refined in acid baths to produce high purity copper and separate the precious metals. During this step the copper is electrolytically dissolved and plated out into high purity (99.99%) copper cathodes. All other impurities report to the anode slime that contains precious metals and special metals. The anode slime is then further refined to isolate high purity streams of the precious metals. Typically gold, silver, and palladium are the only metals recovered from the slimes for economic reasons. The outputs of these processes—the copper, gold, silver, and palladium—are now at sufficient purity for reintroduction into the supply chain.

Other streams from pre-processing can be treated in other end-processing operations. Some plastics (namely thermoplastics) can be remelted into new products. [4] Thermoset plastics, though, cannot be remelted and are typically downcycled. Any plastics contained in metal-bearing fractions are burned as fuel and used as reducing agents in pyrometallurgical processes as they are essentially carbon. However, this is where the use of BFRs and PVCs is problematic as burning these materials produces dioxins as already discussed. The ferrous fraction from pre-processing can be used by steel producers to produce new steel. Steel producers must be cognizant of the other components contained in these ferrous fractions, though, as they need to carefully control the composition of their melts. If producing crude steel they are relatively unconcerned with the purity of the ferrous stream as most of the contaminants can be slagged out. However, if producing steel alloys, the purity is of utmost concern. From an energy conservation point-of-view, it is more sustainable to produce steel alloys from ferrous fractions as this avoids the energy associated with producing crude steel. This is not always practical though, due to purity problems. Likewise, the aluminum fraction can be directed to aluminum melt and casting shops provided the purity is in line with the aluminum alloys being produced.

The glass stream from pre-processing directed towards end-processing presents an interesting challenge. In most "smart glasses" used in smart phones today, the liquid crystal display contains trace amount of indium and tin in the indium tin oxide (ITO) conductive layer. Furthermore, the laminated layers of glass in the display are highly engineered products with significant value associated with them. However, the only commercially feasible way to process glass today is to grind it to cullet. [4] Because the cullet contains the ITO layer and other impurities introduced during post-processing, it cannot be recycled directly to new smart glass. Instead, glass from WEEE is typically downcycled either to commercial glass applications or to filler in the aggregate industries. [19] Today recycling glass in a truly closed-loop fashion remains one of the grand challenges associated with WEEE recycling. [38]

As a stand-alone system, end-processing is the most robust and independent system of the three systems outlined that are component to the recycling ecosystem. This is because the system that handles end-processing is actually the mining and metallurgical industry, which has existed long before recycling rose to prominence. The few copper smelters who do process WEEE process volumes on the order of 100,000–250,000 tonnes per year each. [39] Looking at the Umicore operations in Hoboken, Belgium, they process a reported 250,000 tonnes per year of WEEE, which constitutes 10% of their total processing capacity. [35] Other copper processors are likely in the same range. Viewed globally across the entire copper processing industry, though, WEEE likely makes up a minute percentage of total feed to the copper smelting industry (*ca.* 1%) as the combination of Umicore, Boliden, Aurubis, and Glencore make up 10-20% of total global copper production. Thus, WEEE does not drive the behavior of the metallurgical end-processing part of the recycling ecosystem. Only when end-processing is part of the larger ecosystem does real benefit start to emerge as the leverage of other systems is needed to affect any appreciable influence on the behavior of smelters.

2.1.4 Synthesizing the electronic waste ecosystem

Decomposing the EOL ecosystem into its component systems is a useful exercise to better understand the complexity associated with the larger SoS. However, any hope to improve the overall functioning of WEEE recycling (*i.e.* increasing the efficacy of recycling) must, at least to some degree, operate at the ecosystem level. A truly holistic solution must address the challenges associated with the individual component systems and how the subtleties that emerge from those systems manifest as the overall emergent functionality of the larger SoS. Having now mapped the forms and functions of the component systems it is necessary to provide a detailed analysis of the stakeholders of the larger ecosystem and how the interface at the system level.

2.2 Ecosystem stakeholders

Duygan and Meylan have presented a fairly comprehensive overview of the stakeholder network in the Swiss WEEE recycling industry. [5] Their analysis, though, seems to neglect the role that refurbishers play in WEEE management. They argue that refurbishment is essentially nonexistent in the Swiss economy; this may be true, but it is still important to understand how this stakeholder may or may not influence systemic behavior. In a similar fashion Chancerel *et al.* have presented a highly simplified stakeholder value network (SVN) that shows how information can be passed between different stakeholders. [13] This analysis, though, does not include the role that monetary or material flows have on the SVN. Lane has presented an analysis of the Australian WEEE recycling ecosystem and has highlighted the importance of understanding how individual stakeholders extract value from the interfaces in recycling networks. [40] Finally, Tanskanen presents a list of stakeholders without mapping the value flow between them. [6]

Bearing in mind the previous work done by these authors, it seems important to extend their analysis to a more complete decomposition of the stakeholder value network. A more explicit analysis that shows how various stakeholders interact with each component system has the power to show potential network effects that could be leveraged. The work presented in the literature has been limited to an analysis at the ecosystem level with fairly rudimentary mapping of value flow. The analysis presented below is hopefully more informative, inline with the work suggested by Jay and Gerard. [22] Furthermore, several authors have stressed the need for such a discussion, highlighting how a clarification of stakeholder needs and responsibilities may lead to more operational recommendations. [6, 16]

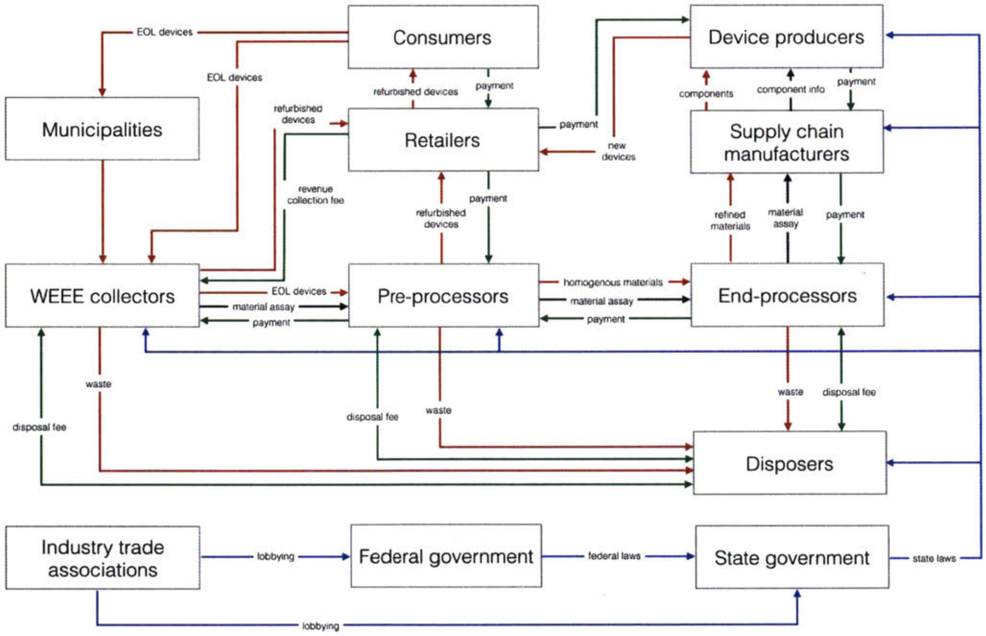
2.2.1 Stakeholder value network (SVN)

In order to build a complete SVN that captures the current state of the ecosystem, it is important to identify all of the pertinent stakeholders:

- Federal government
- Industry trade associations
- Retailers
- Pre-processors
- State government
- Device producers
- Consumers
- End-processors
- Municipalities
- Supply chain manufacturers
- Collectors
- Disposers

The SVN can then be built to show the value flow between these stakeholders. Figure 2-3 shows the current status of the WEEE recycling ecosystem in the United States. From this type of analysis it is possible to identify potential strengths, weaknesses, and opportunities in the system. This, in turn, can yield ways to improve it.

Figure 2-3: Stakeholder value network for the WEEE ecosystem in the United States; material (red), value (green), information (black), political influence (blue)



Beginning with a discussion of material flow, these value flows trace the movement of smart phones from device producers to retailers to consumers. The consumer then uses the devices during the "use" stage of the smart phone lifecycle. At the end of the "use" stage and the beginning of the "EOL" and "recycling" stage the consumer then decides whether or not to recycle the device. For the purpose of this analysis, material flow linking the consumer to the disposer has been neglected as this analysis assumes that the device is recycled. However, the consumer has the option of whether to give the WEEE to municipalities (through their collection infrastructure) or directly to WEEE collectors. Interestingly, there is no monetary or informational flow back to the consumer at this point in the ecosystem. This captures the fact that there are no real monetary incentives for consumers to recycle. Likewise, there is limited information (in the form of advertisement) that makes consumers aware of recycling opportunities.

At this point, the WEEE device is in the hands of WEEE collectors. Again, there is no monetary flow between the collectors and municipalities at this point as collectors make their money selling either refurbished devices back to retailers or scrap material to pre-processors. In some cases, though, WEEE collectors can make money by selling their collected WEEE to disposers if it can be used as a clean fill layer in landfills. This is a link that an improved system would seek to limit so as to divert the most WEEE to pre-processors as possible.

The WEEE then moves to pre-processors who perform the initial demanufacturing and sorting of WEEE components. Typically they will pay WEEE collectors a fee based on the volume of WEEE received. An informational flow connects these two stakeholders as the fee is predicated on the perceived value in the WEEE stream. At this point, pre-processors can divert WEEE to one of three other stakeholders. As already discussed, they may be able to refurbish devices not already captured by the collectors and sell them to retailers. Additionally, some subset of the sorted streams is likely of too little value for the pre-processors to continue handling; this material is then sold to disposers. Ideally, though, WEEE is passed down the supply chain to end-processors. As in the case with the relationship between collectors and pre-processors, information is passed between the pre- and end-processors to determine the value in the WEEE streams being moved.

The end-processors then perform their function by splitting the WEEE into two value streams: secondary raw materials than can be sold to supply chain manufacturers and waste material that is given to disposers. Information flow passes between the supply chain manufacturers as they need to know the purity of the material they are receiving. The monetary flow between end-processors and disposers can be bidirectional depending on the material being disposed of; some material may have value for the disposers if they can extract additional materials out of it. In this case, the disposers would be willing to pay the end-processors. Alternatively, the end-processors must pay the disposers.

The raw materials (*i.e* the purified metal streams from metallurgical processes) sold to the supply chain manufacturers can then be sold to the device manufacturers for production new devices using recycled material. This, of course, is an ideal realization of the closed-loop supply chain. It will be discussed later whether or not this is actually happening.

The flow of political influence is interesting. As already mentioned, there is no systematic legislation emanating from the federal government; the major laws governing WEEE in the United States flow from the state governments. Of course, these state governments are largely influenced by the actions taken overseas by government bodies like the European Union; these interactions, though, are not shown in SVN. However, the effect that industry trade associations can have on government regulation is shown. These organizations lobby on behalf of various stakeholders, including the collectors, pre-processors, and end-processors. However, the associations might also lobby on behalf of device producers or consumers. A classic example of an association lobbying on behalf of one group against another would be Greenpeace.

2.2.2 Stakeholder needs and requirements

One of the utilities that an SVN like Figure 2-3 provides is the ability to identify the needs and requirements of important stakeholders based on the value flow between stakeholders. One could argue that this exercise can (and should) be done before producing an SVN. [33] However, such an approach is probably most useful when designing a system from scratch; when the system already exists, it is useful to analyze how value flows first, and then determine whether or not that value flow matches with what one might perceive to be needs and requirements. In this analysis, the needs and requirements of the most important stakeholders will be discussed. In this context, then, it is important to ask "who are the most important stakeholders?"

In this discussion, the WEEE collectors, pre-processors, and end-processors will be considered the primary stakeholders. They are the entities in the ecosystem who have the potential to facilitate a truly closed-loop manufacturing cycle and the ability to scale WEEE recycling up or down. Additionally, the consumers are the ones who ultimately feed the EOL supply chain; thus, they are considered an important stakeholder. All other stakeholders, for the purpose of this analysis, will be considered to be of secondary importance. Their needs will be addressed tangential to those of the primary stakeholders.

Table 2.1: Needs and requirements of primary stakeholders in the WEEE recycling ecosystem

Collectors
Advertisements to customers
Revenue/profits
Collection infrastructure
Successful business plan
EOL material
Downstream takers
Effective technology
Pollution control technology
Transparency
Permits

Pre-processors
Collection infrastructure
Revenue/profits
Successful business plan
Effective technology
Pollution control technology
Transparency
Permits

End-processors
Revenue/profits
Successful business plan
Effective technology
Pollution control technology
Transparency
Permits

Consumers
Goods and services
Disposable income
Easy waste solutions
Knowledge of waste solutions
Environmental education

A critical need identified in Table 2.1 is revenue; this value flow is also shown in

Table 2.2: Needs and requirements of secondary stakeholders in the WEEE recycling ecosystem

Federal government
Safe environment
Complacent public
Efficient economy
Taxes/income

Municipalities
Safe environment
Complacent public
Efficient economy
Taxes/income
Efficient utilities and services

Device producers
Efficient supply chains
Access to cost effective raw materials
Transparent operations
Customers
High quality goods and services
Revenue/profits
Environmental impact assessment
Clarity of legal landscape
Understanding of customer needs/wants
Take back infrastructure

Retailers
Customers
Products to sell
Understanding of producer roadmap
Understanding of customer needs/wants
Take back infrastructure

State government
Safe environment
Complacent public
Efficient economy
Taxes/income

Industry trade associations
Influence
Results for industry partners
Support from industry partners

Supply chain manufacturers
Access to cost effective raw materials
Clear design mandates
Revenue/profits

Disposers
Access to land for disposal
Pollution control technology
Transparency
Effective technology
Community buy-in
Successful business plan

Figure 2-3. However, underpinning this need are the market conditions that dictate the value of WEEE and its component raw materials.

Figure 2-4: Historic gold prices, January 2000-March 2016

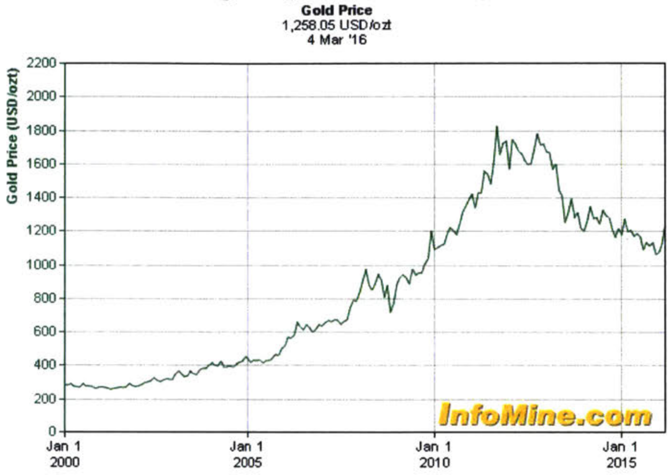
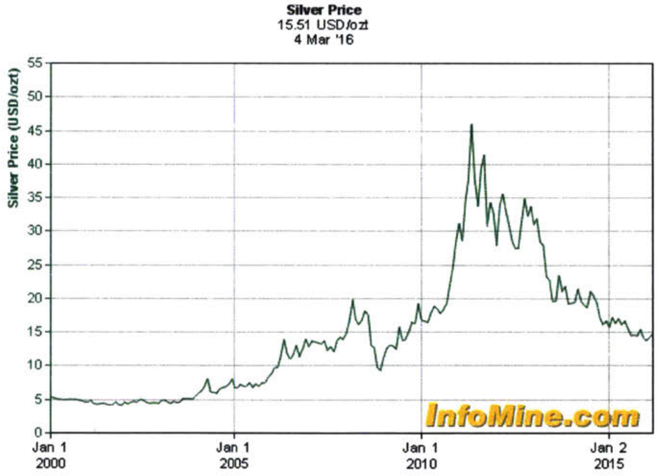


Figure 2-5: Historic silver prices, January 2000-March 2016



At present, most metal prices are at five- to ten-year lows, driven largely by oversupply on the commodity market and global economic downturn (Figures 2-4–2-7, prices from infomine.com as of 05 March 2016). As a result, the intrinsic value of WEEE is much lower than it was even five to six years ago. This, in turn, dramatically affects the prices that different stakeholders in the WEEE recycling ecosystems can charge to process material. These impacts have rippled through the ecosystem as

Figure 2-6: Historic palladium prices, January 2000-March 2016

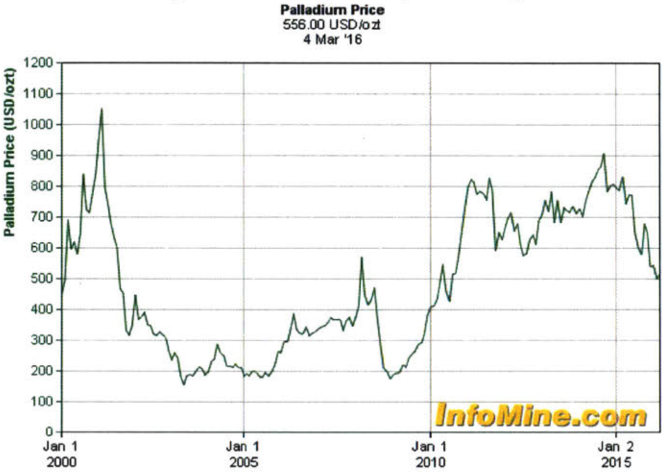
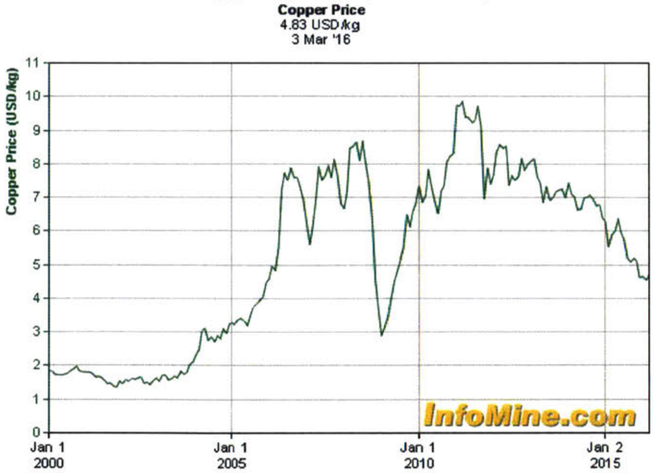


Figure 2-7: Historic copper prices, January 2000-March 2016



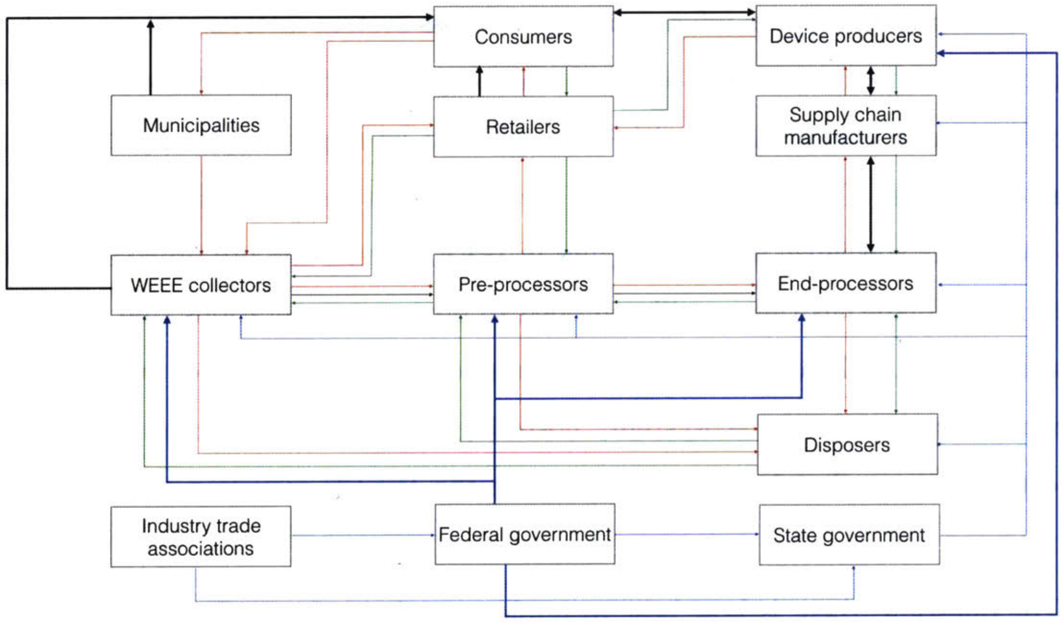
plans to expand processing capacity are stalled, legislation is shelved without an economic driver to support it, and industry momentum to encourage wider recycling efforts is slowed.

Of course, these same economic drivers also push the development of effective recycling technology, another need of all processors identified in Table 2.1. Innovative technology can be born out of economic pressure: the need to cut costs and operate more efficiently can drive new thinking and development of game-changing technologies. The stakeholder in need of the most innovative change is the end-processor. End-processors, though, are part of the wider mining and mineral processing industry, which is known for its extremely conservative and risk-averse pace to new technology implementation. [41] This translates to internal tension for end-processors who do not have the capital to invest in new technologies but are burdened by (relatively) outdated technology that makes it difficult, if not impossible, to process WEEE effectively. With some of the other stakeholders, though, like collectors and pre-processors they are less burdened by high capital costs to implement new technologies. As a result, new thinking in the WEEE ecosystem will likely stem from these stakeholders before it reaches the more entrenched end-processors.

Another interesting aspect of the needs identified in Table 2.1 is how some of the needs extend to other stakeholders beyond the primary ones. For example, generic needs like "transparency" and "environmental education" are only validated in a wider ecosystem context. That is to say, these needs cannot be met by this small subset of primary stakeholders. Processors need to be transparent to each other, consumers (*i.e.* the public), their downstream customers (*i.e.* supply chain manufacturers and device producers) and the government agencies who police them. This implies, then, that this type of information flow should manifest on an SVN as either direct connection between these stakeholders or higher order connections. As previously demonstrated in Figure 2-3, though, this is not always the case. Thus, this need may not be being met as the ecosystem exists today; there, then, is an opportunity for improvement: more clear communication and information flow between pertinent stakeholders.

Finally, it must be stated that the needs and requirements of stakeholders, both primary and secondary, are constantly evolving. The needs identified today are subject to the state of the ecosystem. For example, the legislative landscape in the United States might dictate the flow of certain information between particular stakeholders. A change in that landscape would require different (hopefully better) information transfer. Alternatively, changing sentiments from consumers or device producers—like an increasing sensitivity to the environmental impact of their actions (see Table 2.2)—could make the priority of different information or material flows change. Thus, those responsible for the architecture of the WEEE ecosystem must be cognizant of these dynamics. In turn, the WEEE ecosystem must be as robust as possible to either impulse changes (*e.g.* sudden changes in commodity prices), step changes (*e.g.* introduction of new legislation), or ramp changes (*e.g.* evolving consumer sentiments).

Figure 2-8: Revised stakeholder value network for the WEEE ecosystem in the United States; material (red), value (green), information (black), political influence (blue)



A reimagining of the stakeholder value network is presented in Figure 2-8. In this analysis the new value flows have been shown with greater weight. The added flow are all of either information or political type. With the latter type of value flow, this does not necessarily imply a greater level of legislation or government regulation.

Rather, it simply calls for better clarity and predictability in the American legislative landscape. With regard to information flow, one of the key drivers to improvement will be more bidirectional flow of information. For example, flow of information between consumers and device producers should go both ways: device producers can make more concerted efforts to inform their consumers of the steps they are taking in the WEEE ecosystem and consumers should be given louder voice to express their own sentiments. (Of course, this latter thought should be made simple through social media.) Information flow between device producers, their supply chain, and end-processors should focus on their evolving list of priorities. For example, if device producers are serious about closing the loop on their supply chains, these goals should be communicated to their supply chains, who can then pass this information on to end-processors. In turn, end-processors can pass information along the same conduits with regards to the challenges associated with realizing this goal.

While Figure 2-8 shows information flow across system interfaces there must also be increased information flow within each component system. For example, end-processors must communicate with each other to leverage unique capabilities that each refinery has if maximum material recovery is to be achieved. Likewise, many pre-processors specialize in certain types of WEEE; thus, one pre-processor must be able to send materials they are ill-equipped to process to operations that can handle those materials. These information and value exchanges all happen within a given component system in the ecosystem. Fostering this increased communication is an important change that is necessary to make the WEEE recycling ecosystem more effective.

The question, then, is how best to implement these changes? It is one thing to draw them concisely on an SVN. The first step to realizing any sort of change must be recognizing its need and who is affected; this is accomplished through decomposition of architectures and mapping. But beyond this, it is largely up to the ecosystem stakeholders to embrace the opportunity. The remainder of this thesis will first develop a more data-driven overview of the status of the WEEE ecosystem: where are the major gaps or holes in the ecosystem that, if closed, could have outsized impact on steps towards a more efficient future state. Additionally, what are some of the specific challenges facing the primary stakeholders; are they social, environmental, economic, or some combination of those? Finally, are there sweeping recommendations that have relatively simple implementation with outcomes that can have multiplicative improvement effects?

Chapter 3

Flow of electronic waste in the United States

This chapter will focus on the visualization of WEEE flows using Sankey diagrams. Sankey diagrams date back to the late 1800s when they were used to visualize the flow of material or energy. Perhaps the first use was by Charles Minard in 1869 to visualize the movement of Napolean's army through Russia in 1812. [42] The diagrams are actually named for Matthew Henry Phineas Riall Sankey, an Irish engineer who used the diagram in 1898 to visualize a steam engine cycle. In a Sankey diagram the width of a flow arrow indicates the quantity associated with the vector. As a result, Sankey diagrams are useful for showing multiple dimensions of data. [42]

3.1 Previous work quantifying material flow

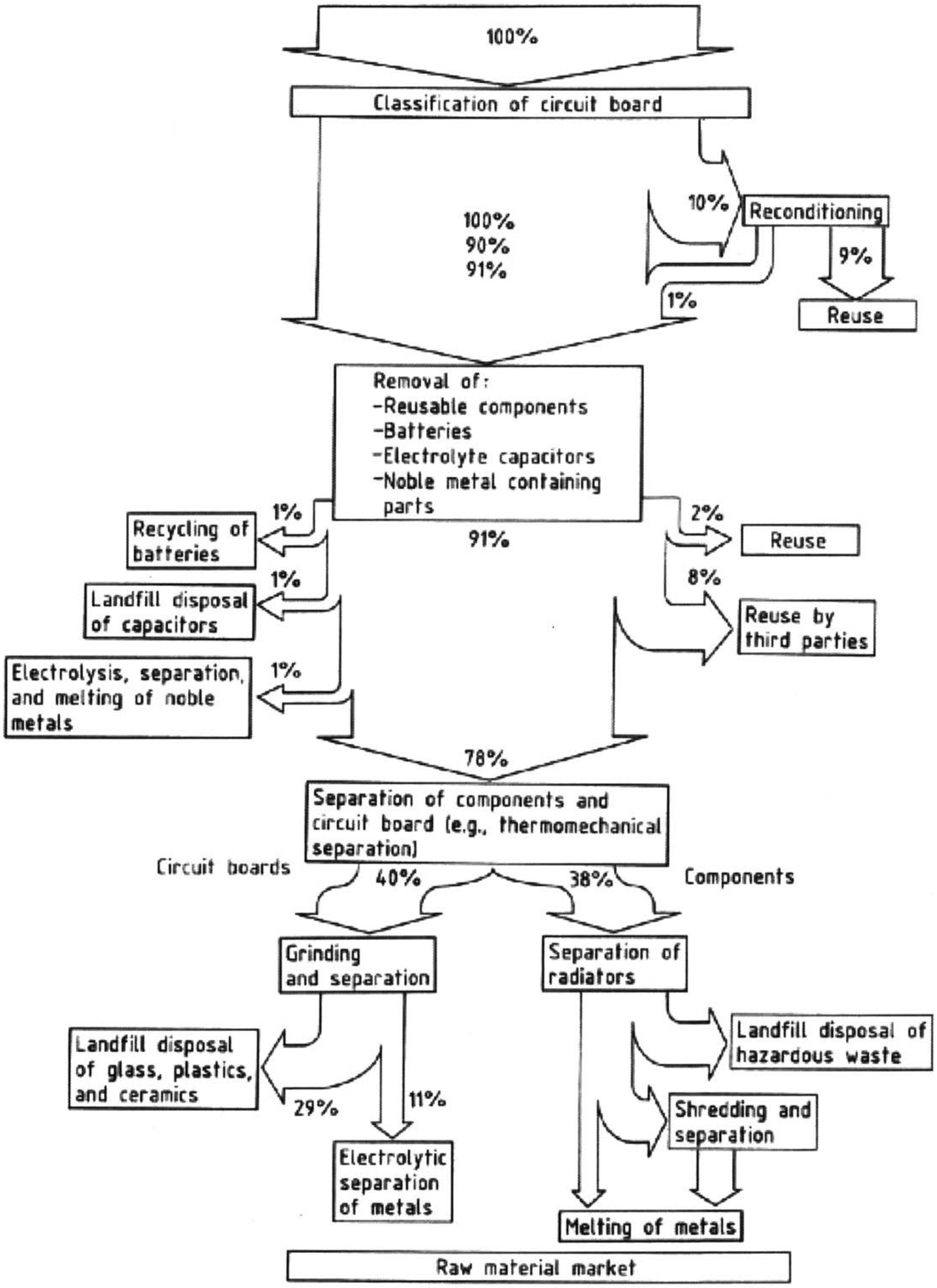
There has been some focus in the literature on trying to quantify (in both mass and value) the flow of WEEE through different economies. Interestingly, most of the focus has been on European countries and developing countries. This focus likely stems from two sources. First, given the extensive regulation in Europe, there is relatively robust data available about WEEE. However, these data only go so far and the majority of the reported mass flow analyses (MFA) and other quantifications draw on significant assumptions. Some of these studies will be discussed below. The second focus of WEEE flow has been on developing countries and their economies. This seems to be an interesting fixation of the literature: quantifying the flow of WEEE through economies with essentially no WEEE recycling infrastructure. The motivation of the authors seems to be a concerted effort to raise the importance of this issue. However, given the extreme lack of hard data, the studies focusing on these parts of the world are difficult to trust.

There have only been a few studies focusing on the flow of WEEE in the United States. [4, 15, 43, 44] Critically, though, these studies are all relatively old. In the intervening years between the publication of these studies and today, the dynamics of the WEEE ecosystem have changed: there has been increasing interest in WEEE, mobile devices have changed dramatically, and the economic situation (namely the price of metals) has shifted. The analysis presented here will attempt to highlight the disparity between available data, its publication date, and the likely status of the ecosystem today.

3.1.1 The flow of electronic waste in the 1990s

Some of the earliest published data on WEEE recycling was published in Europe in the early 1990s. [45] The works cited in Ullmann's Encyclopedia include many studies about WEEE recycling, though their major focus was on the pyrometallurgy of circuit board processing. Interestingly, the work includes a Sankey diagram from 1993 detailing circuit board processing in Germany. Figure 3-1 essentially maps the flow of WEEE (specifically circuit boards) from pre-processing to end-processing. This analysis, therefore, fails to capture the important point that the overwhelming majority of WEEE never actually enters the pre-processing step of the WEEE ecosystem because it is not collected. This analysis also seems to indicate that there are no material losses during pre- and end-processing. Many more recently published works indicate that a significant fraction of material is lost during pre-processing and thus not recovered in the final secondary metal products. Instead, Figure 3-1 focuses on the landfilling of hazardous components without capturing the realities of fugitive dust losses. Additionally, the flow of materials after "melting of metals" and "electrolytic

Figure 3-1: Flow of WEEE *ca.* 1993 [45]

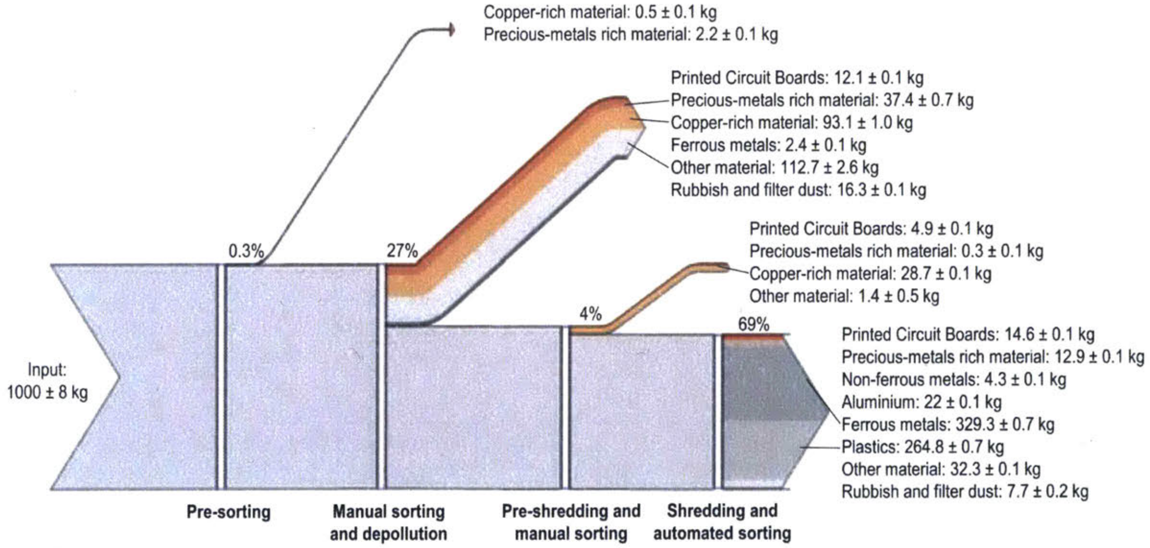


separation of metals" seems to be a black box; more granularity and detail in more recent analyses is available. Interestingly, though, comparing the process presented in 1993 to the modern WEEE ecosystem reveals little difference. The ecosystem to handle WEEE has not changed since the early 1990s and the outlook for evolution soon is bleak.

3.1.2 Recent studies of electronic waste flow

As previously discussed the majority of research outlining the flow of WEEE have been performed on flows in the European markets. Chancerel and her colleagues have done very impressive work quantifying to extremely high levels of detail the flow of precious metals from WEEE in pre-processing. [13] In this work Chancerel *et al.* drew on literature detailing European material flows to determine how different metal fractions partitioned in each step of WEEE recycling from "pre-sorting" to "shredding and automated sorting" (Fig. 3-2). This work was further corroborated by test work in a WEEE processing facility. These data allowed the authors to develop the general flow model shown in Figure 3-2 while also developing metal-specific Sankey diagrams

Figure 3-2: Flow of materials during pre-processing [13]



for gold, silver, and palladium (see page 801 in [13]). Based on this analysis, given that the data were verified against "world class" WEEE recycling operational data, one can assume that similar partitioning would be observed in the United States for pre-processing.

However, the data in [13] do not include the collection and end-processing steps of the WEEE ecosystem. Figure 3-2 demonstrates that there are fairly significant losses during WEEE pre-processing (the upward flows accounting for 31.3% of the initial input), but it fails to capture the quantity of losses incurred up- or downstream of this intermediate step. The data from [13] demonstrate that there are losses on the order of 30% experienced during pre-processing, mainly due to fallout associated with manual processing and depollution. Interestingly, a significant amount of precious metals and copper are lost during this step; as was already discussed, these metals drive the value of the WEEE streams in smart phones. Chancerel *et al.* state that overall recovery of copper, silver, gold, and palladium are only 60%, 11.5%, 25.6%, and 25.6%, respectively. [13]

In the broader context, though, these recoveries will be even worse. One has to consider the collection efficiency that feeds the pre-processing stages and the losses associated with this upstream step when EOL devices do not enter a robust WEEE recycling system. Furthermore, the material that is recovered during pre-processing is still subject to end-processing where additional losses will be incurred during metallurgical refining steps. (Typically, though, the losses during this final system are significantly lower than those experienced in the two upstream systems.)

The data presented by Chancerel *et al.* in [13] are similar to the data presented elsewhere in the literature when visualizing material flows: mass flow of generic WEEE. This is useful because it allows for simple accounting through a mass balance: the mass that goes into a given system must go somewhere thanks to the First Law of Thermodynamics. However, it can be difficult to interpret just what these flows mean. For example, a flow stream with significant mass could jump off the page by having a very thick arrow in one of the Sankey diagrams. But that flow might be very low value because it is steel scrap. Conversely, though, a very low mass flow could be extremely high value if it is precious metals-bearing. In the same vein, low density materials like plastics can be important components of WEEE to consider where their low mass but high volume could be misleading as to the logistical challenges associated with processing enormous volumes (but low masses) of waste plastic.

There are alternative means to present the data to address some of these issues. One option is to present the data strictly in valorized terms based on the commodity value of given components in the flow stream. This brings attention to the importance of losses on the free market: losing a high value stream will be more obvious. However, the value of the commodities in WEEE change daily as commodity prices fluctuate globally. Additionally, it can be difficult to assign value to WEEE at various stages of disassembly. For example, it is relatively easy to determine the monetary value of the raw materials (metals, plastics, glasses, and composites) in a smart phone. However, how should one assign value to a whole printed circuit board that could either be sold as an whole unit for refurbishment or harvested for working capacitors and chips? The presence of entire integrated circuits or circuit boards can significantly increase the value of that component as those modules can be sold on the open market for value far in excess of the total value of the commodities they contain.

Furthermore, how can one weigh the value of a whole smart phone capable of refurbishment and resale versus the potential revenue generated by smelting the device to recover the metal values? Another alternative is to visualize the flow of WEEE as whole "units" of WEEE. In this approach one assumes that WEEE can be measured discretely and fallout or losses at a point in the system are due to losses of fractional WEEE units. This visualization is agnostic to both the mass of components and the value embody. However, it can be difficult, then, to calculate the mass or value flow from this visualization unless additional data are provided.

This latter option will be explored further in the following section. While there are certainly limitations to using this methodology—namely a significant amount of aggregation is required and it can be difficult to back-calculate values for discrete material flows—ultimately this visualization will surface the important issues associated with the status of smartphone WEEE flow in the United States today. After all, Sankey diagrams and any other means of presenting flow data are useful for both their quantitative perspective and their ability to connote qualitative opportunities and observations.

3.2 Analysis of electronic waste flow in the United States

The analysis performed here is based on literature data and industry experience of the author. As already discussed, the literature available must be viewed through a critical lens to assess its timeliness, its geographical relevance, and its level of detail. The goal of this analysis is to visualize the entire WEEE ecosystem from collection through end-processing to demonstrate the scale of the challenge presented by WEEE recycling. Figure 3-3 is visualized in the WEEE "units" discussed above where the flow from system to system is based solely on the percent loss expected at each point as reported in the literature. In the interest of clarity, the flow values for Figure 3-3 are not shown in the graphic; they are presented in Table 3.1.

When possible, data was drawn from sources examining WEEE systems in the United States. This is particularly important when determining the flows during collection—what fraction of EOL devices are collected versus not collected, what fraction of uncollected EOL devices are reused, and what fraction of collected EOL devices are exported. For these subsystems political, social, and economic drivers can dramatically affect consumer behavior, so reliance on European sources was avoided given (potentially) different drivers in those markets.

3.2.1 Discussion of electronic waste flow data in the US

It is generally accepted that overall collection of WEEE is very low. [3, 6, 28, 43] With general WEEE there are several factors that contribute to the collection rates that sit well below 50%. In most cases, the primary driver is simply convenience. This is further exacerbated with smart phones as their small form factor makes it very easy

Figure 3-3: Flow of smart phones through the US WEEE recycling ecosystem

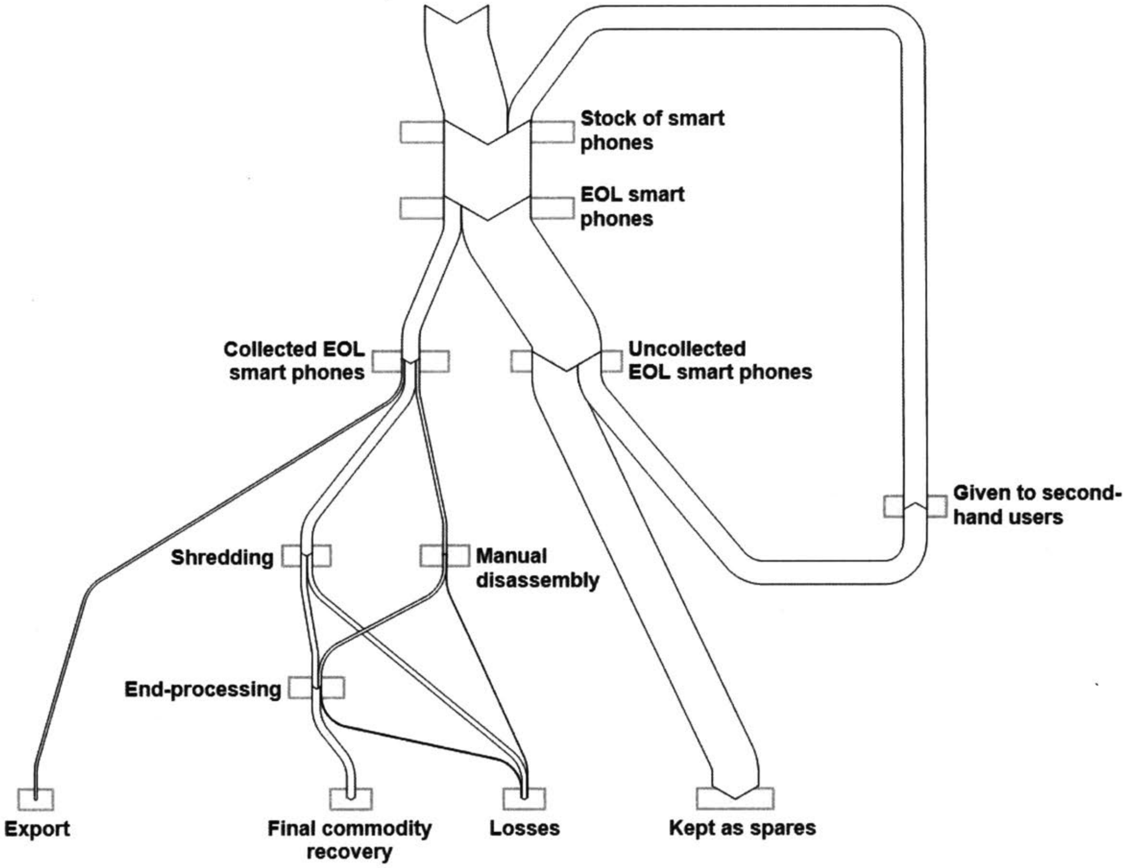


Table 3.1: Data for WEEE flow in the US

Processing step	**Value**	**References**	**Comments**
Collected EOL smart phones	20%	[3, 6, 28, 43]	Wide agreement on collection *ca.* 20%
Uncollected EOL smart phones	80%	[3, 6, 28, 43]	Balance of collection step and also widely reported
Export	3%	[46]	Data originally from US International Trade Commission, disagrees significantly with reports of exports exceeding 80% [15]
Shredding	13%	[23]	It is difficult to determine how much shredding is performed versus manual dismantling; with high grade WEEE streams like smart phones, this is a critical criterion as shredding induces significantly higher losses [14]
Manual disassembly	4%	[23]	Balance of shredding
Kept as spares	53%	[6, 28]	Widely varying numbers available in the literature, this value seems to be an average of available data
Given to second-hand users	27%	[6]	Some sources report much higher reuse of smartphones [3], however these data are older than the [6] data
End-processing	10.6%	[5, 13, 14]	Recoveries during end-processing typically exceed 95%
Losses (shredding)	6%	[14]	Significant losses during shredding, though there is disagreement as to whether losses are mainly due to dusting or due to incomplete liberation of material fractions
Losses (manual disassembly)	0.4%	[13]	Losses are much more limited during manual disassembly compared to shredding
Losses (end-processing)	1.1%	[5, 13, 14]	Balance of end-processing
Final commodity recovery	9.5%	[5, 13, 14]	Balance of end-processing

to store one (or several) devices in a desk drawer and then completely forget about it. For some users, concerns over data privacy and secure destruction of EOL devices negatively affects their willingness to recycle smart phones. All told, these and other factors contribute to the 20% collection rate illustrated in Figure 3-3.

Of the 80% of devices that are not collected for recycling, it is interesting to understand how that majority flow further splits. Some authors argue that the majority of this uncollected fraction ends up in landfills, with reports of 40% of all EOL smartphones (thus 50% of the uncollected devices) end up in landfills. [11] Others argue that as much as 82% of those unrecycled devices are landfilled. [28] These numbers seem extremely high and are likely drawn from older data sets (Ogondo *et al.* for example cite a 2007 report for their landfill numbers [28]). It seems reasonable to stipulate that in US markets there is sufficient public outreach to deter individuals from simply throwing away devices. It seems more reasonable to believe sources like Tanskanen *et al.* who argue that most uncollected EOL devices are either "kept as spares" in a desk drawer or enter into the second-hand market. [6] However, the wide ranges quoted in the literature make it difficult to determine precisely how the split of uncollected EOL smart phones partitions over these different options. As a result, Figure 3-3 shows that 53% of the uncollected smartphones are kept as spares; these devices do not typically reenter the market so they have not been shown to return to the stock of smartphones. Ultimately, these devices likely get recycled; so, in essence, they could be shown reentering the flow as "collected EOL smartphones," but the literature is lacking in quantifying these dynamics.

Figure 3-3 does not make explicit mention of a landfill flow (or of devices that are disposed of "improperly"). This is a deliberate choice as it is entirely likely that every final destination for a flow (and intermediate destinations, as well) have some fallout to landfill. However, whether this number is 1%, 10%, or 50%, it is not possible to say with confidence. This is a significant gap in the literature. [43]

The export data are a very interesting, very active debate in the literature. Interestingly, most academic studies cite very high numbers for the exportation of WEEE to developing countries: 50-80%. [6, 15] This is obviously an alarmingly high number and speaks to the overarching concern that the developing countries of the world are suffering from developed nations' technological progress without any possibility of realizing truly "sustainable" development. Thus, these are the data most frequently referenced by nongovernmental organizations and industry watchdogs (*cf.* [30]) and are the primary driver behind "in-region" recycling efforts (*cf.* [47]). However, recent research conducted by the US International Trade Commission and reported by the Institute of Scrap Recycling Industries, Inc. points to a much lower rate of WEEE exports. [46]

Anecdotally it is becoming more and more difficult to ship WEEE internationally; to do so "by the book" is almost impossible and companies trying to do so must be willing to "look the other way" with regard to certain international regulations like the Basel Conventions (a regulatory framework to which the United States is not a signatory). Furthermore, it begs the question as to how "export" is actually defined and what commodities are exported. With very limited end-to-end WEEE processing infrastructure in the US (principally referring to the lack of large scale end-processing capabilities domestically) there must be some movement of WEEE materials across borders, at the very least to Canada's Glencore smelter. However, the commodities moved to Canada may be in such a form that it is no longer classified as WEEE; it could, in fact, be defined as "copper scrap." This seems like a semantic argument but may be one of the reasons the literature struggles to agree upon a single number for export rates of WEEE.

Moving into the pre- and end-processing systems it becomes much easier to find reliable data for flow splits because these systems are relatively similar across geographical regions in developed countries (*i.e.* it is reasonable to use European data to make assumptions about US operations) and these systems are widely studied in the literature. At this point in the WEEE ecosystem the analysis presented in Figure 3-3 can become troublesome. Often researchers begin to focus on "hypothetical" phones where they model material flow through pre- and end-processing based on a commodity stream comprised of the "average composition" of a smart phone. [48] In some cases there are real data presented based on trial studies conducted in pre-processing plants. [5, 13, 14] The data for end-processing recoveries are almost never quoted precisely as most smelters consider this information to be proprietary to their operational procedures; it is safe to assume, though, the metallurgical recoveries—especially of precious metals—exceeds 99%. At this point, though, most flow data presented in the literature begins to focus on particular materials in the WEEE flow. Thus, the visualization in Figure 3-3 has tried to capture this concept while simplifying the analysis to WEEE "units" used throughout the rest of the figure.

The distinction between shredding and manual is important as most researchers agree that losses (again, mainly focusing on precious metals) are much higher in shredding operations. While most reports indicate that a significant source of losses during shredding is due to the generation of dusts and fines that contain precious metals [14] this argument must be further critiqued. In the author's experience, plants performing size reduction operations are very cognizant of the dusts they create. Especially in the US where strict work place safety rules strictly regulate the generation of fine dusts in working areas, there is usually very effective dust collection equipment in place. This would capture virtually all dust generated during shredding activities. In turn, when operations are well aware that that dust contains high value materials, they will go out of their way to recover it to ensure that there are no material losses during their operations that affect their profit margins. Losses to dusting may have been more common twenty or thirty years ago at the start of WEEE recycling operations. Today, though, it is more likely that losses during shredding are due to incomplete liberation, which is a phenomenon frequently encountered in the mining industry whose operations many recycling facilities mimic. In mining, incomplete liberation occurs when ore is not ground to the necessary fineness to separate the valuable materials from the waste materials in a host rock. This can occur either due to uncertainty about the fineness required given an ore's mineralogy or due to economic constraints as finer grinding requires exponentially more energy. Similar effects manifest during shredding of WEEE: finer grinding is much more energy intensive and often a recycling operation is constrained as to what they can afford to process. Furthermore, heterogeneity of a WEEE stream might mean that it is reasonable to shred a stream to (for example) 2.5-inch fineness with the majority of the stream's constituents, but the smart phone components in the stream might require 1-inch fineness. In this scenario it is likely that the precious metal contents of the smart phone components would not be completely liberated from the metal and plastic fractions, thus leading to (often significant) losses.

Regardless of whether or not WEEE is shredded or manual dismantled it will eventually make its way to end-processing facilities where it will likely be smelted to final commodity values. Again, Figure 3-3 struggles to capture these nuances as in many cases plastic fractions, ferrous fractions, and nonferrous fractions are treated separately and differently in the end-processing system. Admittedly, Figure 3-3 is largely biased towards the precious metals-bearing fractions at this point in the analysis inline with what is frequently reported in the literature. As previously discussed, losses during end-processing are typically exceedingly low at this point in the ecosystem because these operations are performed on enormous scale in well-understood and well-controlled processes that specialize in recovering materials from sources even more difficult to handle than WEEE (*e.g.* ores in the case of the metal fractions). There is potential for confusion in the literature as different authors report recoveries differently during end-processing. Some refer to "overall" metal recovery [13], while others refer to process-specific recoveries [5, 14].

3.2.2 Weaknesses of Sankey visualizations in the US electronic waste ecosystem

Any data visualization is subject to oversimplifications or biases that can convey the wrong message. When visualizing the flow of EOL smart phones in the US as a Sankey diagram several assumptions have had to be made. Figure 3-3 has illustrated the flow of hypothetical WEEE "units" through the US ecosystem; this analysis is based on a digestion of the available literature to attempt to combine studies that track whole units (*i.e.* EOL smart phones) with studies that track individual commodity streams (*i.e.* precious metals, plastics, and glasses). Thus it is important to ask what exactly is Figure 3-3 communicating? The overarching goal of Figure 3-3 is to draw attention to the following:

- ambiguity in the available literature; disagreement based on geographical regions studied and timeliness of data—where possible Table 3.1 sought to identify the literature supporting the flow splits, further analysis was presented in the text
- general themes in material flows; areas of significant losses and potential for improvement in a re-engineered ecosystem
- visualization of the entire ecosystem, not just an individual system; real discussion can only be centered around the whole ecosystem

Finally, Figure 3-3 provides a point of reference to discuss opportunities for improvement in the overall WEEE recycling ecosystem.

Depending on the audience, some may see value in Figure 3-3, while others will see serious gaps. It is anticipated that one of the gaps identified by many will be the lack of value flow communicated. As has already been discussed, this is a surprisingly difficult quantity to capture when visualizing the entire WEEE ecosystem as "value" changes as an individual device moves through the component systems. It would be possible, for example, to quantify the raw material value in an individual EOL smart phone as it enters the ecosystem in the stock of EOL devices (top of Fig. 3-3). This would be on the order of a few dollars given the current commodity prices of metals. This value could then be traced through the ecosystem to determine how much of that final value ends up in the stock of "final commodity recovery." However, this analysis is complicated by the fact that metals do not partition evenly when a flow is split. Early in the ecosystem, they do as whole devices are moved at this point. However, once into pre-processing different metals will split differently. Some of these details are captured in the analyses performed by Chancerel *et al.* in Figure 3-2 and are not repeated here. [13] The drawback to this analysis, though, is that a whole EOL device will almost always have more value than its individual component material streams. In fact, many of the individual components (*e.g.* integrated circuits, chips, or whole modules) will have orders of magnitude more value than the component metals. Thus, the pure "metal value" Sankey diagram can be very misleading.

In a similar vein, trying to capture mass flow through the ecosystem can prove to be futile. First and foremost, there is significant disagreement in the literature just to how much WEEE is out there. Furthermore, WEEE is often comingled with other waste streams (for landfill or recycling) at various points in the ecosystem and it becomes difficult to maintain transparency of just where the WEEE mass has gone.

An interesting analysis that could be performed and visualized as a Sankey diagram could be an estimate of the environmental impact of the WEEE recycling ecosystem. To the best of the author's knowledge, no comprehensive study capturing such an analysis has been presented. Data like that presented in Figure 1-2 is well known and similar data is available comparing different systems in the WEEE recycling ecosystem to individual analogous systems in primary material production. [17] The undertaking of such a study would be significant as it would require mass/substance flow analysis (MFA or SFA), life cycle assessment (LCA), and access to accurate data. However, being able to digest that data and visualize it to show just how important the WEEE ecosystem is in the grander scheme of making life in the developed (and developing) world more sustainable would be invaluable.

3.3 Conclusions about electronic waste flow in the United States

Figure 3-3 communicates just how significant the lack of collection is on the overall efficiency of WEEE recycling in the United States. It further demonstrates that one should focus the majority of his or her attention on evaluating the collection and preprocessing systems when seeking to improve the overall ecosystem. The disagreement in the literature is significant—and real effort should be made to remove some of this ambiguity—but not so impactful as to prevent further analysis on the ecosystem and the development of a set of recommendations that could lead to real improvement. Ultimately Figure 3-3 will serve as the reference point in the following discussion wherein more detailed decomposition of each component system will identify policy and strategy options for future implementation.

Revisiting the concept of a more sustainable future for the electronics industry and society as a whole, it is interesting to incorporate the work being done by the Ellen MacArthur Foundation. The stated goal of the Foundation is to understand how recycling is a component to the circular economy and how that economy can actually be functionalized; *i.e.* is there real financial value in a circular economy? [49] In a similar fashion to the work outlined in Chapters 2 and 3, the Foundation has mapped the flow of WEEE phones through the existing ecosystem and outlined what a transitional ecosystem might look like to encourage a not-shown future-state.

Figure 3-4: The circular economy of mobile phones [49]

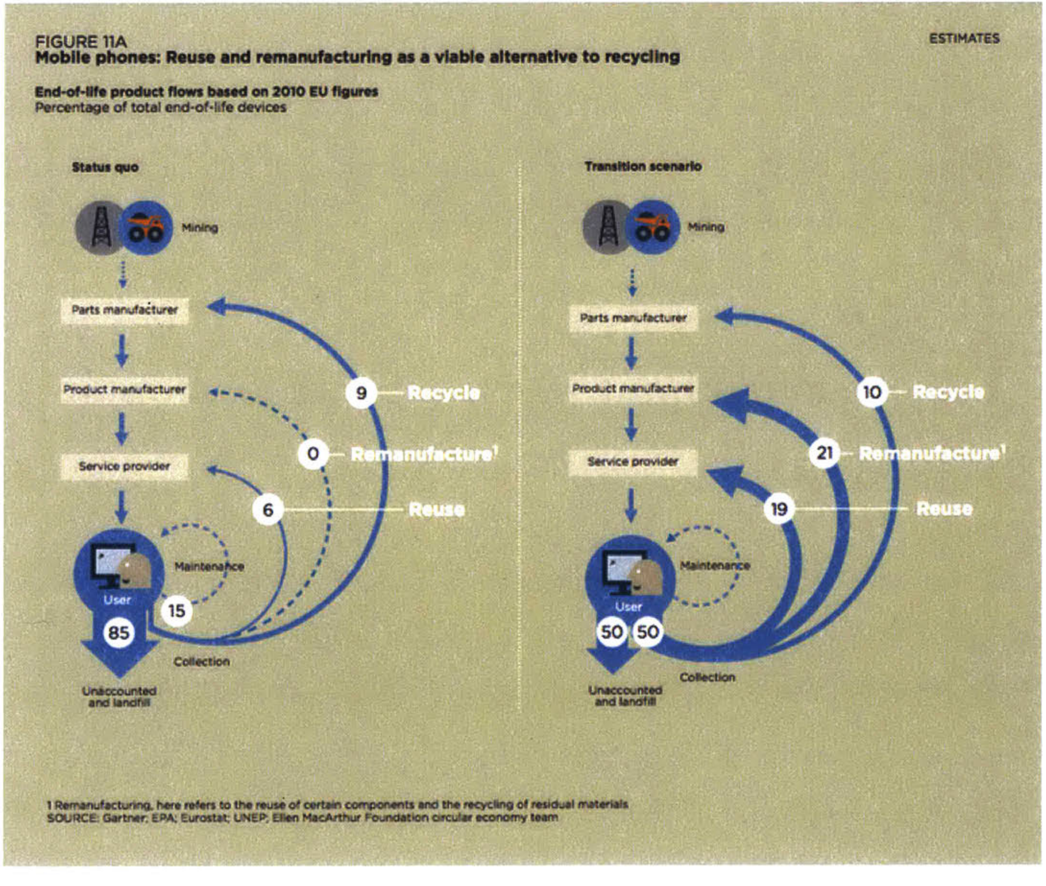


FIGURE 11A
Mobile phones: Reuse and remanufacturing as a viable alternative to recycling

End-of-life product flows based on 2010 EU figures
Percentage of total end-of-life devices

1 Remanufacturing, here refers to the reuse of certain components and the recycling of residual materials
SOURCE: Gartner; EPA; Eurostat; UNEP; Ellen MacArthur Foundation circular economy team

Figure 3-4 outlines how the mass flows through the EOL ecosystem could change to make a circular economy more viable in the context of mobile phones. To the best of the author's knowledge, the Foundation presents the most comprehensive analysis of the economic criteria to make this transition possible (these data will be discussed in more detail below). However, the critical missing link in the Foundation's analysis is exactly how to make this transition possible. It is great (and important) to demonstrate the financial viability of the future-state, but if one cannot outline the roadmap to this future-state it is only a fictional exercise. Many of the statements made by the Foundation are still fairly abstract without offering concrete direction that individual stakeholders can follow.

Chapter 4

Mapping of stakeholder value to the ecosystem: collection

Up to this point, this thesis has discussed WEEE recycling in fairly abstract terms: what is the status of the ecosystem and what has the literature studied to date. At this point, though, it is important to discuss how these observations can be translated into operational realities. How can each system of the broader SoS be parsed to identify the most significant challenges it faces? In so doing, by surfacing the most important issues, it becomes possible to outline strategies for improvement.

As shown in Figure 2-8, one of the primary stakeholders in the collection system are the collectors themselves. In turn, they interact most closely with various stakeholders including municipalities, consumers, and retailers who provide the WEEE and (in some cases) cash flow to process WEEE. The collectors also interface with pre-processors who take the collected WEEE in exchange for money; there is also an information flow between these stakeholders based on the collectors' understanding of the WEEE's composition. The collectors may also interact with disposers if there are components to the WEEE that cannot be recycled further. Finally, collectors are influenced—to some extent—by various agencies through regulations, trade organizational practices, and other political levers. Taken together, the stakeholder value network refocused on the WEEE collectors can be used to reframe the issues associated with WEEE recycling as social, economic, and regulatory factors.

4.1 Social factors

Figure 3-3 showed that collection represents the single most impactful step in the WEEE ecosystem from a yield loss (or recovery) point of view. The simple fact that 80% of devices do not enter the ecosystem means that there is significant opportunity for improvement. As the Ellen MacArthur Foundation notes in its general outline to "accelerate" the circular economy, boosting collection efficiency is the single most important component to realizing a circular economy because it has cascading effects that improve all downstream aspects of closed loop supply chains. [49]

The primary drivers to the low collection efficiency seem to be simple consumer behavior. As shown in the SVN, collection is largely the interface between the consumer (who holds the EOL device) and the collectors who seek to receive the EOL device. It is widely held that there are a few key drivers affecting consumer behavior when it comes to recycling in general, and some of these drivers can be specified to the case of WEEE. For example, many believe that consumers are simply unaware of the significant benefits to the environment that recycling offers. [4, 6] Tanskanen goes on to highlight improved consumer awareness as the most important lever to pull in terms of increasing collection.

An additional factor that parallels consumer ignorance about the benefits to recycling, is ignorance of collection infrastructure. Many consumers are unaware of the various ways in which they can responsibly dispose of their WEEE. [4] Kang argues that this is mainly a failing of the municipalities; but it seems that all major stakeholders have a role to play in this driver. [4] After all, there are many different stakeholders in addition to municipalities who facilitate collection; increasing awareness of the various take-back programs, collection locations, and drop-offs spots can be done by many different entities. Sinha *et al.* showed the impact that various consumer-related factors have on the effectiveness of collection using a system dynamics model. [50] In their work, Sinha *et al.* identified the accessibility of collection pathways as the single system variable having the highest overall impact on the performance of the recycling ecosystem; in fact, in their sensitivity analysis they showed that increasing access by 100% increased the overall efficiency of the recycling system by nearly 10% while decreasing the material losses by a similar margin.

Two more drivers that affect consumer behavior are also closely linked to each other based on the value consumers place in their WEEE: the consumers' concerns over protecting their private information on their EOL devices and the knowledge that EOL devices still have value on the second-hand market. The former driver is a growing concern for both consumers and the recycling industry as consumers are more aware of the sensitivity of their hardware in light of data breaches and identity theft. Perhaps in an effort to mitigate these concerns many WEEE collectors advertise (often aggressively) their secure handling and data destruction procedures. Knowing that consumers want to be sure that their data-bearing WEEE is handled securely and then destroyed completed, many collectors (and pre-processors) highlight that they store WEEE in locked cages guarded by CCTV, will punch out and degauss spinning hard drives before shredding to minus 1 inch particle size, all before complete destruction in a smelter. To many individual consumers this can be excessive to what is required, but to commercial customers this is critical. All the same, though, many consumers with EOL will simply hold onto their WEEE believing that the data might be safer in their own storage than someone else's.

A more financially-focused driver also affects consumer behavior. Many consumers, especially those more in-tune with the technology industry, will seek out the best possible value for their EOL devices. As has been discussed previously, many EOL devices are still functional but have simply become less trendy due to the introduction of newer models. These still functional EOL devices can be sold (or donated) into the second-hand market; as a result, many consumers looking for the best value will attempt to sell their EOL devices to someone looking for a second-hand device. [3] These two drivers of consumer behavior are not actually bad for the environment; however, they do not benefit the recycling ecosystem because they delay (or even preven)t WEEE from entering the system at the collection stage.

The final social driver of consumer behavior is a result of the increased miniaturization of WEEE: it is simply too easy to store EOL smart phones in a drawer because they take up little space. Many times consumers will purchase the newest smart phone and hold onto their now EOL one in the belief that they need a spare; however, this same behavior repeated over multiple generations of smart phones means one can quickly accumulate three or four smart phones in a drawer. In fact, this final driver underlies the other four drivers in that it is part of the rationalization for the other behaviors that prevent consumers from recycling their EOL smart phones. [28] If a consumer has concerns about privacy, it is simply easiest to hold onto the device where the consumer can be sure that it is safe. Likewise, if a consumer does not know that WEEE can be recycled, it is easy enough just to stick it in a drawer with the belief that maybe he or she will figure out how to recycle it later. If a consumer is searching for the best deal for his WEEE he can hold onto it until that deal presents itself; there is no significant opportunity cost (from his point of view) to storing the device. Interestingly, though, there is significant opportunity cost to the collectors as EOL devices quickly lose their value on the second-hand market the longer they sit in a consumer's drawer. [3]

4.2 Economic factors

From the point of view of the collectors and consumers (the key stakeholders in the collection system) there needs to be an economic reason to take part in the WEEE collection system. The economics of WEEE collection have been studied by many researchers and are often part of larger discussions around "reverse logistics." [3, 22, 4, 14, 5, 15, 6, 49]

Geyer presents one of the most comprehensive reviews of the costs associated with reverse logistics showing the price points at which collection can be financially viable. [3] In fact, Geyer argues that reverse logistics, which essentially encompasses collection and getting WEEE to pre-processors, accounts for 80% of the total costs associated with recycling. This work goes on further to compare the potential revenue from recycling (really just pre-processing, and thus no metal recovery) to revenue from refurbishment. It is interesting to note how the estimates made by Geyer compare to the estimate made by the Ellen MacArthur Foundation:

Table 4.1: Comparison of collection costs (USD) from [3] and [49]

Process step	**Geyer estimate, [3]**	**EMF estimate, [49]**
Return incentive	3.00	—
Collection and shipping	1.90	1.00
Inspection and sorting	2.80	5.40
Total	7.70	6.40
Pre-processing costs	0.18	3.00
Pre-processing revenue	0.75	0.10
Refurbishment costs	2.10	16.60
Refurbishment revenue	17.00	6.20

Table 4.1 is interesting because the collection costs seem to be fairly similar in the two estimates from a total cost perspective. The difference, though, is that Geyer has assumed a return incentive to promote consumer behavior; the EMF has taken a (likely) more realistic approach that the industries will not provide a financial incentive. However, there is a marked differences in the pre-processing and refurbishment cost and revenue estimates. These major differences (factors of three to seven) are part of the reason it is so difficult to discuss with much certainty the economic situation surrounding WEEE recycling. It is fairly simple to calculate a raw material value of an WEEE smart phone (to be discussed later), but estimating the value of a refurbished device is much more difficult given the variability in the WEEE smart phone flow. Furthermore, finding the average cost associated with pre-processing and refurbishment is very difficult as these are often closely guarded company secrets. However, knowing that collection (and parts of pre-processing depending on how one draws the system boundary) account for approximately 80% of the total cost associated with WEEE recycling is a powerful reference point. [3, 4] In addition to being the point at which the most mass flow is lost in the recycling ecosystem, collection is also the point at which the greatest cost is incurred.

Table 4.1 also makes an estimate of the associated revenue with various WEEE processing options. Underpinning these estimates has to be an understanding of the raw material value (*i.e.* the metal value) in WEEE phones. It has already been stated that this is a relatively simple calculation; several authors have made estimates or have tracked the metal composition of smart phones over time. [5, 13] Cucchiella *et al.* provide one of the most comprehensive overviews of the typical composition of twenty-four different types of WEEE including smart phones. [11]

Table 4.2: Average smart phone composition [11]

Material	**Mass percent, %**	**Value percent, %**
Palladium	0.001	13.0–15.7
Beryllium	0.003	
Platinum	0.004	22.4–22.7
Praseodymium	0.004	
Selenium	0.009	
Gold	0.036	25.9–29.1
Neodymium	0.047	
Antimony	0.079	
Silver	0.229	0.356–0.379
Lead	0.564	
Tin	0.940	
Zinc	0.940	
Nickel	1.411	
Aluminum	2.727	
Cobalt	5.924	
Iron	7.523	
Glass	9.968	
Copper	13.166	34.8–35.6
Plastics	56.424	

The breakdown of recoverable value for the average smart phone in Table 4.2 is based on the 52-week low and high prices available on the London Metal Exchange. The metal value is only shown for the major metals typically valorized and recovered during WEEE recycling operations. Interestingly, these data are slightly different from other sources in the literature that report a much higher value associated with the gold content in smart phones (discussed above). This is likely due to the relatively extreme price volatility associated with certain metals and the difficulty in determining from where researchers draw their phone composition data. For example, a very recent paper published by Bian *et al.* shows very similar composition based on mass (*e.g.* 0.035 wt.% Au and 0.14 wt.% Ag) but a valorization significantly different from that in Table 4.2 (*e.g.* 78.8% for Au, 3.9% for Ag). [51] Bearing in mind that the values shown in Table 4.1 are based on the ability to make predictions outlined in Table 4.2 it is clear what types of challenges stakeholders face during collection when the value proposition of WEEE recycling is first made. Interestingly, an industry survey conducted by Resource Recycling, Inc. showed that the changing composition of WEEE streams ranked as the fourth most important issue facing the industry today. [52] The same survey showed that the volatility of the metal markets—and especially the depressed nature of those markets recently—was the second most important issue. To further complicate the calculus, it is widely known that the amount of valuable metals is decreasing in smart phones, which in turn leads to decreased overall value of the WEEE stream. [24] Both of these issues drive to the economic value proposition with which collectors struggle. This value proposition will be discussed further below.

4.3 Regulatory factors

The patchwork regulatory situation governing the WEEE industry in the United States has already been discussed. To some extent, one could hope that such a regulatory environment could promote innovation in the industry in such a way that truly great collection schemes would out-compete the status quo of meagre collection efficiency. In addition to the regulations that vary from state to state, there are also several certification bodies available to recyclers. In general, these certifications are most applicable to collectors and pre-processors; in this sense, the boundary and differentiation between the two stakeholders quickly blurs.

Resource Recycling, Inc. has conducted a periodic industry survey to gauge how regulation is impacting the WEEE recycling industry. [52] In addition to gauging the sentiment of the industry with regard to macroeconomic trends and next steps for key stakeholders, the survey also asks for impressions of how the various certifications are affecting the industry. The key certifications that can be sought by collectors and pre-processors are R2, e-Stewards, WEEELABEX, Canadian RPQ, and EPEAT. (Some of these standards, like EPEAT, are also sought by EEE manufacturers.) Interestingly, the survey data shows that certifications, which were meant to "level the playing field" for recyclers so that OEMs, and other stakeholders could be sure that they were dealing with environmentally responsible collectors and pre-processors, have actually had negative effects. In 2012, 82% of survey respondents agreed that certifications were helping level the playing field inasmuch as responsible recyclers were able to compete against recyclers operating irresponsibly. To the respondents in agreement, the certifications demonstrated why their services typically came at a premium price point; it also allowed them to win large contracts with governments or major corporations who were required to recycle with certified operations. However, the percent of respondents in agreement has fallen: in 2013 it was 78% and last year in 2015 with reached a new low of only 62%.

Interestingly, survey respondents have noted a significant negative shift in the industry as a result of these regulatory and certification impacts. Recently, the main source of competition in the industry has been between certified and non-certified recyclers whereas historically it was between different types of certifications. [52] As mentioned above, some of the appeal of doing business with certified recyclers has worn off as the non-certified operations can offer significantly cheaper services. In parallel to this effect, most WEEE generators "remain unaware of the difference between 'good' and 'bad' recyclers" meaning that many WEEE generators do not even know that they should be looking for operations that are certified. All in all, these sentiments note that certification has done little to improve the overall situation in recycling; in fact, it may have made it worse by making it more difficult for "good" recyclers to compete. This issue of competition is largely driven by the cost of getting certified. Many survey respondents noted that it is simply too expensive to achieve—and then maintain—the necessary certifications, though most of them (51%) believe it improves their reputation with WEEE generators.

A more nuanced point of tension for WEEE recyclers is the existence of weight-based reimbursement programs implemented by various states. Many states in the United States have regulations that effectively reimburse OEMs or recyclers for the mass of WEEE they process. However, WEEE recyclers argue—and rightfully so—that with the miniaturization of EOL devices, assessing performance on a strictly mass-basis can be unfair. [52] It is interesting to note here, though, the disconnect that seems to exist between much of the academic literature that cites the rapidly growing volumes of WEEE and claims of most WEEE recyclers that the "e-scrap stream is getting lighter." [52] Unfortunately the survey does not discuss this point further, but it raises an important issue that regulation that encourages recycling on a mass-basis may not incentivize the most effective recycling solutions that, for example, recover the most value or offset the greatest environmental impact.

In addition, many recyclers note that regulation that focuses on tracking the mass of material recycled can, and often does, act as a disincentive to refurbishment. The recyclers state that the recycling standard's "requirements for paperwork and documentation are especially hard to comply with for smaller businesses... the standards' reuse guidelines were originally written for PCs and laptops," which differ in reuse significantly from smaller WEEE like smart phones. [52]

All told, the regulatory environment facing collectors is daunting. Beyond the challenges they face if they operate in different states with different legal frameworks, collectors are forced to navigate an only semi-formal world of certifications that can often pose more cost than benefit to their operations. On top of this, much of the certification, though originally well-intended, is out of date or too burdensome to cope with how the nature of WEEE has changed over the past 10 years.

4.4 Opportunities for improvement

Understanding that collection faces social, economic, and regulatory hurdles to improvement, it is important now to outline how these barriers can be addressed in aggregate. It is also important to note that, in true systems thinking fashion, none of these barriers exist individually in a vacuum. For example, the depressed metal prices of recent years have made it increasingly difficult for WEEE recyclers to turn a profit (this is an economic factor). The relatively archaic certifications required (or at least sought) by many recyclers has made it difficult for certified recyclers to compete against non-certified recyclers (this is a regulatory factor and an economic factor). And individual consumers have shown only slow moves towards increasing their commitment to recycling (this is a social factor). However, all of these factors are related; starting at one factor and moving to the others: if consumers increased their interest in recycling (through some abstract effect), recyclers would have more volume to process. At this point the effect of low metal prices could be mitigated as recyclers could take advantage of economies of scale. In turn, more efficient recycling operations would be able to drive better price points against non-certified recyclers while also pushing for better certification procedures.

As a result, it quickly becomes obvious that the myriad factors facing collectors is truly a systems issue demanding system solutions. One could imagine visualizing the relationships between the stakeholders and their respective affecting factors in a System Dynamics framework. In fact, Sinha *et al.* performed such an analysis and showed that collection (in addition to increasing the useful lifespan of mobile phones) represented the single greatest opportunity to improve the recycling ecosystem. [50] However, their work only highlighted the existing programs—efforts like Extended Producer Responsibility and Advanced Recovery Fees—as solutions to the problem. This section will outline additional real-world, tangible strategies that could be implemented by businesses and/or governments.

4.4.1 Making recycling interesting

All of the stakeholders in the collection system suffer from low volumes, which in turn is driven by low collection efficiency. To have the greatest effect here, the WEEE industries (beyond just collectors) need to make WEEE recycling interesting for consumers. If one can remember back to when recycling was first gaining traction in the United States, public service announcements and public interest were driven to recycle more; this was around the same time that "reduce, reuse, recycle" was born. [53] In a more modern context, the state of California typically leads the nation in adopting more environmentally friendly policies, like banning plastic bags or making recycling and composting disposal as frequently available as traditional landfill garbage cans in public places. Similar types of thinking are required to make WEEE recycling second nature.

A real-world example of this has come in the first quarter of 2016. In March 2016, Apple led off its Keynote session to launch two new consumer products with a message from its Vice President of Environment, Policy and Social Initiatives, Lisa Jackson about the work Apple was doing to make operations more sustainable. To conclude her statements, she revealed that Apple had been spending the past few years developing a robot to disassemble iPhones to make them more recyclable. [54] In the time since this robot was unveiled, the promotional video highlighting its capabilities has been viewed nearly 2.3 million times on YouTube (https://youtu.be/AYshVbcEmUc). Over that same time period, Google Trends has shown that internet searches for the term "e-waste" has gone up 34 percentage points and "e-waste recycling" has gone up 20 percentage points. However, interest seems to be waning as the popularity of these searches has begun to decline to pre-announcement levels.

This type of publicity, on a more sustained cadence, could help affect consumer behavior. Previously the parallel was drawn between consumers who buy organic food with consumers who make sustainability-minded decisions with their WEEE. The comparison is certainly not one-to-one as in addition to being better for the environment and workers, organic food is believe to be better for our health. But the same sorts of marketing campaigns that put organic food (back) on the map could help put responsible WEEE recycling and the sustainability of the smart phone market at the forefront of people's minds.

Many of the statistics already quoted above would probably surprise most people: 80% of all smart phones do not get recycled; even the fraction that are recycled only a tiny fraction of that is actually recovered for reuse; the amount of gold and other metals lost when WEEE is landfilled, etc. Making these data more widely known to the public will go a long way towards making consumers think twice before throwing away or storing their WEEE. In concert with making data about recycling more widely known, OEMs must make information about their supply chains more available as well. Of course, with these disclosures companies will wish to protect their trade secrets. However, educating consumers about where the metals, plastics, and composites in their smart phones is coming from should be part of the process when pitching them on the latest features. While consumers may not value that information at first, it will encourage all stakeholders to take a closer look at the sustainability of their choices. OEMs can help explain the recycled content of their devices, or how they are working with suppliers to recover more value from waste, etc.

One smart phone manufacturer looking to embody this model is Fairphone. While not specifically focused on the recycling aspects of the smart phone industry, Fairphone is looking to create the world's first "smart phone with social values." However, from a recycling point of view, Fairphone is able to highlight the modularity of its device; this in turn can prolong the useful life of an individual smart phone while also allowing for easier dismantling. Anecdotally, though, the quality of the Fairphone devices is far inferior to the devices produced by the large smartphone manufacturers in the industry. This inferior quality could translate into much lower product lifespans, which would mean that Fairphone devices become WEEE much more rapidly than their higher quality competitor devices. Thus, the question becomes whether the modularity and assumed ease of recycling can offset this tradeoff for lower quality.

Another foray into this modularity concept was embodied by Google's Project Ara. However, the project was cancelled. There are certainly many reasons the project was abandoned but one key driver was likely the unproven market for such a device.

In terms of making recycling more interesting, it is clear that most of the options are strategic and lay at the feet of industry. While government can certainly help drive some of these initiatives, through programs modeled after Extended Producer Responsibility frameworks, it seems that the evidence to date shows that government regulations often lag too far behind the relatively rapid pace of the smart phone industry. However, recent work in China has shown that the EPR model increased recycling of WEEE nearly 24-fold since its implementation in 2009. [55] However, the same work goes on to highlight several examples of government inefficiency in regulating WEEE (*e.g.* mandating mass-based collection rates). Recent successes at boosting WEEE collection in Canada have been attributed to the work of not-for-profit organizations working to increase awareness of WEEE problems. [56]

4.4.2 Making recycling easy

If, and it is certainly a big if, consumer interest can be piqued, and more EOL devices are made available to collectors, it will be important to make recycling easier. Recycling is made easy when consumers are not burdened with any extra requirements to recycle. However, this seems to be difficult topic to tackle as none of the literature seems to understand what the consumer tolerance is for "burden." As has been discussed there are several existing models that have been implemented in various locations to facilitate WEEE collection. However, to the best of the author's knowledge, no one has looked systematically at which models out-performed others. To be fair, though, there are likely significant enough differences between regions that one collection scheme that works well in one region is not likely to work well in another without at least some modification. For this reason, it seems that significant focus should be placed on understanding how the actual reverse logistics of WEEE collection can be improved. [57]

One of the major issues highlighted in the literature quite frequently is the lack of reliable data. The EPA has published a fairly comprehensive review of WEEE recycling in the United States, but the pace at which the industries involved evolve will quickly (if it has not already occurred) make this data out of date. [43] For this reason, one suggestion for improved regulatory involvement in WEEE recycling would be better transparency of the types of WEEE processed and the volumes sold by OEMs and the volumes seen by collectors and recyclers. Such regulation should be focused on generating the types of data researchers and industries need to develop a better understanding of just how the WEEE ecosystem is changing. It is clear that the types of WEEE seen 10 years ago are significantly different from the types of WEEE seen toady. The regulation should demonstrate this by requiring the key stakeholders involved in the ecosystem to report out (to some degree of granularity) the volume of WEEE processed, the composition (*i.e.* types of WEEE seen and its approximate age) and how it was processed. Many NGOs are already starting to voice these concerns by drawing attention to the illegal dumping of WEEE overseas. [58]

4.4.3 Closing the loop on stakeholder value

The difference between Figures 2-3 and 2-8 is the nature of the loops through which value flows in the ecosystem. The original SVN in Figure 2-3 is largely open loop with unidirectional flow of value; Figure 2-8 has attempted to make some of these relationships more closed loop. Ultimately, to improve collection rates it will be important to make value more visible to all of the stakeholders involved. At the highest level, policy changes like valorizing the externalities associated with production and disposal of WEEE (*i.e.* carbon taxes) will drive enormous change in operational behavior. However, at lower levels, simply letting more information flow back up (and in some cases down) through the stakeholder network will allow stakeholders to make more informed decisions.

For example, improving the information flow to consumers will hopefully make them more educated actors in the network. This in turn will hopefully increase the chances that they decide to recycle WEEE at EOL. In this similar vein, if a consumer is more aware of the impact her decisions will have, her barrier for burden might be raised. That is to say, that individual consumer might be willing to undertake a greater burden to recycle WEEE if she understands the types of impacts landfilling can have.

As another example, more closed loop information flow will better equip collectors to valorize what they are receiving. Information flow from the consumers to the collectors about the WEEE involved in a transaction can make significant differences. While most of this discussion has focused on the actions of individual consumers, collectors are also dealing with commercial customers who may have hundreds, if not thousands of devices, for collection at a given time; this means the amount of information that must be transferred can quickly explode. Management of this information will become a challenge in its own right.

Chapter 5

Mapping of stakeholder value to the ecosystem: pre-processing

The pre-processing system is the start of recycling as it is known to a layman. Much of the actual pre-processing done at these facilities look a lot like the types of recycling operations one would see at municipal recycling plants. Pre-processors are caught in the constant tension of trying to do what is best for the environment while also generating a profit. Unfortunately, in many instances it is difficult to accomplish both goals due to low value recovery, low market prices, expensive and inefficient processes. In general, the types of challenges facing pre-processors can be grouped in technical, social, and economic factors.

5.1 Technical factors

The low yields in pre-processing have been illustrated in Figure 3-3. These losses represent significant value for the pre-processing option. There is debate as to whether the majority of losses are due to dusting during shredding stages or incomplete separation of materials. The former scenario would be relatively easy to address as most operations have rigorous dust control procedures to protect workers and prevent fugitive emissions. The loss of value (namely the precious metals) to dusting may have been an issue in older pre-processing plants but it does not seem to as significant an issue in modern facilities; the literature's insistence on this being the main cause of losses seems to be anachronistic.

Rather, the main root cause of losses during pre-processing today seems to be a side effect of the increased miniaturization of electronic devices—especially smart phones and other handheld consumer electronics. As devices have become smaller, the payable metals (again, mainly the precious metals) have become more closely associated with plastic substrates in an effort to save space and weight. In turn, traditional shredding and separation techniques that rely on the ability to differentiate between plastics and various types of metals (essentially ferrous and non-ferrous) are no longer able to pick out the minute quantities of precious metals mounted on, or closely associated with, plastic substrates. This leads to payable metals following very low value streams (like the plastic fractions) generated during WEEE pre-processing.

The means to address this issue are to grind to increasingly finer top sizes. However, doing so generates significantly more dust and brings on new material handling and material separation challenges. Pre-processors are forced to try to find an optimum grind size that yields the highest recovery of payable metals without increasing the complexity of downstream operations.

To strike this balance, pre-processors face two more challenges: separating various fractions (including new materials not previously seen) and the heterogeneity of the stream. As illustrated in Figure 2-2 pre-processors typically generate several different material streams as WEEE is broken down. Figure 2-2 can be misleading, though, as the output streams are rarely as cleanly separated as indicated. Often an operation will have several rough cuts to generate a stream that is, for example, mostly non-ferrous metal; that rough fraction will then go through cleaner separation stages to pick out residual ferrous metal components. Furthermore, the technology used to separate different metal types (induction, permanent magnetics, and occasionally scanning optics) is good at identifying bulk metals. As more and more composite materials are used (either as alloys or close juxtaposition of different materials) these technologies struggle to effectively generate clean output fractions. For example, many smart phones contain tungsten that is used as a counterweight in the vibrating motor of the phone. When a smart phone is shredded the incredibly hard tungsten component likely goes through the shredder unscathed. And because of its properties, tungsten is not separated during the pre-processing unit operations so it reports to the precious-metals bearing copper fraction. Ultimately, this tungsten is lost during end-processing because copper smelters cannot recover tungsten using process chemistries.

The heterogeneity of the WEEE feed to a pre-processing operation also poses a significant challenge. As discussed above, pre-processors must try to find the optimum processing scheme (including grind size) to recover the most value at the least cost. However, a very unpredictable feed stream can make this task almost impossible. To try to balance their feed composition, many pre-processors will stockpile WEEE, doing a "pre-sort" on the material to try and put like devices in the same piles so that when it comes time to process that material a plug of like material is moving through the plant. Pre-processors have a very good idea of what they are processing; good pre-processors know which brands or models contain the most material, are easiest to process, and can fetch the best return as a refurbished device. That being said, though, there is significant opportunity cost to the business as they are forced to stockpile devices. Sometimes pre-processors will stockpile devices so as to try and process when metal prices are high and the pre-processor can fetch the highest return for their output material. The cost of maintaining that inventory can be burdensome, though. A means to make the input streams more homogenous would benefit a pre-processing operation as they would have a better ability to forecast production and plan for ways to increase productivity.

5.2 Social factors

The social factors that influence pre-processing are much more limited than those that affect collection. For most consumers, their responsibility—whether it is real or perceived—ends once they have transferred their EOL devices to a collector. However, pre-processors are still influenced by the overarching accountability they have to other stakeholders in the system.

Typically, this accountability remains behind the scenes as consumers take the "out of sight, out of mind" position with regard to WEEE recycling. However, when reports come out—as they do periodically—that highlight the many inefficiencies of the industry, pre-processors' accountability to their stakeholders rises to the surface. For example, recent work by the Basel Action Network (BAN) and MIT has highlighted the flow of WEEE (mostly printers and computer monitors) from collection and pre-processing operations to developing countries. [58] Critically, the BAN report states that devices were exported despite the promises of the recycling stakeholders to process the WEEE domestically.

Figure 5-1: The flow of e-waste from US sites to developing countries as tracked by the Basel Action Network and MIT, http://senseable.mit.edu/monitour-app/

This breakdown in trust can make consumers even more unlikely to recycle their WEEE. It can also shine a negative light on the industry and invite unnecessary criticism. While criticism is important as it hopefully drives improvement, it can also derail the discussion. For example, the BAN report identifies all of the ways in which the WEEE recycling ecosystem has failed, but it fails to address some of the underlying causes of these failures. Notably, the lack of end-processing infrastructure in the US that makes it more economically viable for a company to ship material halfway around the world rather than processing it in-region.

5.3 Economic factors

Pre-processors face a "chicken or the egg" dilemma in the economic factors that affect their ability to become between WEEE recyclers. On the one hand, there are very real ways in which they can generate new value and thereby boost their revenue streams. On the other hand, though, these steps are typically very capital intensive and the precarious economic situation facing most pre-processors make them wary of taking on new risk. To aggressively pursue new value streams could pay dividends in the long run, but how to finance this venture? Going all in on a risky capital improvement will expose the pre-processor in the short run in the hopes of long term returns, but what if the heterogeneity of their feed stream changes in an unpredictable way? As a result, there are three key economic factors pre-processors face: identifying existing value, generating new value, and deciding whether to refurbish or to recycle.

In terms of identifying value, much of the conversation focuses on the precious metals; after all, the typically represent at least 70% of the contained metal value in EOL smart phones. It has already been mentioned that most pre-processors have a fairly good idea of where the value is in the types of materials they see on a daily basis. For example, pre-processors can look at a phone and have a good idea what the recoverable gold content is. To this point, pre-processors are doing a good job at knowing the precious metal value in WEEE that they see routinely. Being able to identify this value more objectively, though, would be an improvement. In some pre-processing arrangements, pre-processors will pay the collection agency for the WEEE that is transacted based on an assay that calculates the average precious metal content of the lot. However, this can typically only be done with large batches that are aggregated by large scale collectors. It is difficult to aggregate such large batches of WEEE smart phones given the low collection rates. A more effective means of valorizing small batches would be helpful to pre-processors. This, in turn, would also help them build more homogenous inputs to their operations.

In tandem with identifying existing value (the precious metals), pre-processors are forced to find ways to generate new value. Much of this conversation has focused on the various other metals found in smart phones. Rare earths have already been mentioned for their use in permanent magnets. Other examples include tungsten that is used to provide weight to the vibrating motors in smart phones, tin used in solder, cobalt used in lithium-ion batteries, and indium used in liquid crystal displays. [59] Pre-processors are facing pressure from many different stakeholders to recover these metals in addition to the traditional precious metal, ferrous, and non-ferrous recovery streams. It behooves the pre-processors to demonstrate this capability as these metals represent new value streams. Especially given the added social and environmental complications associated with some of these metals (*e.g.* tin and tungsten are considered conflict minerals, the majority of cobalt is sourced from the Democratic Republic of Congo, and indium is only produced as by-product from zinc mining), many stakeholders put added significance to the recovery of these metals over and above their actual monetary value in the metal exchanges.

Given that pre-processors are inextricably tied to the precious and base metal markets, they face significant downward pressure from the low prices existing today. Being able to find new value—either by recovering more metals like those listed above or by providing new services or recovery options of things like plastics—could drastically improve the economic situation. However, as already discussed, completely reconfiguring a pre-processing circuit to generate this new value is technically challenging and capitally intensive. As already mentioned, the appetite for this new risk simply is non-existent today.

Table 4.1 outlined the potential economic value associated with refurbishment over recycling. Pre-processors must decide whether or not refurbishment is a service they can provide. The Ellen MacArthur Foundation argues that refurbishment (and reuse) represent the highest value preservation in a circular economy of smart phones. [49] Given the short lifespan of most smart phones today, many EOL phones that come to pre-processors may be able to be refurbished and resold at higher margins than the raw materials contained in the phones. However, refurbishing a highly integrated device like a smart phone is much more difficult than larger WEEE like printers (*cf.* ifixit.com). [60] In the case of smart phones, their actual "repairability" is usually quite low meaning that for a refurbisher to be able to resell the device it has to be in nearly pristine condition, otherwise it simply is not worth it to try and repair the device. Typically it is possible for a pre-processor to perform cosmetic refurbishment to yield a salable device, but anything requiring work on the internals of an EOL smart phone is cost prohibitive. Thus while refurbishment and reuse represent the most compelling realization of the circular economy, in reality they can be very hard to realize. It is often simply easier to teardown the device completely at pre-processing and recycle the WEEE.

Interestingly, though, the overall economic challenges facing pre-processors can be difficult to disaggregate in systematic fashion. A system dynamics modeling of the ecosystem showed that many of the "economic" levers typically considered in WEEE recycling were ineffective at making the ecosystem more efficient. [50] Most notably, an increase in the metal prices or a decrease in processing costs had essentially no impact on the overall ecosystem efficiency or the recovery of metals. The authors state that such outcomes stem from the fact that the overall ecosystem costs is dominated by other system costs outside of metal recovery operations (*cf.* Table 4.1 showing that the collection costs dominate total ecoystem costs). In this context, the argument for creating new value by recovering new metals or finding new ways to refurbish and reuse devices is more appealing.

5.4 Opportunities for improvement

Identifying some of the technical, social, and economic factors that affect pre-processors also allows for surfacing of some of the potential strategies and regulations that might improve pre-processing.

5.4.1 Improved disassembly technology

The Liam technology developed by Apple represents a possible direction the pre-processing industry could go. [54] Using robotics to rapidly disassemble WEEE could be a means to automate the process, generate new value, and increase recovery efficiency. With regard to automation, pre-processing is still a fairly manual process, at least at the outset where depollution (battery and hazardous material removal) is performed. This is also an inherently hazardous process; therefore being able to automate this could not only save money but also make pre-processing safer. Apple has highlighted that Liam enables them to generate new value by recovering certain components out of the iPhone that contain critical metals (like the tungsten in the vibration motor) that are typically not recovered during pre-processing or end-processing. Lastly, robotics increase recovery efficiency through repeatability and the generation of discrete WEEE fractions that can, in turn, have discrete end-processing schemes.

However, robotics will not be the panacea to EOL smart phone pre-processing. Many commentators have pointed out the limited scope that Apple's Liam technology address. [61, 62] Liam can only disassemble iPhone 6 and can only handle a limited annual volume. All told, Liam addresses a small fraction of the WEEE stream. However, Apple is quick to point out that Liam is meant to be a prototype that demonstrates one type of pre-processing technology and encourages others to think about the problem in innovative ways. In fact, other researchers have already started to propose robotic systems that are more holistic solutions to pre-processing. [63]

To this extent, improved disassembly technology does not need to be a fully robotic system that can handle the whole heterogenous stream of WEEE that a pre-processor sees. Instead, robotics can assist the human operators performing much of the manual disassembling. For example, robots capable of screening different WEEE to identify those devices that need depollution or those devices that have high enough intrinsic value that they should skip pre-processing altogether. [6]

5.4.2 Pre-processing specialization

The EPR model adopted in many countries requires smart phone manufacturers to be responsible for their own devices. As a producer takes back its EOL smart phones, it aggregates a stockpile of these devices. At this point, that producer can become highly specialized at pre-processing these devices. To some extent, the Liam robot at Apple is an outgrowth of this effort. In its Liam announcement, Apple stated that knowing how the devices were built gave them the knowledge of how to take them apart. [54] This same approach can be adopted by other device producers.

From a regulatory perspective, a requirement that producers of smart phones maintain responsibility for their products through the EOL means that they will have the opportunity to take ownership at EOL and therefore be responsible for pre-processing. And who better to disassemble those devices than the companies that assembled them. Of course, this can be complicated by the fact that many producers outsource manufacturing to third-parties. But even still, there is real value for producers in doing this pre-processing as it empowers them to build circular supply chains while keeping most of the pre-processing work in-house. [49]

Therefore, pre-processing specialization can, and perhaps should, shift towards device producers. This can be encouraged through EPR legislation. However, business strategy can justify it, as well.

5.4.3 Design for recyclability

If and when extended producer responsibility takes hold in the United States, it will behoove smart phone manufacturers to ensure that their devices are designed with this in mind. The Ellen MacArthur Foundation and others would argue that design for *repair* would be the most environmentally benign design choice manufacturers could take. [49] However, the tension that exists here is that it can be harder for producers to control quality if devices are easily repaired on the open market. As Ulrich and Eppinger point out, environmentally conscious design is about finding opportunities where the resulting product has both higher quality and lower environmental impact, not where one has to trade off between the two. [29]

Resolving this tension and finding the win-win situations will be up to the producers as the EPR model forces them to deal with their WEEE. The question remains whether producers will look to adopt design for repair, design for recyclability or design for some other lifecycle property. That being said, the author argues that design for recyclability would be the most prudent approach. Repair, refurbishment, and reuse of WEEE are admirable goals but they seem to only prolong the inevitable: a device will eventually reach its EOL at which point it will be waste. Whether or not the environmental impact of that device can be mitigated at that point will stem from its recyclability, not its reusability. Design for recyclability also empowers producers to build circular supply chains as they recover more of the materials out of their devices; in turn, this builds to a more sustainable producer model.

This position sits in contrast to the stated opinions of the Ellen MacArthur Foundation, which stresses the power of the "inner loops" in its circular economy diagram (Fig. 3-4, [49]). However, the Foundation seems to neglect to pay ruthless attention to quality many producers have. Reuse and refurbishment is important, but it corrodes a producer's ability to control the quality of its devices in the market. Second-hand devices also cannibalize the producer's installed base of devices. It seems unlikely, then, that smart phone producers are very eager to pursue these so-called "inner loops;" therefore, striving to maximize the efficiency of the "outer loop" (*i.e.*, recycling will lead to greater benefits).

However, pushing for higher recyclability of devices means one has to be able to actually measure recyclability objectively. The tension here is just what makes a device recyclable? Is it the ability to disassemble the device? Is it the ability to recover the most monetary value of the device? Is it the ability to mitigate the most environmental impact at EOL? Obviously one's definition of recyclability is largely driven by where on sits in the stakeholder value network. Many researchers have tried to come up with a workable definition of recyclability; these definitions often get confused with the environmental friendliness of a device. [28, 64, 65, 66] A metric that outlines the recyclability of a device must at least address the following: how much energy is required to yield final usable materials, the actual recovery rates of those usable materials, the ratio (in terms of mass, environmental impact, and value) of recovered material to unrecovered material, and the cost to perform such recycling. Of course, the recyclability of a device is highly temporally dependent: as technology improves it is likely that devices will be more easily recycled. But measuring the recyclability of a device should not be done under the assumption that the technology required to actually recycle a device or component will be invented before the EOL. Rather, recyclability should be benchmarked against available technology.

Designing for and measuring the recyclability of smart phones is no easy task. But it is an important one. It can put pre-processors on a level playing field and make producers more integrated with this part of the WEEE recycling ecosystem. Just as many of the strategies outlined in opportunities for improvement in the collection system sought to better integrate consumers with the collection system, this strategy seeks to do the same with producers and the pre-processing system. A more detailed discussion of Design for Recycling will be presented later.

5.4.4 Discrete regulations

The EPR model is one example of regulation that could help improve WEEE recycling by facilitating better integration between producers and pre-processing. Another potential route that regulation could follow is similar to the regulation suggested for collection: promote better data collection. When pre-processors produce various output fractions those output fractions are sold. Each of these sales comes with documentation that indicates where material goes. If government regulation could better track these data, the general public would be able to shine a powerful light on where material ends up, thus encouraging more in-region pre- and end-processing.

With better regulation that simply seeks to collect data and make it readily accessible for the public to review, the ecosystem would not need to rely on whistle-blowers like the Basel Action Network to surface the issues it is facing today. Better availability of data does not need to compromise integrity of proprietary information of pre-processors. Even if the data only disclosed the composition of the material outbound from pre-processors and its ultimate location, various stakeholders would be able to understand the flow of macromaterial streams globally. These data could highlight how difficult it is for pre-processors to find domestic end-processing options for the various output streams from WEEE pre-processing.

5.4.5 Avoid pre-processing

One of the most radical changes to the WEEE recycling ecosystem that could be proposed would be to skip pre-processing altogether for highly integrated WEEE like smart phones. Many end-processors have advocated for this approach already. [6, 14] By skipping pre-processing many of the technical and social challenges associated with the system could be avoided. The major challenge, though, is in the ability of end-processors to recover the myriad materials out of EOL smart phones without some form of pre-processing. As already discussed, end-processing is typically focused on the recovery of one base metal (usually copper), therefore tuning these processes to recover additional metals is difficult.

However, many in the WEEE industry are highlighting the need for pre-processors and end-processors to become more tightly integrated. [67] There are multiple reasons to do this, not least of which is economic where pre-processors can work closely with end-processors to develop capabilities in both systems that generate more value for both stakeholders. Additionally, though, increased vertical integration would allow pre-processors to leverage economies of scale in end-processing and *vice versa.*

Chapter 6

Mapping of stakeholder value to the ecosystem: end-processing

The challenges facing the collection system and the opportunities to improve it are largely social in nature. The underlying challenges facing the pre-processing system are economic while the opportunities for improvement stem from technical solutions. The end-processing system is interesting, though, because the stakeholders in this system and the infrastructure with which they interact are largely borrowed from other systems. Most notably, most end-processing technologies and facilities are mining and metal refining facilities. In facing such an incumbent and entrenched system that is mature in its ways, the challenges encountered by the end-processing system are different and more complex.

6.1 Environmental factors

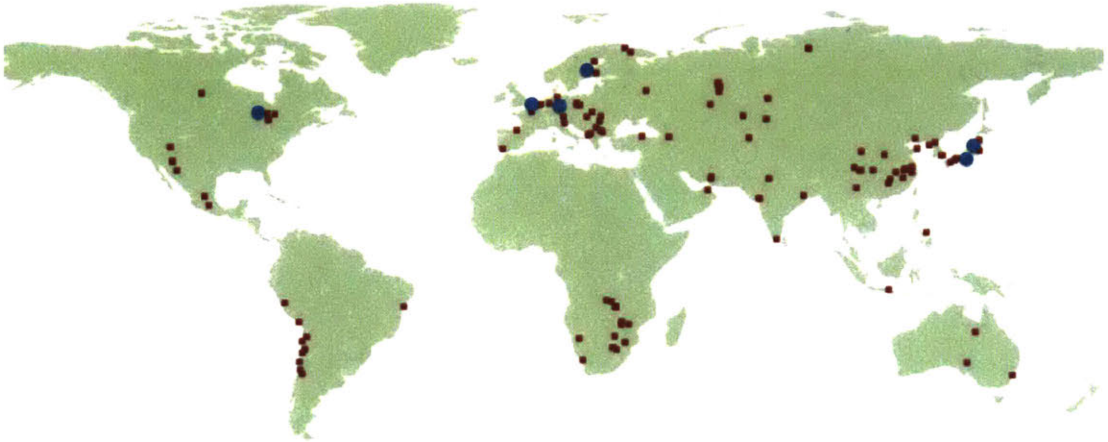
As has already been discussed, there are only a few "integrated smelters" in the world who process WEEE on a commercial scale as part of their typical furnace feed. These smelters—Glencore, Aurubis, Boliden, Umicore, and to a lesser extent JX Nippon and DOWA—can be considered the top flight end-processors. These smelters all use a copper smelting process to recover copper, precious metals and, in some cases, other special metals.

The "integrated" nature of their operation means that they can leverage multiple metal processing technologies in an essentially continuous process to recover more than just copper. For example, a normal copper smelter would convert copper ore concentrate to copper anodes or copper cathodes through subsequent smelting, converting, and anode refining furnaces. However, the other metals typically found in copper concentrates—elements like lead, precious metals, and other transition and special metals—would not be recovered because these smelters lack that technical capability. In integrated smelters the copper processing furnaces are linked to other metal processing furnaces to enable facile transfer of non-copper fractions for additional processing and further refining. In the case of Umicore, for example (which is also the most widely cited integrated WEEE smelter in the literature [14, 13, 68, 37, 38]), the copper smelter is closely coupled with a lead blast furnace that is capable of recovering the special metals normally lost to copper smelting slags.

Additionally, in order to process WEEE in an environmentally acceptable way, smelters need to have fairly advanced (and expensive) gas handling equipment. Many components of WEEE contain brominated flame retardants (BFRs) and polyvinyl chloride (PVC) plastics. When combusted the halogens in these materials catalyze the formation of dioxins and furans that are highly carcinogenic. [19] Integrated smelters processing WEEE use afterburners in their gas handling systems to superheat the off gases from their smelters to destroy these compounds before the off gas is vented to the atmosphere. This single requirement is one of the greatest hurdles that prevents typical smelters from handling WEEE; halogens typically are not found in normal copper concentrates at high enough concentrations to warrant installation of afterburners in normal copper smelting operations. In turn, despite the abundance of copper smelting operations around the world (Fig. 6-1), an extremely small fraction of these facilities has the infrastructure to handle WEEE and the capital requirement to begin handling these material streams can be prohibitive.

However, there are several new processes in various stages of development that seek to offer new means to process WEEE. The primary motivation behind these technologies is the desire to find "green" methods to process WEEE. The copper smelting

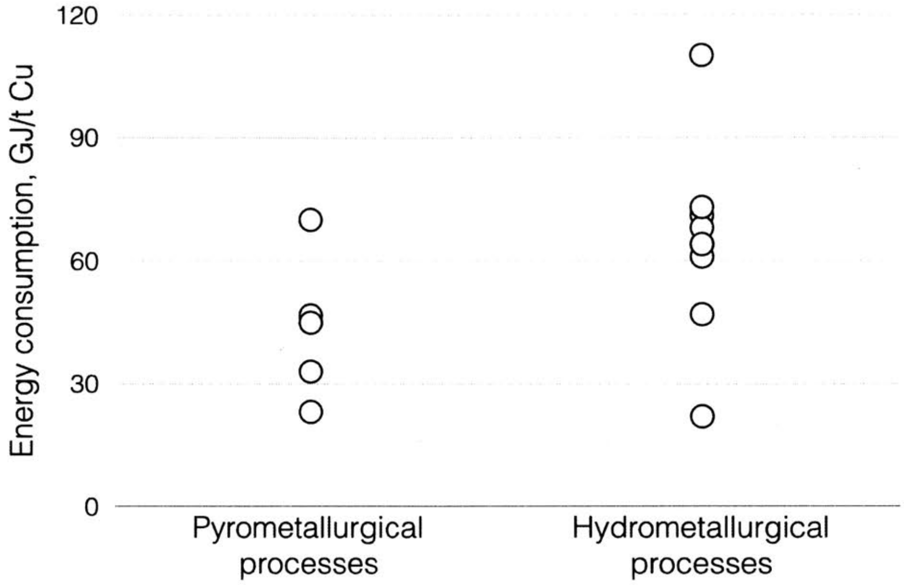
Figure 6-1: Location of copper smelters [69] (red) and integrated copper smelters processing WEEE (blue)



routes currently used by the integrated smelters are all based on pyrometallurgical processes; many of the new "green" technologies use hydrometallurgical methods to extract the metal value out of WEEE at significantly lower temperatures and lower emissions to the atmosphere. In the hydrometallurgical processes that have been proposed, the WEEE is shredded at a pre-processing facility and then leached using a combination of acids to yield a pregnant leach solution that contains the copper and precious metals. Various refining technologies (solvent extraction, selection precipitation or crystallization, electroplating, etc.) can then be used to differentially separate metals from each other in solution. [36, 35, 39]

On the surface, hydrometallurgical processes are attractive because they seem to offer lower environmental impact than their pyrometallurgical alternatives. However, many comparative studies of copper processing routes have shown that depending on how the system boundary is drawn, accounting for the production of the acids and other chemicals required in leaching operations, the overall impact of hydrometallurgical processes can exceed those of traditional smelting operations. [48, 70] Figure 6-2

Figure 6-2: Energy consumption in copper production using pyrometallurgical and hydrometallurgical processes



highlights the wide range of energy consumption associated with different production processes; each point represents an analysis of a different process either in operation or under development. It is apparent, then, that there are hydrometallurgical processes that are lower impact than some pyrometallurgical processes. However, there are also a few hydrometallurgical processes that are significantly more impactful than their pyrometallurgical counterparts.

Furthermore, leaching processes struggle to scale as efficiently as smelting operations. While they can recover a majority of the metals of interest in WEEE, the ultimate separation of these individual metals can be extremely difficult and inefficient. Thus, while "green" hydrometallurgical processes are interesting, they are not the complete solution that some would believe them to be.

6.2 Economic factors

End-processors face the same economic realities as the other stakeholders in the WEEE ecosystem. Beyond this, though, they also struggle with issues of scale: the copper processing industry is enormous and the total installed capacity of the largest integrated smelters is roughly 5.4 million tonnes of copper bearing-feed. Compared to the total estimated volume of copper contained in WEEE it becomes apparent that the host industry of the end-processing system operates at completely different orders of magnitude than the WEEE systems.

Figure 6-3: The relative volumes of copper processing capacities of integrated smelters and EOL smartphones globally

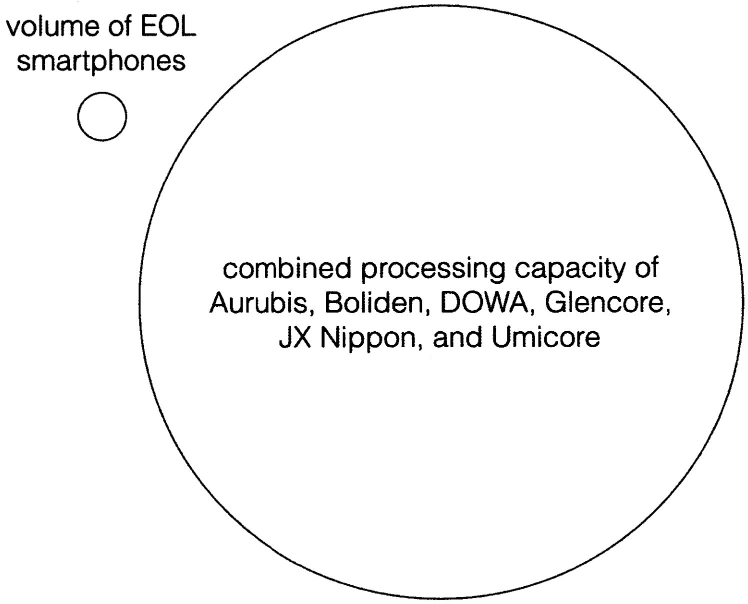


Figure 6-3 represents the total processing capacity of the world's major integrated smelters who readily accept WEEE materials. This significant disconnect illustrated by Figure 6-3 means that the WEEE industries have very little leverage over the individual WEEE end-processors and even less leverage of the entire industry. The difference between the two material streams is over two orders of magnitude: 39,000 tonnes of EOL smartphones per year versus approximately 5,400,000 tonnes of annual copper-bearing feed capacity. For additional scale reference, the global annual production of copper is approximately 5600 times greater than the total amount of copper contained in EOL smartphones. [71] Of course, the total volume of WEEE produced each year is approximately 2000 times greater than the total volume of smartphones, but the amount of copper contained in other segments of WEEE is proportionally smaller than the amount contained in smartphones on a mass basis. As a result, smartphones (and other small information and communication technology, ICT, devices) represent the most interesting stream of WEEE to copper smelters.

There is a fixed amount of overhead for an integrated smelter to process WEEE materials: the smelter must sample, assay, and determine the payout of each lot of WEEE. This activity must be performed whether the amount of WEEE received is one tonne or one hundred tonnes. As a result, the end-processors typically require pre-processors to aggregate a minimum volume of WEEE before accepting shipment of a batch to be processed. This makes it very difficult for other stakeholders in the ecosystem to try and work directly with end-processors. For example, individual electronics producers operating in the EPR model typically cannot recover sufficient volume on their own to engage directly with end-processors. Instead they need to then pool their WEEE streams with other producers or with the output of pre-processing operations. This action, though, can dilute the overall value of the WEEE stream reaching the end-processor who has different types of commingled WEEE: materials very low in payable metals are mixed with high-grade streams like smartphones.

In response to this disconnect between available capacity and actual supply, new business models have evolved to fill the void. For example, many pre-processors have started offering end-processing services. However, the overall efficiencies of these operations are typically very low and focus mainly on recovering the precious metals contained in the WEEE. Furthermore, additional refining is typically required, so the integrated smelters are still involved. A more promising approach has been adopted by a relatively new company called BlueOak Resources. BlueOak seeks to adopt the highly successful model developed by NuCor steel mini-mills to the world of WEEE end-processing. In much the same way that NuCor disrupted the steel industry by offering extremely small-scale, distributed, and efficient steel refining services to scrap yards, BlueOak hopes to build a network of small-scale WEEE refining operations close to major WEEE generation sites. [72] BlueOak is using plasma furnace technology because it is more scaleable than traditional smelting furnaces and offers potentially higher material recoveries at lower operating cost and environmental impact. However, one of the challenges facing BlueOak is the fact that they still must interact with large-scale end-processors: the material produced by the plasma furnace is at the purity of blister copper and still requires refining before the precious metals can be recovered.

Still other companies are offering end-processing as a service wherein they will lease the processing technology to pre-processors. Companies like MINMET based out of Hong Kong have developed highly modular hydrometallurgical "plants on a pallet" that can be installed at a pre-processor's facility and used to recover the major payable metals. While attractive because it creates new revenue and value for pre-processors, this model requires stakeholders to develop new areas of expertise that might be outside of their core business capabilities.

On the whole, many of these new business models are found wanting in that they do not provide the "one stop shop" with which many pre-processors (or even collectors) are familiar. Adding additional complexity to the WEEE ecosystem by introducing new links into the processing chain instead of making the chain shorter or simpler seems like an unsustainable solution. Stakeholders in this system want a simple scheme where the WEEE can be passed to a single stakeholder capable of meeting their needs. Many of the start-ups or alternatives looking to disrupt this industry are incapable of filling this core requirement at present.

6.3 Technological factors

The inability of start-ups to fill the core "one stop shop" need is largely driven by technological factors. To this point, technological limitations stand in the way of end-processors creating new value propositions for other stakeholders in the wider ecosystem. Especially in depressed commodity markets where the historical economic drivers that made WEEE processing more financially viable, end-processors have struggled to create new value by offering additional services. This applies not only to the start-up companies looking to fill small niches in the ecosystem but also to the large incumbent firms with an established processing base.

On one hand, one of the key technology factors standing in the way of additional value creation by end-processors relates to the various material fractions created by pre-processors. Materials like plastics, glass, and speciality metals are largely lost during end-processing because these facilities are based on copper pyrometallurgy not optimized for recovery of these materials. As previously discussed, the plastics in most WEEE streams that are not separated during pre-processing are used as fuel and reductants during the initial stages of end-processing. Likewise, any glass still contained in the WEEE stream acts as a flux to form slag during pyrometallurgical processes.

The additional metals contained in WEEE are often lost during end-processing. The focus on recovering gold and other precious metals and copper has meant that the steadily increasing use of other metals in electronic products has gone largely unaddressed by the end-processing system. Notably, the average smartphone uses at least seventy different elements, which represent 84% of the stable elements on the periodic table. [73] This has increased over the past decades from only a couple dozen different elements used in electrical components to the current state-of-the-art where just about every element is used with increasing use of "critical" elements like rare earths and conflict materials. [74, 75]

With elements like the rare earths there is significant supply risk associated with their sourcing as China currently supplies more than 90% of the world's supply. However, current end-processing technology cannot recover these materials. Rare earths are found in smartphones as permanent magnets (NdFeB magnets); when going through pre-processing steps, these extremely brittle materials are pulverized and report to multiple fractions as they are drawn to other magnetic materials. [76, 77] This chaotic distribution means that the rare earths are not concentrated in a single material stream for targeted recovery by end-processors. When rare earths do pass through end-processing, they almost always report to the slag of smelting operations because of their high oxidation potential; recent research has shown that many slag piles are unusually rich in rare earths. [78] Other critical materials often lost during end-processing include tungsten (used in the vibrating alert modules of smartphones), indium (used in the ITO layer of touchscreen displays), tin (used in solder), and transition metals like gallium (used in integrated circuits).

An end-processing operation capable of recovering these materials in addition to the typical copper and precious metals would offer additional revenue streams to other stakeholder in the WEEE ecosystem. Additionally, and perhaps more importantly, these end-processors would be able to offer value in terms of decreased reliance on risky supply chains, lower overall environmental impact, and greater opportunities for closed-loop supply chains.

6.4 Opportunities for improvement

With the various environmental, economic, and technological factors affecting end-processing there are several opportunities for improvement that span more than one type of factor. For example, with a not-so-recent push to eliminate PVCs and BFRs from electronic products, the need to restrict their end-processing to exclusively integrated smelters is disappearing. [30] At this point, the presence of legacy products in WEEE streams are the only reason these materials must continue to be processed in integrated smelters. If stakeholders in the ecosystem could better identify those products that do not contain dioxin-forming materials, they could open the door to a wider end-processing market, thus addressing environmental restrictions and economic factors to make recycling of these WEEE materials more viable.

In a similar vein, newer EOL smartphones contain the critical materials outlined above; developing the technological capabilities to recover these materials yields new economic value for many stakeholders in the ecosystem and addresses many of the environmental factors associated with end-processing. However, most of the technologies that target these critical materials (and the less valuable materials like plastics and glass) are not available at commercial scales. Figure 6-3 illustrates that the WEEE industry and its stakeholders do not hold enough leverage over the end-processors to demand that they invest in and adopt these developmental technologies. As a result, the start-up or more risk tolerant members of the ecosystem will have to bear the burden of deploying these new processes. This, then, implies that their roll-out will likely be slow and at small scales initially. However, this affords the entire ecosystem to evolve; it may also force a radical paradigm shift much in the way NuCor affected the steel industry and how BlueOak hopes to in this system of systems. That being said, greater attention paid to this emerging (and growing problem) can only help bring about change sooner. In the meantime end-processors need to work with other stakeholders further up in the value chain to find improved ways to aggregate WEEE so that economies of scale can be made available to smaller players in the ecosystem. These economies of scale would benefit multiple stakeholders: collectors and pre-processors would be able to get better financial returns on the material they collect and end-processors would be able to operate more efficiently.

From a strictly American point of view, much of the real innovation in the WEEE recycling ecosystem—particularly in end-processing—is happening overseas. The exact reason for this is difficult to pinpoint, but it is likely largely attributable to the greater and more mature emphasis placed on resource efficiency found in the European Union and developed Asian countries. As a result, the push to find domestic end-processing technologies in the United States is further complicated by the fact that there is comparatively little fundamental research being done by American stakeholders. A seemingly successful model has emerged in the European Union where industry/academia consortia have been established to promote research and development. Furthermore, government-funded organizations like the Fraunhofer Institute in Germany (loosely modeled on the Bell Labs model) have been used to incubate nascent technologies before spinning them into commercial realities.

Finally, the economic drivers that anchor the end-processing system likely suffer from unrealized externalities. The conversations had in the energy industry where concepts like carbon pricing and assessing the real value of energy sourcing decisions can also be had in the WEEE ecosystem. In much the same way that researchers and industry have tried to place dollar values on decisions around renewable energy technologies and policies, a similar effort could be made to assess the real value of an improved end-processing system. Such an analysis, where the real value of increased recycling or improved material recovery is identified, could be used to justify the large-scale investment and behavior change that are required.

Chapter 7

Ecosystem opportunities

Dissecting the WEEE processing ecosystem into its three major subsystems is an important exercise and useful for understanding some of the operational challenges each subset of stakeholders face. However, it is important to zoom out to a higher level of abstraction to see the wider ecosystem and understand where opportunities at the aggregated level exist. At this level of decomposition the whole ecosystem problem statement can be framed as

to enable sustainable operations in the electronics industry
by creating opportunities for close-loop supply chains
using WEEE recycling infrastructure.

In this sense WEEE recycling functions to make the use of recycled materials in next generation electronics possible. Harkening back to the concepts of sustainability outlined in Chapter 1 and the ecosystem overview provided in Chapter 2 it is easy to see why groups like the Ellen MacArthur Foundation have placed such a strong emphasis on WEEE recycling as part of their mission to realize a circular economy. [49] Chapters 4, 5, and 6 have outlined the opportunities that exist within individual systems to improve the overall dynamics of the wider ecosystem. However, as described by de Weck *et al.* the greatest opportunity for improvement in a System of Systems lies in the interactions between systems. [34] Therefore, one has to ask what types of cross-system interactions and interfaces can be improved to make WEEE recycling better as a critical component to a wider circular economy in the electronics industry.

7.1 Design for Recycling, DfR, and measuring recyclability

Design for "X" where "X" is any modifier like "manufacturing, environment, repair, etc." is not a new concept and represents the importance of including various aspects of a product lifecycle in the design phase. In their critique of the WEEE ecosystem, Chapters 5 and 6 highlighted that it is simply very difficult to pre-process and end-process WEEE. Therefore, the simple solution is to make recycling electronics simpler. Design for Recycling, or DfR, is concept that there are certain design considerations and choices that can be made to make recycling at EOL significantly easier. However, it is one thing to say that products should be designed for recycling and it is another thing for it to actually happen. One of the key issues here is that no one seems to be sure what recycling at EOL means; the lack of agreement on the fate an EOL smart phone will take means that it is difficult for a designer to understand how their design decisions will affect the ultimate fate.

7.1.1 Measuring recyclability

The key issue here, then, is the lack of measurement of "recyclability." If a designer is looking to make a product more recyclable at EOL he or she needs to be able to measure the difference between two or more design options to understand how the differences in design will impact the recyclability. Of course, as has been outlined in previous chapters, "recyclability" can quickly become a difficult factor to quantify as an individual smart phone will go through multiple processes as it is recycled. Realizing this, researchers have started to develop potential methods of quantifying recyclability. [28, 64, 65]

Yamasue *et al.* have put forth a method that effectively views EOL products as "urban mines" and then compares the difficulty of recovery materials from the urban mine to an actual mine. [66] This method could be extended to set benchmarks that can be used to determine whether an EOL product's design make it easy enough to recover the material value such that it is more advantageous to recycle instead of mine virgin material. Of course, a critical issue is that the method proposed does not outline a means to convert a design into an auditable quantity for comparison to virgin mines. Further extension of this work should emphasize the connection between original design choices and the ease with with pre-processing and end-processing can recover the material value.

A step closer to this realization was put forth by Cong *et al.* in their analysis of hard disk drives and how the physical connectivity of the drive affected its recyclability and potential value recovery. [79] The really interesting aspect of this work is that the authors took a truly systems thinking approach to modeling EOL treatment of WEEE by showing a network visualization of the product architecture (see Figure 2 in [79]). As a result, the authors illustrated how the connectivity of the drive translated into value recovery during pre-processing and how this ultimately affected the opportunity for revenue creation during recycling. This method highlighted that acquiring EOL hard disk drives and dismantling them (during pre-processing) were the major cost drivers in recycling; however, the work did not extend these considerations to how they could be affected by different design choices. The work of Cong *et al.* sets a very good framework for how researchers can measure the ultimate recyclability of a product; these findings need to be parsed against the design decisions that affect these results.

Some of the most comprehensive means of measuring recyclability have been put forth by the Ellen MacArthur Foundation and by researchers in the European Union. The EMF has outlined its concept of "circularity indicators" alluding to their emphasis on building closed loop supply chains as part of the circular economy. [80] In its indicator algorithm, the Ellen MacArthur Foundation weighs four factors: what share of materials used to manufacture a process are from virgin sources versus recycled sources; how does the useful life of a product compare to the average useful life of similar products; how much of the product at EOL is landfilled versus recycled; and how efficient are the recycling processes that are currently available for discrete material streams at EOL. These four metrics are part of a database developed by Granta that presents the designer with indicators assigning a single value to a material that can be rolled up in a Bill of Materials for a total product to show just how "circular" a final product is. This, in turn, can be used to show how different material choices make a product more or less circular—largely by choosing materials that are more recyclable and extend a product's useful life. Some of the criticisms of this methodology, though, are that it is strictly focused on material selection: in many cases it is the mix of materials and their interfaces that can dramatically affect recyclability. For example, mixing incompatible plastics can make recycling plastics virtually impossible and this is not necessarily captured in the recycling efficiency metric, which looks at the recyclability of the individual plastics, not the composite. The EMF methodology does not highlight this interaction for a designer.

A similar approach has been taken by Chancerel and Marwede in their draft report to the Joint Research Council of the European Commission. [81] This report highlights that in methodologies like those proposed by the EMF it is crucial to understand the actual recycling rates achieved in the industry if one is to weigh recyclability of design choices. Chancerel and Marwede promote methodologies that highlight how material choices affect ultimately value recovery and they set out to propose a method to periodically calculate the recyclability/recoverability rates (RRR) of different materials routinely used in electronic products. This effort, then, is tangential to the concept of DfR as it functions as the groundwork used to provide more quantitative feedback on different DfR metrics.

7.1.2 "Rules" of DfR

If an effective method of measuring recyclability can be found this can be fed into a DfR process to weigh different design choices. Ultimately, this would hopefully lead to the development of useful "rules" for Design for Recycling as key levers for improved recyclability could be highlighted. It would seem that this effort is still in relative infancy given the relative vagueness of the published "rules" today. For example, the Institute of Scrap Recycling Industries (ISRI) has four incredibly non-specific rules of DfR: make consumer products more recyclable, reduce environmental risks associated with consumer products, control special environmental problems, assist manufacturers of consumer durables. A few more useful concepts have been proposed.

Reuter and van Schaik have provided real world examples of applying design considerations to make products more recyclable. [82, 83] In their work the authors highlight the importance of understanding the WEEE recycling ecosystem in the development of their ten rules for DfR. They correctly point out that there are several limitations that currently inhibit increased recycling of WEEE; in turn, they argue, that DfR can address some of these limitations while other stakeholders or components in the ecosystem must be addressed to increase overall recycling. Their ten rules of DfR taken from [82] are outlined below. The first five rules set the general framework in which specific rules must be developed on a case-by-case basis; the second set of five rules are more specific rules that could be imposed.

- DfR rules are product and recycling system specific; oversimplification of recycling by defining general DfR rules will not produce the intended goal of resource efficiency
- DfR needs model and simulation based quantification
- Design data should be accessible and available in a consistent format, which is compatible with the detail required to optimise and quantify recycling performance of products for all metals, materials and compounds present
- Economically viable technology infrastructure and rigorous tools must be in existence for realizing industrial DfR rules and methodology
- CAD, Process and System Design tools must be linked to recycling system process simulation tools to realize technology based, realistic and economically viable DfR

- Identify and minimize the use of materials, which will cause losses and contaminations in recycling due to material characteristics and behavior in sorting
- Identify components/clusters in a product, which will cause problems and losses in recycling due to combined and applied materials
- Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options
- Labeling of products/components based on the recovery and/or incompatibility so that they can be easily identified from recyclates and waste streams
- Be mindful of liberation of materials in design

While it is certainly true that trying to develop overly specific rules for DfR can be futile, the latter fives rules from [82] highlight the general importance of material selection. In general, it seems that successful DfR comes down to understanding how different materials are processed at EOL. For example, a fundamental—even if simplified—understanding of how different metals are processed in pre- and end-processing system can guide design decisions. Taken further, this understanding can motivate the necessity of minimizing the number of different materials used, the need to make materials compatible with one another, and the need to make separating dissimilar materials easy. As an example, it has been described how non-ferrous and ferrous metals are separated in pre-processing; thus, making these metal fractions more easily separated in the pre-processing of a device is crucial to increasing the overall recyclability of a product.

Overall, DfR is a business strategy to make products more recyclable as part of the broader goal of making operations more sustainable through the development of closed-loop supply chains. However, DfR can also be viewed as a subset of other design initiatives like Design for Environment, DfE. In this sense, improving the overall ecosystem for WEEE recycling can be thought of as an ongoing collaboration between product designers and the broader ecosystem. This collaboration stems from the requirement that designers understand how the ecoystem operations—both functionally inasmuch as how the technology operates and what its limitations are, and economically inasmuch as what are the drivers that make recycling financially viable. Some companies have started to highlight this as part of their broader DfE strategy. Huawei, a rapidly rising star in the smart phone industry, has published its efforts to improve the overall environmental impact of their products. [84] The authors highlight that "it pays to pursue green innovation" and that the overall "eco-design" (essentially DfE) of a product has to consider the entire EOL of a product. As a result, Huawei considers collection, pre-processing, and end-processing of its products; this, by definition then, must involve some sort of DfR. Their focus on DfR is mainly quantified by the "recyclability" of the materials in their products; it has already been shown that this is a fairly restrictive focus. But Huawei is making important steps.

7.1.3 Additional design steps beyond DfR

Emphasizing recyclability and proper WEEE management is an obvious strategy. However, in addition to better, more recyclable designs, manufacturers and other stakeholders in the ecosystem can emphasize a few other critical design strategies that address the WEEE problem. For example, in addition to making products more recyclable, material selection can seek to use fewer non-renewable (and non-recoverable) materials (this is inline with the sixth point in the "rules" of DfR). Additionally, devices can be designed for longer lives with increased durability. While this strategy may not extend the product's life for the first user, it does enable a product to be used by second- and third-generation users, thereby keeping the product in circulating stock longer. Such a strategy can shrink the flow of WEEE entering the ecosystem. Finally, product design should seek to minimize the use of toxic or hazardous materials—both in the final product and in the product's production process.

In general, these strategies are part of a broader design focus that should acknowledge the impact smartphones and other electronic products have at EOL. Opportunities beyond product design will be illustrated below.

7.2 Improved communication and prioritization in the ecosystem

The work by Huawei shows that companies are starting to push other stakeholders in the ecosystem to begin thinking systematically about WEEE recycling and how to realize a circular economy. As has been highlighted above, a critical weak link in the ecosystem exists at the interfaces between discrete systems. The weakness stems from various stakeholders communicating how they are going to prioritize recycling and recyclability. Many electronics companies have already begun emphasizing the overall sustainability of their supply chains. However, the emphasis so far has focused mainly of the low hanging fruit of sourcing renewable energy sources and improving material efficiencies. Both initiatives are certainly important, but they can only take a supply chain so far and ultimately will never truly close the loop by reintroducing recycled material to the "start" of the supply chain.

To make this possible, at least one stakeholder in the ecosystem needs to put a stake in the ground that they will require recycling as part of their product development cycle. As discussed in the previous section for product designers (the manufacturers) this could mean specifying a minimum recycled content in new devices or a minimum recycling rate that must be achieved. For collectors, this could mean requiring a minimum collection rate or return on investment that must be met through their collection activities. To some extent, many of the EPR policies in place across the globe already seek to drive toward this goal. For pre-processors, similar goals could be developed and communicated out to other stakeholders. Finally, for end-processors, recovering a greater variety of materials from WEEE at lower cost could be a critical milestone.

In general, the industry seems to be looking towards the device manufacturers to take the lead on this initiative. And to some degree, this seems logical: the wider recycling ecosystem (from collectors to end-processors) handles significant volumes from many different source industries; the electronics industry (and the smart phone industry, more specifically) is only a subset of their business. So the actual "recyclers" in the ecosystem have little incentive to drive this change. However, device manufacturers have limited visibility into what is actually capable in the recycling space. As a result, greater communication needs to be driven between the two halves of the ecosystem. The device manufacturers should certainly push the industry to its limits and specific requirements that will be difficult to achieve.

Communication that comes as top-down (*i.e.* from device manufacturers to others in the ecosystem) will be successful at establishing goals but it will struggle to set a roadmap for how to achieve these goals. For example, if a device manufacturer says that its next product must contain 20% recycled content it will be an important milestone that members of its supply chain must target. However, the communication must extend further to outline how to achieve this goal. This communication would be best in a bottom-up approach where other members of the ecosystem communicate their vision for achieving this. For example, collectors can communicate out how they will seek to increase collection to increase overall flux of recycled material into the ecosystem. Pre-processors and end-processors must communicate out how they will recover material at high efficiency (and lower cost) to make increased recycled content in new products actually viable.

Device manufacturers with greater control over, or at least visibility into, their supply chains will likely be able to drive this change most effectively. Interestingly, a company like Fairphone—essentially an extremely minor player in the smart phone industry—has been able to achieve some of these successes. [85] Fairphone's success demonstrates that all companies—not just the mega producers like Apple and Samsung—can achieve great things in managing their supply chains to make them more sustainable, and hopefully, more circular.

7.3 Defining success in the ecosystem

Along the way, industry stakeholders have to decide how to actually measure recycled content in the broader view of a circular economy. This measurement comes down to the traceability in a circular economy and how to define its success. Obviously, WEEE recycling is part of the circular economy (see Figure 3-4) and success means making the supply chain as "circular" as possible. But ultimately an individual stakeholder in the ecosystem wants to know how it is contributing. Total success could be defined as having complete traceability throughout the supply chain (whether it is linear or circular) so that one could confidently understand the source and destination of every material; this would make a figure like Figure 3-3 significantly more accurate and more useful.

This traceability—in theory to an atomic level of each element in a product—would make measuring success easy. However, in reality, this level of detail will be extremely difficult to achieve. Therefore, perhaps the simplest approach would be a mass balance approach. If a stakeholder can track the amount of material they put into a subsystem of the ecosystem and the amount of material they take out of the subsystem, it could sum these inputs and outputs to understand how its material flows through different systems. For example, a device manufacturer interested in increasing recycled content in its devices would need to know the volume of EOL products collectors receive. The amount would then pass to pre-processors and end-processors with some known efficiencies ultimately resulting in a known quantity leaving end-processors as raw material the device manufacturer could use in new product manufacturing. Knowing the necessary data to perform this calculation will be extremely difficult. However, if this is a (or the) metric used by a company to define success, the company can go build these circular supply chains in such a way that these data will be collectable. To some extent the manufacturers of the Fairphone 2 have tried to accomplish this with the conflict minerals (tin, tungsten, tantalum, and gold) in their smart phone. [85]

Ultimately, the mass balance approach is effectively a statement that "we put a known amount of material into the recycling ecosystem and we are going to pull an equal amount out of it, whether or not it is actually ours." An improvement on this model would allow a stakeholder to say whether or not the physical material taken out of the ecosystem is actually the same material put into the ecosystem. There are increasingly complicated ways to do this from batching material entering the ecosystem such that "plug" of material moves through the ecosystem in a "plug flow" manner analogous to fluid flow with no mixing. A more complicated—and likely more expensive—manner to achieve this would be to build an entire supply chain dedicated specifically to an individual stakeholder's needs such that the only material entering and exiting is that stakeholder's. This, though, would require an extreme amount of ownership of one's supply chain.

However the ecosystem's definition evolves over the coming years it will be critical that the ecosystem work with external stakeholders—namely consumers and governments—to shape expectations. The industry must embrace both stakeholders as potential champions who will keep them honest and focused on the ultimate sustainability-oriented goals. This means that ecosystem stakeholders must communicate both their successes and their shortcomings. The successes will highlight victories and maintain the momentum that necessary to keep driving innovation and interest. The shortcomings, though, will highlight areas that new thinking is needed. For example, in the end-processing system, the stakeholders seem brutally focused on the business-as-usual concepts that will inhibit innovation and increased recycling. The real progress being made in this system is with the stakeholders seeking to disrupt the business models used in the business-as-usual concepts. Highlighting these cases will bring new thinking critical to making new concepts realities.

7.4 Involving regulators

While the responsibility to develop DfR standards and definitions of success rests largely with the manufacturing industries, regulators—whether they are governments or NGOs—must also be part of this conversation. As previously highlighted, many pre-processors feel like the regulations and certifications that apply to their operations have been unable to keep up with the evolving nature of their industry. In this light, if OEMs develop their own vision for the WEEE recycling ecosystem without effectively communicating it to regulators, the entire industry could find itself in a situation where orthogonal requirements and expectations from different stakeholders make efficient and financially viable operation difficult.

To accomplish this, regulators must give OEMs and key stakeholders in the WEEE recycling ecosystem a place at the table when considering new regulations. A balance needs to be struck where both sides of the negotiating table can trust each other and that all stakeholders have a fundamentally aligned view on their role in the future sustainability of the world. Regulators have to find a means to encourage innovation and risk taking while ecosystem stakeholders in the recycling industries need to find ways to work with regulators to effectively communicate their concerns.

One key example is the current overarching burden that international movement of WEEE incurs. In theory the purpose of the regulation is to restrict the movement of hazardous waste streams to developing regions of the world ill-equipped to process them responsibly. However, as the recent BAN report highlighted, this is still happening. [58] The next generation of regulation needs to understand the end-processing landscape inasmuch as that there are certain regions of the world extremely well-equipped to process specific types of secondary materials. For example, because it dominates rare earth production, China also leads the world in rare earth refining technology; if companies were able to move rare earth-containing materials to China easily it would be possible to significantly increase the amount of secondary rare earths on the market. In general, as has been discussed, the United States has fallen behind the rest of the developed world in developing innovative recycling technologies. In order to make recycling more efficient for American recyclers, then, they need to be able to move material overseas to the hubs of state-of-the-art recycling technology. Furthermore, some argue that overly strict regulation prevents access to "qualified" recyclers and drives WEEE to the "informal" sector, which is significantly less efficient at processing materials and extracting value. [50] Future regulations should respect this reality.

Alternatively, some authors argue that regulation needs to be stricter in certain areas of the ecosystem. For example, Hageluken *et al.* argue that regulation needs to be structured to encourage "quality" recycling, which is essentially that idea that the final products of a recycling process must be of sufficient purity and quality that they can be reused in the highest possible value application. [24] Of course, the authors of this paper come with certain biases as they are representatives of Umicore and have a vested interest in more material being processed by their company. However, they make a valuable argument inasmuch as it is important to encourage WEEE recycling in processes that can recover the most material in the highest value form. In support of this argument the authors outline nine regulatory approaches that could support higher quality recycling systems, some of which of been mentioned above: a consistent method to measure recycling efficacy, a uniform requirement for EPR, a precise target for landfill reduction, a more harmonious regulation of international WEEE shipment, certification of recycling facilities, a focus on recycling specific WEEE products (namely cell phones), a means to make shipment of WEEE to certified recyclers easier, clearer regulation governing "hazardous" substances, and more support of innovation in recycling.

These seemingly contradictory options highlight a key result of systems thinking: finding and applying leverage at the right point. Both camps—those for and against stricter regulation—demonstrate that blanket regulation is (and has been) ineffective. Rather, targeted regulation that addresses the underlying root causes of inefficiencies is needed. For example, regulation needs to encourage flow of WEEE to the best available recyclers and discourage flow to regions (areas in the developing world) unequipped to handle the material effectively. This means that it needs to be easier to move WEEE internationally *if* that WEEE is going to a pre- or end-processor capable of handling it; that means that it should be possible to export certain WEEE streams (*e.g.* rare earth-containing materials) to specific places in China even though China faces real challenges managing general WEEE streams. Likewise, regulation needs to encourage "quality" recycling while discouraging mass-based recycling that measures success only in terms of the sheer volume processed and not the quality of the material recovered. Furthermore, given the declining value contained in smartphones, stronger EPR regulations need to account for the lower economic returns received by ecosystem stakeholders.

7.5 New business models

An opportunity that spans the WEEE ecosystem is the chance to introduce new business models governing how businesses and consumers interact with recycling systems. Some have pointed out that other recycling ecosystems that handle different material streams are significantly more efficient than the WEEE systems. [24] Hageluken *et al.* argue that the two factors supporting these highly efficient ecosystems are the presence of business-to-business (B2B) relationships and extremely aggressive regulations. In the former factor, a quintessential example is the fluid catalytic cracking catalysts where the refinery using the catalyst is able to return the used catalyst to the catalyst producer who will recycle the materials and return a fresh catalytic material. The latter factor is best exemplified in the case of lead-acid car batteries where consumers have access to a robust infrastructure makes recycling old batteries possible and they receive a deposit back on returned batteries.

Many have argued that the smart phone industry would enjoy higher recycling rates if it moved towards a B2B model wherein individual consumers would essentially lease a device and purchase a service rather than a product. On the promise of receiving a newer model when the lease was up, consumers would return EOL devices at much higher rates than are currently seen. Of course, this thinking is well aligned with the general shift in consumer markets towards the "sharing" economy where individuals are less inclined to ownership and are more interested in on-demand services. In fact, some device manufacturers and cellular service providers have started to offer contracts that effectively lease devices on fixed terms. However, it should be noted that the motivation for these new business models is unlikely to be the potential recycling opportunities; the primary motivations lie in the opportunity to drive upgrade cycles (*i.e.* the frequency at which consumers trade-in an older model for a newer model).

While the B2B model may help move WEEE recycling in the right direction, it would really only address the collection system. To improve the other systems in the ecosystem innovative business models that create new value for multiple stakeholders will be required. To some extent BlueOak is trying to do this by changing the scale and manner in which pre-processing and end-processing are done. In general, though, because the end-processing system is dominated by smelters whose primary business is not WEEE recycling it will be difficult for them to be change leaders in the recycling ecosystem. Holistic thinking is required to drive initiatives like increased vertical integration (or at least increased supply chain control) from device manufacturers so that they have greater control of the amount of recycled content in their products. Similarly, finding ways to drive increased efficiency while minimizing costs (or finding new value to offset costs) will be necessary to combat the unfavorable economic climate facing many stakeholders today.

Chapter 8

The role of the manufacturer

Up until this point, this thesis has focused almost exclusively on the role that the collection, pre-processing, and end-processing systems play in the wider ecosystem of smartphone recycling. However, Figure 2-8 shows that device producers—the ultimate manufacturers in this ecosystem—also play a fairly central role. To this extent, an analysis that does not discuss the opportunities available to the manufacturers would be lacking.

Some of the more obvious opportunities were discussed in Chapter 7. Design for Recycling constitutes the control a manufacturer has over the initial design of a product to ensure that it is more easily recycled at EOL. Ultimately, this translates into higher recoveries and greater profitability for the recycling ecosystem as the collection, pre-processing, and end-processing systems are able to function more efficiently. However, DfR and some of the other design strategies already illustrated represent what could be called "if only" solutions: if only manufacturers made the products more easily recycled, the ecosystem would operate more efficiently and the industry as a whole would become more sustainable. This position is weak; while DfR would certainly improve things, it has to be part of a wider solution set.

Chapter 7 begins to elucidate some of these other solutions from an ecosystem perspective. Avoiding the "if only" solutions, the manufacturer also has a greater role to play in terms of their ability to facilitate communication. The manufacturer needs to shift its paradigm from that of a participant in the ecosystem to that of the ecosystem's architect (or at least the ecosystem's "system integrator"). Because it sits at the nexus of the "start" and "end" of the recycling value chain, the manufacturer has the unique opportunity to reach into the interfaces between systems and control information flow. In this sense, if manufacturers were to take a more architectural role, they could recast the ecosystem to drive efficiency and profitability. There are several reasons that the manufacturer's role as architect could drive change and improve the overall status of the ecosystem; they will be enumerated below with the goal of making these opportunities operational.

8.1 Internalizing savings

When end-processors recycle metals they usually do so in a batch that contains both recycled content and virgin content. The resulting final product is a metal ingot (or other product shape) that meets the necessary purity specifications to be traded on a metal exchange. By mass balance the ingot contains an amount of recycled content and an amount of virgin content, but this composition is not specified on the exchange and is rarely reported. However, to the end-processor, there is a difference: profit margin. The end-processor typically buys metal scrap for recycling and incorporation into final product at a discount of the exchange price; however, when the metal is sold on the exchange it is sold for full price. Additionally, since the amount of processing required to refine the scrap metal to final product is much less than the amount of processing required to refine the virgin metals, the profit margin on the scrap is higher than the margin on the virgin material. As a result, the end-processor makes more money selling recycled content than virgin content. However, since the market does not distinguish between the two types of final metal products, the price of what is sold does not distinguish between them either, and the end-processor is the only one with the ability to internalize these savings.

This represents an opportunity for whomever is interested in sourcing more recycled metal for their products. At present, there is no motivation to distinguish between the sources of different metals (aside from certifying that metals are conflict-free, when necessary). However, if a manufacturer could specify a required recycled content in the metal it buys it could construct a pricing structure that guarantees that the end-processor receives a fair margin. In essence, the manufacturer promises to pay a margin that accurately reflects the virgin and recycled content of the ingot. The benefit to the manufacturer is obvious because they would be able to source metal at lower overall prices. For the end-processor, the guarantee that a margin will be maintained is beneficial. It is also beneficial that the contract requires the manufacturer to take a specified volume of both recycled and virgin content, which allows the end-processor to begin to more strategically source recyclable scrap.

(It should be noted that such pricing structures are already in place for many recycled plastic feedstocks, though depressed oil prices have erased much of the price advantage held by recycled plastics. [86, 87] The key difference between plastics and metals, though, is that the physical properties of recycled plastics are often different from the virgin plastics.)

Such an arrangement requires that the manufacturer reach very far into its supply chain; it is unlikely many manufacturers are currently sourcing their raw metals themselves—they likely rely on their component manufacturers to handle this task. This increased exposure to the upstream would be required if the manufacturer was to effectively internalize these savings. This exposure could allow the manufacturer to dictate better purchasing terms, as well, but it could also expose them to greater supply risks. From a corporate social responsibility (CSR) perspective, though, better control of raw material sourcing is always progress in the right direction. Further discussion about vertical integration is provided later.

In effect, this arrangement allows both the manufacturer and the end-processor to internalize the savings that recycling metals produces. In the current system, only the end-processor realizes these opportunities. Of course, as soon as the manufacturer is able to internalize savings from recycling, its incentive to increase recycling increases dramatically; a positive feedback loop emerges and the ecosystem (hopefully) improves. Furthermore, this system would complement the goals of programs like EPR: EPR essentially seeks to make producers and manufacturers more account-able for the negative externalities their products and operations create. EPR is, of course, a positive step as those who create externalities should bear the weight of those actions. However, as Ulrich and Eppinger point out, real innovation can be found when "win-win" opportunities are identified. [29] This arrangement, then, allows manufacturers to internalize more of those externalities, except now they can realize the positive along with the negative. The result is the win-win designers, manufacturers, recyclers, environmentalists, and the rest of us, are looking for.

8.2 Creating demand for recycled content

In much the same way that enabling more members of the ecosystem to internalize savings brought on by recycling can drive change, manufacturers have the unique capability to significantly increase demand for recycled content. While the smartphone industry is only a small player in the global market for different metals, it is significant in its potential for growth and exposure to consumers. As a result, the smartphone manufacturers wield enormous amounts of power through their supply chains, customer bases, cash flows, political power, and general public exposure. Therefore, even a small movement by the manufacturers has the potential to have multiplicative effects on the rest of the ecosystem. In no small part, as previously mentioned, manufacturers could simply stimulate demand for recycled content by specifying it in their products. This, in a capitalistic world, would raise the price members of the recycling ecosystem could fetch for their recycled content thereby motivating market efficiency improvement in the functioning of the overall system. Setting a new level for the recycled metals market would encourage increased recycling rates (as some of this new value reaches individual consumers and system stakeholders) while also furnishing incentive to drive investment and research.

To this point, the manufacturer who is willing to begin creating this demand is the one that is most capable of applying a Systems Thinking approach to the recycling ecosystem. Such an approach will not be trivial. However, by sitting at the interfaces within the ecosystem, the manufacturer can strive to make the interfaces more efficient. The manufacturer can promote information sharing, identify new economic opportunities, or provide additional incentive for material recovery and utilization. These new relationships, in turn, would likely yield actionable information for the manufacturers when they make design decisions and evaluate trade-offs. This perspective would mark a departure from the historical perspective wherein the three subsystems—collection, pre-processing, and end-processing—are viewed separately. This additional level of integration is perhaps the only way the entire industry can work more sustainably.

8.3 Integrating into the supply chain

Vertical integration into a supply chain is a risky endeavor. However, for the manufacturers in this ecosystem it may become a necessary step in order to ensure that they can receive the materials they demand. This step would certainly allow them to better internalize the savings outlined above. Likewise, it would permit better control of the supply-demand balance of recycled (or even hard-to-source virgin) materials. Ultimately, though, the reason for integration has to be grounded in a need (and will) to architect the ecosystem to deliver greater value for the key stakeholders. As part of this, expanding the boundary and including more stakeholders in the ecosystem will surface many of the sustainability challenges outlined at the beginning of this thesis.

As manufacturers consider the wider influence they exert in the world economy, they will realize how tenuous their consumption of non-renewable resources is. Thus, a strategy that places increased recycling at its center is critical to the overall movement to more sustainable development. In addition to internalizing economic savings as outlined above, this move would also permit (and force) the manufacturer to internalize environmental and social outcomes of its actions—factors that were previously externalities. As discussed above, this paradigm shift will allow manufacturers to capture positive externalities as they tackle the negative ones—a perfect instantiation of win-win resolutions.

Chapter 9

Conclusions

WEEE recycling must be viewed as an ecosystem to make improvement possible. Historically, the stakeholder industries involved have seen themselves as individuals operating in distinct systems with little influence over each other. And this may have once been an accurate outlook; however it has changed as electronic devices—particularly smartphones—have become more complex. The evolving electronics industry has made managing the EOL of devices too complicated for a disjointed network of individual systems to manage. As a result, the WEEE recycling systems have, whether they wanted to or not, coalesced into a larger ecosystem with overlapping stakeholders responsible for management of WEEE.

Management of WEEE has already become one of the fastest growing challenges facing the industrialized world as it runs out of space to dispose of material. Thus, key stakeholders are looking for more responsible solutions that make developing a more sustainable supply chain possible. In this search, though, it is obvious that there are real challenges facing every component system in the ecosystem. The three main systems: collection, pre-processing, and end-processing all face economic, social, and technical challenges that make recycling at scale and efficiency challenging. A lack of communication seems to be at the heart of most of these challenges.

In this sense, the real opportunities for improvement in the broader ecosystem likely lie in the ability for different stakeholders to see the how they fit into the broader ecosystem and how their choices can impact overall productivity and efficiency. Addressing the economic, social, and technical challenges facing each component system can, in theory, be done by each system individually. However, as was illustrated for each system, it is important to see how the interfaces between systems affect the materials (namely the WEEE) passing between systems. Thus, an effort for one system to optimize its operations irrespective of how that optimization will affect the upstream and downstream systems will be futile. There are real opportunities for innovation in the ecosystem and most of them cannot be done without a holistic view of the challenges facing the broader system. It seems that the stakeholders who have plans for disruption are starting to take this holistic view and understand that the highest points of leverage lie at the interface between ecosystem systems.

Ultimately, WEEE recycling itself is part of an even broader system. This system captures the way humans interact with our natural world and our consumption of nonrenewable resources. One cannot suggest that human civilization will continue to grow without the growth of technology; as technology is inherently reliant on natural resources, we need to find ways to make our use of these resources more sustainable. WEEE recycling is part of this equation and plays a critical function in developing a circular economy that seeks to minimize the consumption of new nonrenewable resources. Many key stakeholders in the WEEE ecosystem are starting to reframe their value propositions (*i.e.* their system problem statements) through this lens. This is an important first step. The recycling ecosystem is still relatively immature and lacks much of the formal definitions seen in traditional, more mature industrial systems. The only way to evolve quickly and effectively is to communicate.

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