The Electronics Recycling Landscape

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The Electronics Recycling Landscape Report

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Introduction

With the increased adoption and use of electronic and electrical devices has come the increased generation of used equipment as products are replaced by newer models and older technologies become obsolete or no longer meet the expectations of the consumer. Electrical and electronic equipment (EEE) no longer useful to its first owner may still have considerable value, so market solutions have evolved with the waste stream to capture this value.

Used electronics management systems have, in turn, evolved to enable the flow of material into processes that improve value recovery, including device reuse and refurbishment, and to manage the potential risks to individuals and the environment. This, in turn, closes the loop. Increasing the efficiency of used electronics management will foster development of the circular economy for the EEE value chain.

The challenges these systems face originate with the nature of the devices themselves – assemblies of a large number of mixed materials connected for functionality and configured to optimize manufacturing, assembly, and distribution. This situation will become worse over the next five years due to electronics industry trends that are creating smaller, lighter, and far more interconnected and complex devices. Further challenges for effective reuse and recovery are evolving as any given device contains less of any given material or element and as these smaller devices are being distributed more extensively through society as electronics are integrated into our cities, homes, and even automobiles. Solutions to the reuse and recovery challenges these materials present have been slow to emerge because no one clear path is evident, and the multiple industries working in this space have been slow to collaborate to create more effective approaches to used electronics and e-waste management. To realize an effective used EEE management system in the United States, the industries that intersect in managing used equipment will need to modernize the system in place and prepare both technology and processes to handle the devices that will be received. To fail to do so is to lose the economic and material value of the devices and forfeit the environmental and societal benefits of a robust used EEE management system.

The goal of this report is to provide a complete overview of the used electronics management landscape within the United States to understand 1) the types and quantities of materials that are currently and will be moving into the waste stream in the next five years; 2) what type of programs are in place currently and how effective they are; and 3) how changes in consumer desires and behavior, device technology, governmental regulation, and practices in the electronics and recycling industries will impact the effectiveness of recycling programs and demands in the next five years. This analysis is then used to identify the opportunities available, and provide solutions to address the challenges identified to support the development of a resilient used EEE management system.

Scope and Definitions

The scope of this report is the electrical and electronic equipment market in the United States, now and forecasted five years into the future. The focus of this report will be on EEE sold in the consumer market rather than the commercial market. Managing used electronics in the business-to-business, first-use context is different than in the consumer context due to contractual agreements, the higher value of the used devices, and the much higher levels of capital investment involved. Nonetheless, business-to-business waste management activities will be used to illustrate alternative methods of collection.

Used EEE Terminology

Many of the terms used when discussing used EEE management do not have clear, widely accepted definitions. This is in part due to the fact that the electronics recycling industry began as part of the metal scrap industry, and terms like recycling, recovery, and disposal carried over as electronics recycling evolved into its own industry. Even though electronics recycling has evolved and expanded beyond treating devices simply as a source of metal, the language used to describe the stages of device management has not evolved and has become misleading in its simplicity. In this work, "used EEE management" or "used electronics management" system will be used to describe processes that take place after a device reaches the end of its first useful life, or the point when the original purchaser no longer has use for the device but the device is still fully functional and can be of use to someone else. This broad consideration of the used electronics realm aligns with the language used in the National Strategy for Electronics Stewardship (Interagency Task Force on Electronics Stewardship, 2011). In the pre-treatment stage, "reuse" and "refurbishment" will be used to refer to interventions that increase the life span of used devices through whole product or component reuse or product repair and refurbishment. In the ideal treatment stage, materials of value (economic or otherwise) are fully recovered. "Materials recovery" includes the disassembly of used devices to remove potentially hazardous parts, such as batteries, and further processes aimed at commodity recovery, the first step in product treatment and disposal as illustrated in Figure 1. The treatment stage can also be described as "recycling" in the same way that the recycling of bottles or cans recovers materials to be returned to commodity markets. Those organizations dealing with material recovery will be referred to as "electronics recyclers". International convention is to use the term "e-waste" as a shorthand term for the entire used EEE management space (Step, 2014). Here, e-waste will be used in a narrower sense, referring only to materials that may have some value in recovery but are, for the most part, destined for landfill or incineration. These designations allow for a clearer description of the unique opportunities unique available for used EEE management.

In addition to traditional information technology products (e.g., computers, monitors, accessories such as mice or keyboards) and consumer electronics (e.g., televisions, stereo equipment, set-top boxes), small appliances (e.g., toasters, coffee makers) will be included in the scope of this work. Large appliances (e.g., refrigerators, washing machines), while qualifying as electrical equipment, will not be included in the scope because **1)** the recycling systems and companies handling this equipment are usually separate from that of the smaller appliances and electronics, **2)** the materials that make up the large appliances are different, and **3)** frequently, recycling large appliances is tied to energy efficiency initiatives developed and run by utilities rather than by the municipal government bodies or voluntary organizations that run consumer electronics recycling programs. These differences suggest that the conclusions reached for the other devices classes may not be relevant for large appliances, which are therefore not included in the scope of this work.

Methodology

A combination of research and stakeholder surveys were used to collect the information used in this report. The information provided in this report has largely been drawn from a series of stakeholder surveys conducted in August and September of 2015. The surveys took the form of one-hour interviews between the research staff and representatives of the participating organization. 37 organizations participated, including representatives from the consumer electronics industry, NGOs, government agencies, refurbishers, recyclers, trade groups, and other organizations with interests in this space. A list of participating organizations can be found in Annex A. The questions asked of interviewees focused on trends in both the electronics industry and the electronics recycling industry, on what constitutes a working used electronics management system, and on key barriers and opportunities to improving the overall performance of the system. The interview questions from this process can be found in Annex B. Additional literature research is included to provide background information and quantitative analysis of the electronics and recycling markets.

Used EEE Issues

Hazardous Materials

- Electronics can contain lead, mercury, cadmium, PVC, and plastics with brominated flame retardants that can present risks to human health and the environment if handled improperly.
- Even though many of the most hazardous materials are no longer used in EEE manufacturing, devices with these materials will still be in the waste stream for the foreseeable future.
- Irresponsible handling at device end of life compounds worker exposure, especially when devices are burned.

Environmental Impacts

- Irresponsible treatment of used devices also leads to contaminated land and water around material recovery facilities.
- Illegal dumping of equipment in the environment, especially lead-containing CRT displays, leads to expensive clean-up and environmental contamination.
- The energy and material resources that went into creating a device are lost when devices are thrown away. There is no opportunity to recapture the energy or offset mining impacts without repair and recycling.

Economic Impacts

- Disposal costs money. Even if used devices are included in regular municipal waste streams, communities still pay for dumping this equipment in landfills.
- Landfilling rather than recycling or repair costs jobs.
    - According to the Institute of Scrap Recycling Industries (ISRI), the electronics recycling industry employs more than 45,000 workers as of 2012 (ISRI, n.d.).
    - According to iFixit, 200 repair jobs can be created for every 1000 tons of used electronics, which equates to approximately 45,000 jobs for the estimated 455 million tons of devices collected in 2015 (iFixit, n.d.).
    - Repair and refurbishment organizations provide jobs to under served populations, such as individuals with criminal records and disabled and disadvantaged adults—opportunities lost without robust repair and recycling industries.

Personally Identifiable Information

- Devices today, especially mobile and wearable devices designed to collect information about their owner, contain a great deal of personal information that must be removed before a device is repaired or recycled to avoid data breeches.
- Information can be erased and devices reused rather than destroyed if handled by a responsible and qualified refurbisher or recycler.
- For equipment coming from commercial enterprises, an additional risk of the loss of proprietary information is present when used equipment is not handled responsibly.

Managing Used Electronics

EEE constitutes a unique waste stream in that scattered issues faced by other recycling streams are all found together in this one. First, while these devices contain commodities, they are not commodities themselves. Unlocking the value of used equipment requires either reuse, repair, or refurbishment approaches, or a disassembly and material recovery approach, all of which add significant labor and/or equipment costs not seen with other waste streams, such as plastic bottles and aluminum cans. Material recovery may bring workers in contact with the potentially hazardous materials in these devices, which require the same levels of management as other hazardous wastes. The electronics industry has made strides in removing or reducing some of these materials, such as lead in solder, but batteries, mercury lamps used for backlighting displays, and plastics with brominated flame retardants (BFRs) will be in the waste stream for at least the next decade. Finally, unlike any other waste stream, EEE contains a significant amount of personally identifiable information (PII). Destroying this information is critical for equipment reuse and refurbishment, actions where the highest economic value and lowest environmental impact are realized. Shredding is an effective option to destroy PII, but the value that can be recovered from shredded materials is small compared to an intact device or component.

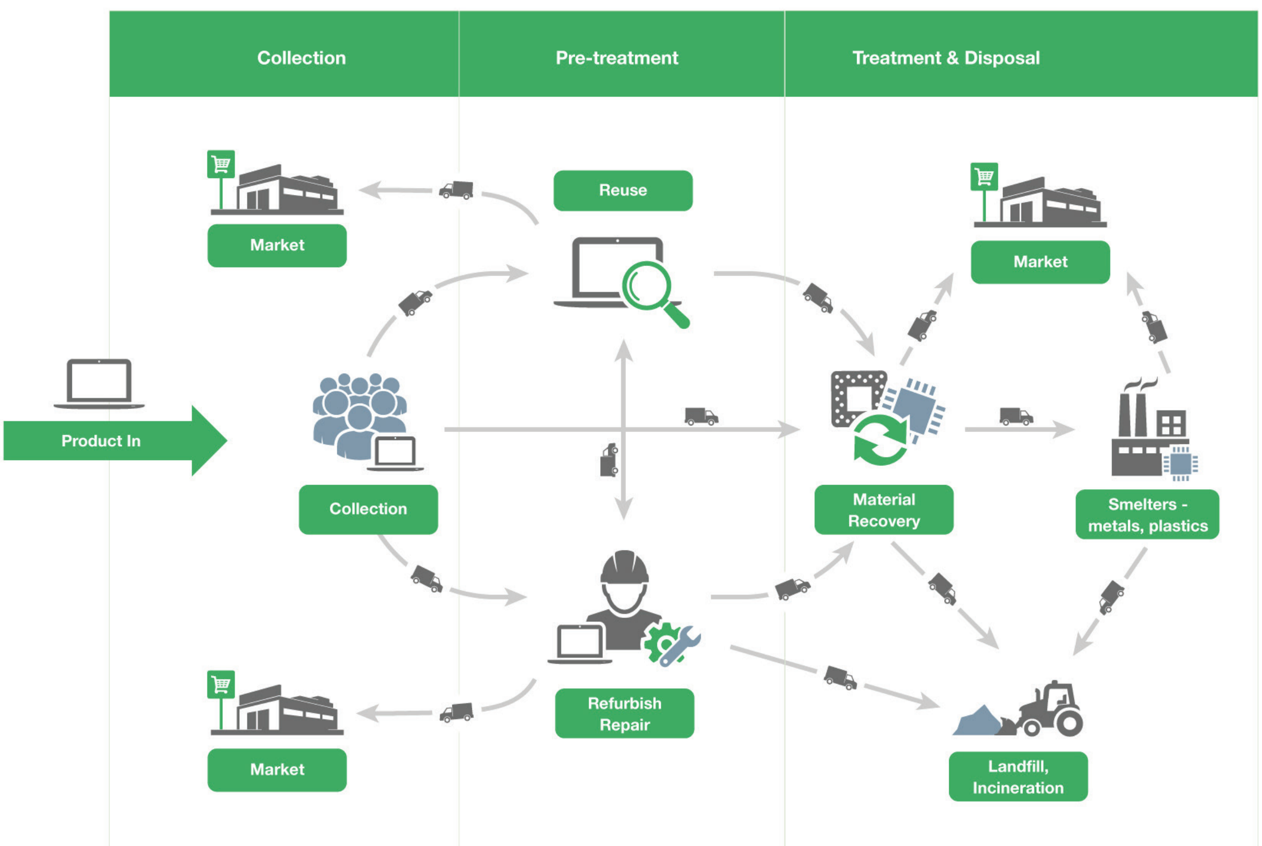


FIGURE 1: Diagram showing basic material flow stages for used electronics

To understand the system that currently exists in the United States, it is helpful to understand how material enters and moves through the system and the actors that influence the processes (Kang & Schoenung, 2005; Mars, Mangold, & Nafe, 2014). Figure 1 illustrates the paths along which used EEE may travel. Further details on these steps and the value of the devices in the system can be found in Annex C.

The basic steps of the used consumer electronics management system can be described as:

1

GENERATION: The device reaches the end of its first useful life for the first user, a point often indicated by the purchase of a newer device or another device that has the same functionality but may not be a direct replacement (e.g., when a mobile phone with camera functions replaces a regular camera). From here, the user has multiple options for discarding the device – they may hand it down to others, store it, sell it directly on the secondary market (e.g., eBay), or turn it over to a collector. Devices coming from business, institutions, or commercial facilities are handled in the same system, but have a different set of issues and opportunities associated with them, and also tend to be worth more both on the reuse market and in material recovery. While some of this equipment will return to business applications, a majority will move into the consumer space because of the age and short equipment replacement cycles in commercial settings.

2

COLLECTION: Devices reaching the end of their first useful life may be collected by a wide range of organizations with a wider range of business models. Collectors may be non-profit organizations, private recyclers, recyclers managing manufacturer takeback programs, municipalities and other local- or state-level government agencies, or retailers. This point is the interface between the user/consumer looking to dispose of a device and the used electronics management system and is considered one of the weakest points in the system (M. Watson, personal communication, August 14, 2014).

Specific organizations operating at this step include Information Technology Asset Disposition organizations (ITAD). These organizations tend to focus on commercial or business-to-business equipment flows, which have much higher margins in reuse and refurbishment. Equipment managed by them tends to be newer technology or capital equipment with high repair and refurbish value and comes in quantities that make resale of both whole devices and components more desirable. Many organizations choose to focus on such equipment exclusively rather than deal with the costs associated with material recovery from consumer electronics. This creates a very competitive market for business equipment appropriate for reuse and refurbishment management, which represents a relatively small portion of EEE.

3

PRE-TREATMENT: After devices are collected, they are taken to a facility where they are sorted. Those devices with value for reuse or refurbishment are separated out, and the remaining devices are disassembled and have their hazardous materials removed (e.g., batteries, mercury lamps in flat panel displays) and parts harvested for reuse or separate treatment. The sorting and triage steps vary greatly among organizations, depending on the business model used and the process and technology intellectual property licensed and owned. The degree to which devices are broken down prior to moving to the next stage will also depend on the model used by the organization handling the material. The further a device is disassembled into its components and component materials, the higher the value of material, due to decreasing contamination issues (Mars et al., 2014). Disassembly is expensive, though, as it requires manual labor, which can represent a significant cost to an organization. Technology to reduce devices and sort materials mechanically is under development but not yet widely used in the industry.

Organizations involved in this stage include refurbishers in for-profit or non-profit organizations and electronics recyclers that might manage disassembly and material reduction, but not necessarily perform the material recovery steps. These organizations may collect directly from the public or work with another organization to collect materials. Any given device or components harvested from devices collected may move through multiple organizations in this stage, depending on the residual resale value of the product or parts and on what commodity streams it may produce. Also involved at this stage are brokers, whose primary function is to aggregate different products or material streams into lots that are large enough to be cost-effectively shipped and treated by recyclers and smelters.

4

TREATMENT: The components and materials separated during the pre-treatment step that do not return to a secondary market are then moved to facilities that perform materials recovery. These organizations take materials that come out of the pre-treatment phase, whether these are full devices with batteries removed, the batteries themselves, other hazardous materials, plastics, or other material streams generated during disassembly. The remaining material is further reduced mechanically and shredded to create consistent sizing and is either sent to commodity recovery at a smelter or plastics recovery facility or for final disposal at a landfill or incinerator.

Inherently, this system follows the waste management hierarchy of reuse, refurbish, recycle, then disposal, with residual value extracted from the material flow at each step, until, ideally, no further value is left and remaining materials are moved to landfill or incineration. Importantly, many organizations are active in multiple steps, so the boundaries between different management stages are very fluid. The same company may manage all stages, at least up to the commodity recovery point (e.g., smelters), or multiple organizations may partner across stages and move material through their networks. There is also a logistics consideration. The number of steps required to move material through this process may require a large number of transport steps to get devices, components, and materials to the facilities that can manage them, depending on the size and focus of the organizations involved in a given value chain.

Finally, this system is regulated at the local, state, federal, and international levels. One of the most common policy mechanisms related to used electronics is extended producer responsibility (EPR). The Organisation for Economic Co-operation and Development (OECD) defines EPR as:

> *"[An] environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle. An EPR policy is characterised by:*
>
> 1. *the shifting of responsibility (physically and/or economically; fully or partially) upstream toward the producer and away from municipalities; and*
> 2. *the provision of incentives to producers to take into account environmental considerations when designing their products.*
>
> *While other policy instruments tend to target a single point in the chain, EPR seeks to integrate signals related to the environmental characteristics of products and production processes throughout the product chain." (OECD, 2015)*

Implementation of the principles of EPR varies widely. In the United States, local municipalities and states regulate electronics management through landfill bans or a variety of EPR programs, all of which influence the way the system described above works. The programs in force today are primarily funded by electronics manufacturers; their obligation is based on how much they sell in a given state or how much of their product is collected in a given state or a combination of both. They may also run their own program in a state, paying a registration or annual fee. The one exception to this model is the advanced recovery fee in place in California, where the consumer pays an additional fee when the product is purchased, which is then used by the state to reimburse recyclers for handling these products at the end of life. In addition to the variation in funding mechanisms, the products covered and entities that can use the programs vary from state to state (Linnell, 2011). The confusion and inefficiency induced by this system tends to keep conversations regarding potential improvements centered on whether manufacturers are adequately funding these programs. This single-point focus overshadows the intent of EPR to improve product design and involve the whole product chain in managing this equipment. While implementation in the U.S. has been spotty at best, EPR can be part of effective management programs, as demonstrated by the programs under the Waste Electronic and Electrical Equipment (WEEE) Directive in the EU and the provincial programs in Canada managed by the Electronics Product Recycling Association (EPRA). As national legislation is unlikely to evolve in the U.S., which would enable EPR implementation in a similar fashion as in the EU or Canada, incorporating the EPR principles as one aspect of a broader, supply-chain-integrated initiative provides a solid policy option to further responsible used electronics management.

At the global level, electronics and electrical equipment are considered hazardous waste by many countries under the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention, 1989). This Convention regulates what constitutes hazardous waste and how it may move between countries, with the goal of protecting human health and the environment from improper disposal of the materials. For EEE, the Convention has particular relevance regarding what constitutes legal, and therefore illegal, export of material between countries that are parties to the Convention.

Electronics Industry

U.S. consumers were expected to purchase more than 1 billion devices in 2015, producing sales reaching $285 billion, which includes a 15% year-over-year increase in the number of mobile and wearable devices entering the market (CEA, 2015; Euromonitor, 2015). This equates to approximately 24 devices per household, where at least 4 of those devices were connected to the internet (CEA, 2010; McCue, 2014; Nielson, 2014).

A recent survey of EEE available on the market showed just over 24,000 SKUs (stockkeeping units), or individual models, of products. The majority of the products listed are “traditional” electronics and electrical goods: computers and tablets, mobile phones, small appliances, and televisions & home theater equipment (Figure 2). As each SKU corresponds to a unique model number, this distribution provides a view of the degree of product-to-product variation across a category.

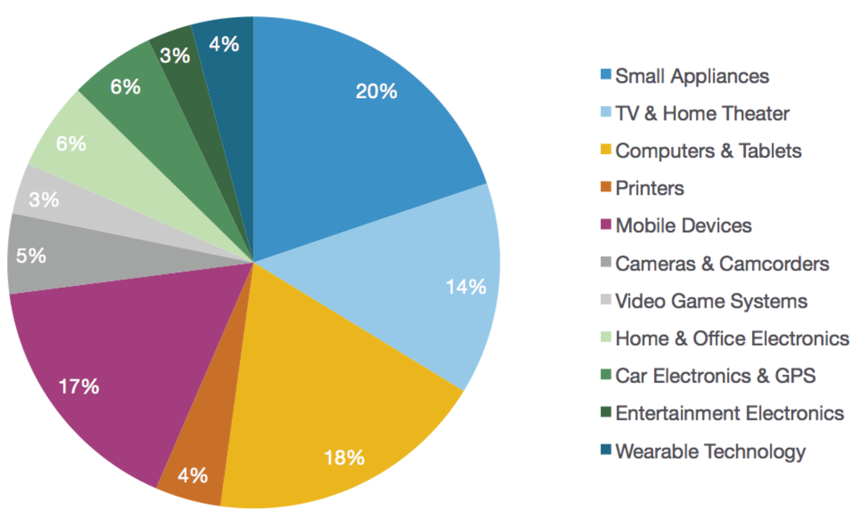


FIGURE 2: Market share of EEE by number of available SKUs per product type
The percentages refer to the number of SKUs in a given category, compared to the total number of SKUs counted in these categories.

[1] Analysis of the BestBuy online marketplace conducted July 19-20, 2015. Cables and accessories are included with the product type they support; excluded are non-powered accessories, such as mobile phone cases (without batteries), consumables, such as printer ink or CDs/DVDs

Also of note are the final three categories: car electronics & GPS, entertainment electronics (aerial drones, robots, app-enabled toys, musical instruments), and wearable technologies. These three categories, while not making a significant contribution to the market today, indicate where the market is going as individuals and their environments become more highly integrated in the Internet of Things (IoT). This implies that there will be an even further diversification of products with recovery value, both in terms of reuse and material recovery opportunities.

The significance of the variation and diversity in products currently on the market is that, when managing used consumer products, an organization needs to be prepared to handle low volumes of this highly diverse product population. This creates challenges because different types of products have to be handled differently to ensure worker health and safety and to maximize value, which may not be high enough to cover the cost of handling the majority of products on the market today, assuming a strictly economic-driven model.

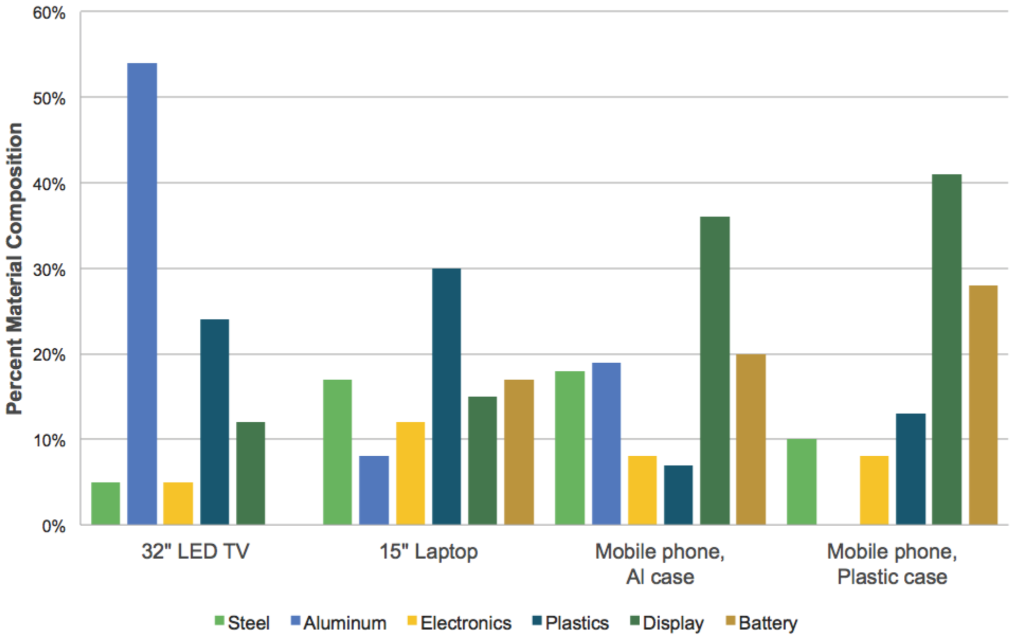


FIGURE 3: Average material composition for select devices

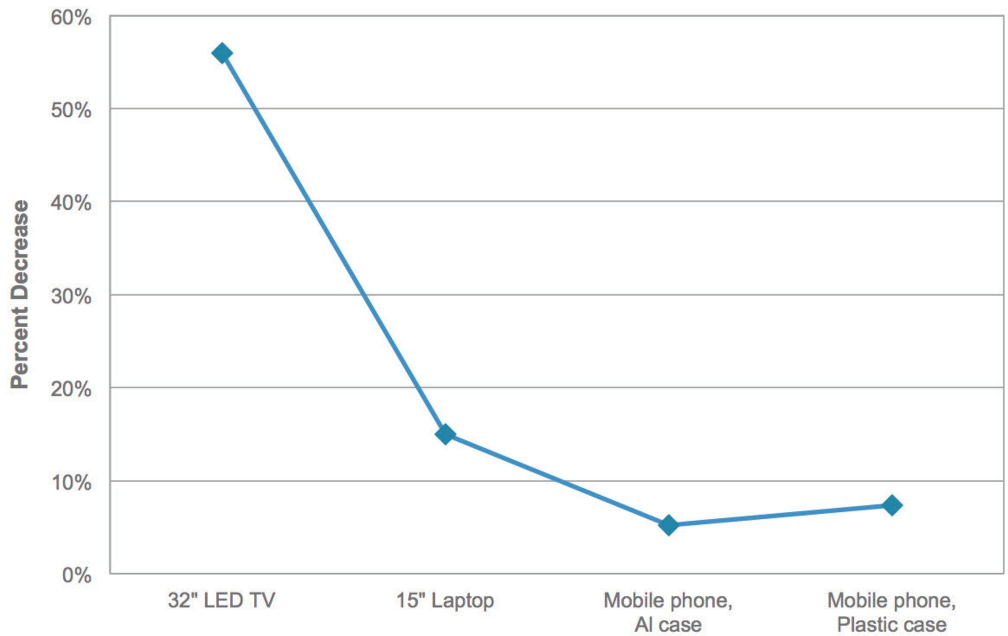


FIGURE 4: Change in product weight over 5 years
% Decrease is calculated between the 2010 and 2015 model years.

Smaller, lighter, faster—these are the trends for consumer electronics in the current market. These trends create products made with less material that have more complex circuitry that is more integrated than in larger devices. The trend towards miniaturization is most noticeable in the evolution of wearable devices and ever-thinner smartphones, but is not limited to these products. Larger consumer electronics such as desktops and televisions are also undergoing significant dematerialization. The number of devices owned by a given individual is expected to increase as well, as wearables further penetrate the consumer market over the next five years. How quickly the smart appliances available on the market today become standard in households will depend in part on the lifespan of existing equipment. Most small appliances are expected to last seven to ten years, so widespread integration into households and adoption of true IoT devices is expected across a similar time frame. Figure 3 provides a snapshot of the materials that are found in products on the consumer market today; Table 1 provides more detail on product material composition. Figure 4 illustrates the weight decrease over the past five years for the same set of products. All weights have decreased slightly, most notably televisions, with an approximate 60 percent reduction in unit weight for flat panel screens. This decrease is significantly larger if the plasma televisions on the market in 2010 are used as a point of comparison instead.

Closely coupled to EEE sales is the rate at which older equipment reaches the end of its useful life. Figures 5-7 show the relative percentages of a wide range of devices that will be generated, stored in-home, and collected in 2015 and 2020. Annex D provides more details on the number of units and weights of electronics ready for end of life treatment today and in 2020, as well as a discussion of calculation methodology. The estimate for products ‘generated’ (i.e., ready for end-of-life treatment) covers devices that have reached end of life based on sales year and lifespan of the product. ‘In-home’ devices sum units still in use by members of a household plus units that have not reached their end-of-life point but are no longer in use or stored in the household. Estimates of used electronics and electrical equipment ready for end of life treatment will be nearly 700 million units in 2015, based on sales year and product life span (Miller, 2015). In the year 2020, households in the U.S. will generate approximately 800 million units of used EEE. If small appliances are excluded from these totals, as in Figures 5-7, the numbers change to 270 million units in 2015 and 354 units in 2020. The increase in devices stored or in use, however, will increase to over 4 billion units. The decoupling of the increase in weight and number of units is due to the changing form function of products on the market today. Since these devices will be smaller and lighter than their predecessors, the number of units can increase while the weight of those new units decreases in comparison to old technology over time.

For some electronics, such as printers and small appliances, recycling numbers are difficult to find. These devices are rarely covered under any type of legislation in the United States, so there is no driver to track their fate. Anecdotal evidence points to some degree of recycling, especially for printers and other IT devices, as these products are frequently returned at the same time as computers or monitors.

For cathode ray tube (CRT) displays, the US EPA estimated that, in 2013, there were 6.2 million tons of displays containing CRTs stored in U.S. households that would move into the recycling stream over the subsequent decade. The Consumer Technology Association conducted a consumer survey in 2014 where 40 percent of U.S. households reported having a CRT television in their home; this number dropped to 34% for the survey conducted in 2015. For CRT monitors, the rates were 21 percent in 2014 and 20 percent in 2015. Converting these survey results into pounds, the National Center for Electronics Recycling (NCER) calculated that roughly 7 billion pounds of CRT displays were left in households in 2014, down to 6 billion lbs. in 2015 (NCER, 2015). Even though the volumes of displays stored may be decreasing, they are still expected to dominate the used electronics stream by weight for at least the next five years. There will continue to be issues related to abandoned stockpiles and wholly irresponsible management of displays for at least that long.

New products entering the electronics market do not have generation, in-home volume estimates, or recycling rates in Figures 5-7 because these devices have yet to work their way into the recycling stream. The current assumption in the reuse and recycling industries is that products such as smartwatches, fitness trackers, or personal camcorders will follow the same trends as mobile phones, where consumers replace devices in 18 months or less and the primary source of recovered value will come from reuse and refurbishment. There is no indication of whether consumers will treat these products as electronics and turn them in as such or just throw them away. There is also no understanding of the eventual fate of emerging non-traditional EEE such as electronic toys and electronic textiles.

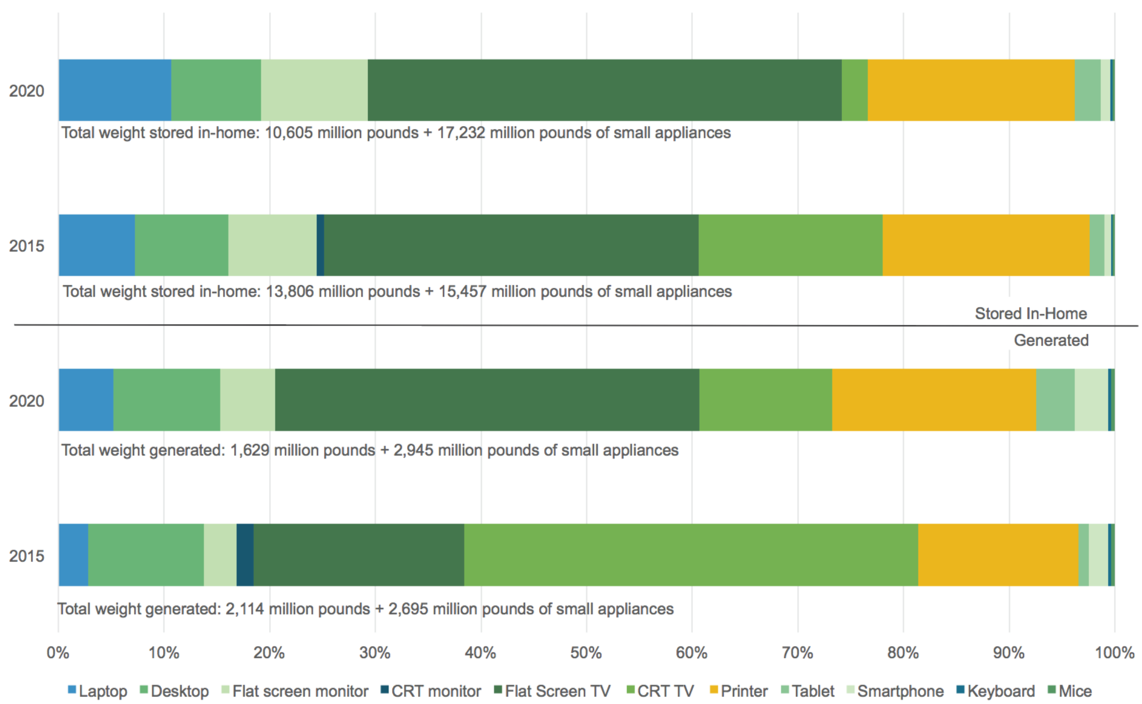


FIGURE 5: Percentage by weight of devices generated and stored in-home, 2015 and 2020 (million pounds)

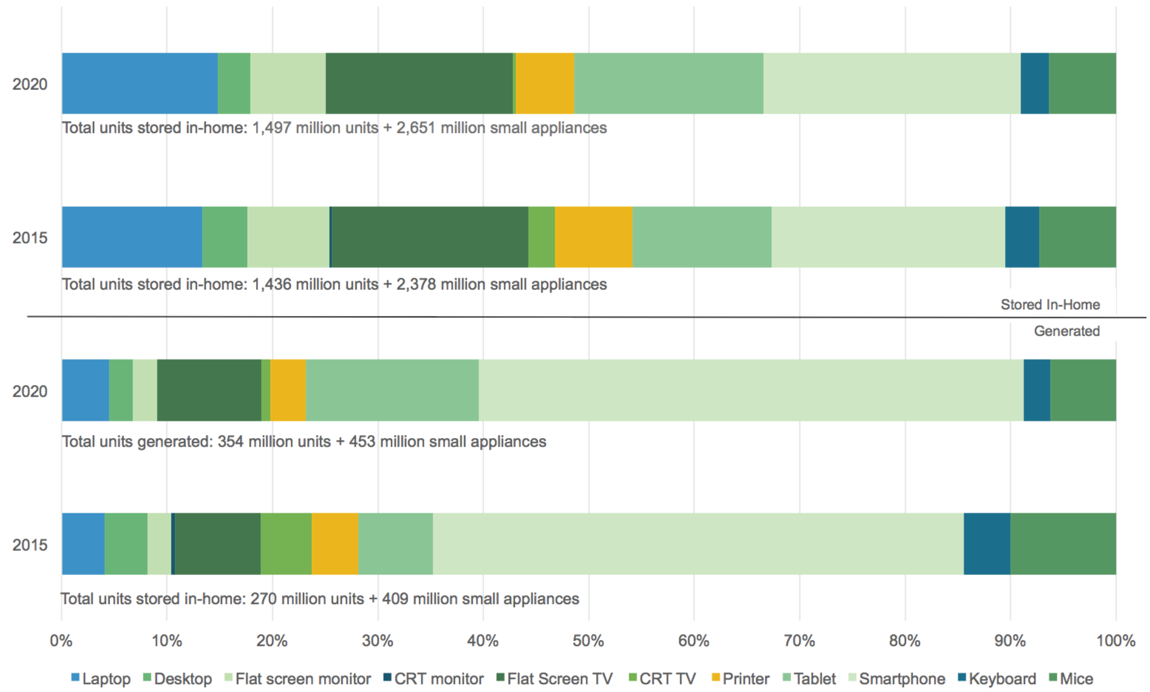
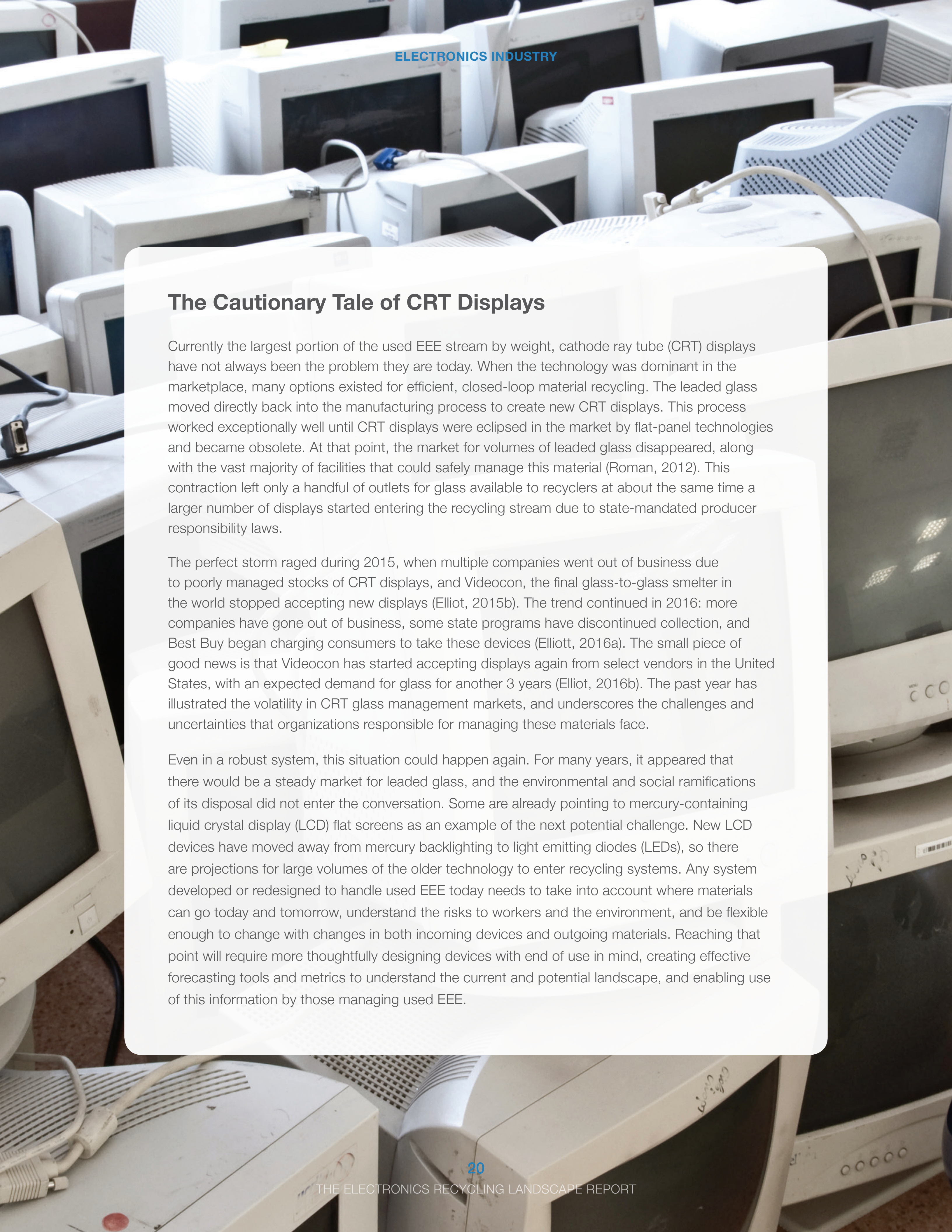


FIGURE 6: Percentage by number of devices generated and stored in-home, 2015 and 2020 (million devices)

FIGURE 7: Percent of collection estimates from different device categories based on calculated recycling rates, 2015 and 2020



The Cautionary Tale of CRT Displays

Currently the largest portion of the used EEE stream by weight, cathode ray tube (CRT) displays have not always been the problem they are today. When the technology was dominant in the marketplace, many options existed for efficient, closed-loop material recycling. The leaded glass moved directly back into the manufacturing process to create new CRT displays. This process worked exceptionally well until CRT displays were eclipsed in the market by flat-panel technologies and became obsolete. At that point, the market for volumes of leaded glass disappeared, along with the vast majority of facilities that could safely manage this material (Roman, 2012). This contraction left only a handful of outlets for glass available to recyclers at about the same time a larger number of displays started entering the recycling stream due to state-mandated producer responsibility laws.

The perfect storm raged during 2015, when multiple companies went out of business due to poorly managed stocks of CRT displays, and Videocon, the final glass-to-glass smelter in the world stopped accepting new displays (Elliot, 2015b). The trend continued in 2016: more companies have gone out of business, some state programs have discontinued collection, and Best Buy began charging consumers to take these devices (Elliott, 2016a). The small piece of good news is that Videocon has started accepting displays again from select vendors in the United States, with an expected demand for glass for another 3 years (Elliot, 2016b). The past year has illustrated the volatility in CRT glass management markets, and underscores the challenges and uncertainties that organizations responsible for managing these materials face.

Even in a robust system, this situation could happen again. For many years, it appeared that there would be a steady market for leaded glass, and the environmental and social ramifications of its disposal did not enter the conversation. Some are already pointing to mercury-containing liquid crystal display (LCD) flat screens as an example of the next potential challenge. New LCD devices have moved away from mercury backlighting to light emitting diodes (LEDs), so there are projections for large volumes of the older technology to enter recycling systems. Any system developed or redesigned to handle used EEE today needs to take into account where materials can go today and tomorrow, understand the risks to workers and the environment, and be flexible enough to change with changes in both incoming devices and outgoing materials. Reaching that point will require more thoughtfully designing devices with end of use in mind, creating effective forecasting tools and metrics to understand the current and potential landscape, and enabling use of this information by those managing used EEE.

There are approximately 3.8 billion devices estimated to be in use or stored in households in 2015, which equals approximately 30.5 devices per household for the 125 million households estimated in the U.S. (Mc Cue, 2014). Excluding small appliances, the number of devices per household, based on the calculations in Annex D, drops to 11.5 devices per household. In the literature, the best estimates for stored products excluding those devices in use by household members come from a survey conducted by Saphores and colleagues in 2009. Based on responses from this national survey, they estimate that the average household stores 2.1 large items (including televisions with screens greater than 21"; excluding large appliances) and 4.1 small items (including mobile phones, tablets, and IT equipment; excluding small appliances) (Saphores, Nixon, Ogunseitan, & Shapiro, 2009). The authors note that, while based on survey data, these values underestimate the true levels in storage because it is "time consuming for a household to precisely inventory all of its obsolete e-waste" (Saphores et al., 2009). Assuming no change in the storage or recycling rates between 2009 and 2015, 6.2 units per household would equal 774 million units of used electronics in storage in the U.S. This agrees well with the 11.5 devices per household noted above, considering the higher number includes devices in use. This illustrates that there is a great quantity of material, and therefore opportunity, stockpiled in the U.S. today.

Devices stored, however, create one of the largest uncertainties for electronics recyclers. Not only is it difficult to estimate what individual households may have stored, but when and what motivates people to recycle this equipment is not at all clear. One notable challenge created by storage is for mobile devices. These devices have significant resale value, but only if they are returned to the market within two years of purchase. After that, there may be some additional value from the parts, if the make and model were particularly popular, but otherwise the device will go to materials recovery, where only the metal fraction of the circuit board is usually recovered.

The recycling rates given in Figure 7 are best estimates based on the data available today and range from the 40%-90% (Duan, Miller, Gregory, Kirchain, & Linnell, 2013; US EPA, 2015; US EPA, 2011). The values presented are the average of two different methods for estimating the recycling rate, which is further discussed in Annex D. One interesting result to note in Figure 7 is the difference between device shares of the total number of devices estimated for collection. When looking at the weight of devices returned, televisions dominate the product mix, with the weight of CRT televisions shrinking and flat panel televisions increasing between 2015 and 2020. The units returned, however, are dominated by mobile phones and tablets in both 2015 and 2020. This highlights a performance-tracking challenge for stakeholders: By only considering the weight of total devices collected, a large number of lighter-weight devices are essentially ignored. Figuring out a better way to track success is necessary to assess used electronics management programs, regardless of the type of organization responsible for program operation.

Unfortunately, product-level recycling rates are difficult to estimate because the data collection systems do not exist, so the category recycling rates are based heavily on the data collected in a handful of states that consider category-level recycling as part of their electronics recycling legislation. The US EPA Office of Resource Conservation and Recovery has launched an initiative to develop a more robust analysis of flows of electronics within the United States that includes products not normally covered by state laws and non-regulated states (E. Resek, personal communication, Sept 30, 2015).

TABLE 1: Material composition of representative EEE

Product	Ferrous (iron, steel)	Non-ferrous (Al, Cu)	Printed Circuit Board	Plastics[1]	Other (incl. glass)
Small Appliances[1]	19%	1%	No data	48% (PP, ABS-SANS, PC)	480
CRT TV (29") [2]	9%	5%	6%	12%	68%
LCD TV[2] (32", CCFL)	24%	2%	PWB: 6% (Electronics: 10%)	20% (PPE-PS, PC-ABS)	45%
LCD TV[3] (32", LED)	5%	54%	5%	24% (PMMA, PET)	12%
CRT Monitor(17")[4]	1%	1%	2%	15% (ABS, PA, EPS)	69%
Desktop[4]	66%	9%	PWB: 2% (Electronics: 14%)	11% (ABS, PC-ABS)	<1%
Laptop[4] (15" display)	17%	8%	PWB: 3% (Electronics: 12%)	30% (ABS, PC-ABS)	Display: 15% Battery: 17%
Printers[5]	21%	3%	5%	52% (PS, HIPS)	18%
Tablet[6]					Other: 4% (both)
Al case	0%	19%	9%	4%	Battery: 26% Display: 39%
Plastic case	1%	5%	8%	14% (Not identified)	Battery: 22% Display: 46%
Smart phone					
Al case (iPhone 6)[7]	18%	19%	8%	7%	Battery: 20% Display: 36%
Plastic case (Galaxy S5)[8]	10% (estimate)	No data	8%	13% (PC)	Battery: 28% Display: 41%

1 Buekens & Yang, 2014
2 Stobbe, 2007b; non-ferrous category includes copper related to external cabling. CCFL stands for cold cathode fluorescent lamps, the source of light used to illuminate the liquid crystal display (LCD). The CCFLs are the source of mercury in LCD television technology.
3 Peeters et al., 2011; the Philips LED television model listed here won the 2011 Green Awards for most eco-friendly TV, so may not best represent the market.
4 Jonbrink, 2007
5 Stobbe, 2007a
6 GEC, 2014
7 Rossignol, 2015; display weight is for both the display itself (OLED) and glass housing/cover
8 Galaxy S5 material composition estimated on weight of primary components (battery, PWB, display, case; Amazon.com) versus total product weight; display weight is for both the display itself (OLED) and glass housing/cover

TABLE 2: Common electronics plastics

Abbreviation	Plastic
ABS	Acrylonitrile butadiene styrene
EPS	Expanded polystyrene
HIPS	High impact polystyrene
PA	Polyamide
PC	Polycarbonate
PPE	Polyphenylene ether
PS	Polystyrene

TABLE 3: Grade and value of printed wiring boards

Grade	Product Examples	Copper		Silver		Gold		Palladium	
		Weight (%)	Value Share	Weight (ppm*)	Value Share	Weight (ppm*)	Value Share	Weight (ppm*)	Value Share
High	Mainframes, mobile phones, capacitors	13%	9%	3500	13%	340	64%	130	14%
Medium	Computer boards, tablet boards	20%	18%	1000	5%	250	61%	110	15%
Low	Televisions, monitor boards, printer boards, small appliances, shred-ded bulk material after Al/Fe separation								
	Televisions	10%	50%	280	7%	20	22%	10	7%
	DVD Players	5%	42%	115	5%	15	32%	4	5%

from Hagelüken, 2007

*ppm – parts per million of metal content by weight on a printed wiring board

Electronic Products Material Profile

The primary materials used in EEE have not changed much over the years: metals such as steel (containing iron and manganese) and aluminum, a variety of plastics, precious metals, and a variety of supporting elements and materials that evolve with changes in technologies. Table 1 shows the material compositions of a range of typical consumer devices, with Table 2 providing a key to the range of plastics common in EEE. For smaller devices, batteries and integrated displays have become the dominant components by weight, whereas the chassis weight is still dominant for less-mobile products. The exceptions are CRT displays, where the glass tube dominates the weight of the product. This further underscores the challenge CRTs present to the recycling industry:

The majority of weight coming into the system is dominated by leaded glass, a material that is cost-negative to recover.

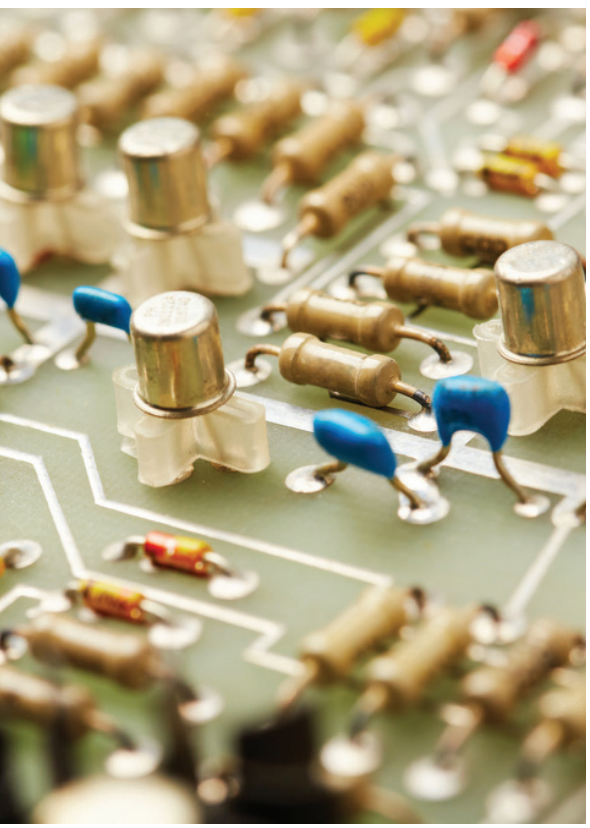
Some data in Table 2 may seem out of date, as the studies referenced were published eight years ago as part of the European Commission's preparatory work on eco-design of electricity-using products (EuPs). However, a recent study shows that the evolution of the bill of materials for a given product model does not change significantly over time, once the form factor is set. Size variations within a product category, such as a 12" laptop compared to a 14" laptop, created a greater weight variation according to the products' bills of materials than was observed between different model years. This implies that older numbers are adequate as a rough estimate of the materials available from EEE (Kasulaitis, Babbitt, Kahhat, Williams, & Ryen, 2015). Additionally, the delay between the purchase and collection of a given device means that older devices are what electronics recyclers today see in the scrap stream.

While not a dominant source of weight, electronic components, printed wiring boards in particular, constitute 40-70% of the recoverable value in EEE due to the concentration of precious metals found in and on these components. Gold (Au), silver (Ag), platinum (Pt), and palladium (Pd) are found in the wires and interconnects on the printed wiring boards, making these boards the most valuable part of a given device. There are, however, variations in board types that affect the overall recovery value of a board. Three different board grades exist, as summarized in Table 3. High-value boards have a large amount of precious metals due to the performance requirements of the products they are found in, and, in the case of mobile phones, an overall higher metal-to-product weight ratio because the wiring board constitutes a larger part of the total material present in a single device. Au is the driver for board value regardless of the grade, even though it is present in the lowest concentrations.

Beyond those components worth the metals recovery effort, there are a large number of elements present that do not currently have recovery processes. One example of the variety of elements present comes from a study by Christian and colleagues that analyzed the presence of 38 different elements in 85 different cell phone models released from 1998 to 2013 (Christian, Romanov, Romanov, & Turbini, 2014). They note that the content of some elements, such as iron (in steel components), nickel, manganese (in batteries), and copper, has remained steady across the time frame analyzed. The mass used of elements regulated during this time, such as lead and beryllium, dropped dramatically. Some rare earth elements, such as neodymium and erbium, have become more prevalent in recent model years, but the difference in components used among manufacturers makes it difficult to see which elements have seen the greatest increase over time. Within liquid crystal displays (LCDs), recovery efforts have targeted the indium found in the layer of indium tin oxide (ITO) that serves as the transparent conductor at the front of the display. The difficulty is the very low concentrations of indium on a given display and the lack of an effective chemistry to extract the element at reasonable cost (Huisman et al., 2008; Boni & Widmer, 2011).

Evolution of Electronic Materials

Looking forward, there is a large potential for material profiles to change. Not only is less material being used as products become smaller and lighter, but technology is evolving so that some materials, especially the expensive ones, are no longer used in great quantities or at all. There are also other pressures to eliminate certain materials. Decreasing the overall metal content of products, especially gold and palladium, not only decreases manufacturing costs but can also decrease the environmental impact related to EEE, as mining and related activities dominate these impacts. An example of where societal forces are driving the removal of precious metals, gold in particular, is in observed in the management of conflict minerals. Revenues from ores of the four metals found in conflict minerals - tin, tungsten, tantalum, and gold - have been tied to funding armed groups in conflict regions, in particular the Democratic Republic of Congo (DRC) and surrounding countries. In the United States, the Dodd-Frank Act requires that companies disclose the source and use of these elements (Dodd-Frank, 2010). The focus of these regulations has been the information and computer technology (ICT) sector, so companies have been further motivated to move away from these materials. Interestingly, the consumer electronics industry is responsible for no more than 15% of tantalum consumption globally and no more than 5% of the other three metals, but it has been the focus of human rights campaigners (Fitzpatrick, Olivetti, Miller, Roth, & Kirchain, 2015).



One technology development that will have significant impact on the overall recovery value of products is the move away from gold wire bonding for components on printed wiring boards to copper wire bonding. By one estimate, this change would drop the recovery value of a laptop computer from ~$12.00 to ~$0.40 (Handwerker et al., 2015). Eventually, metals may not even be necessary, as manufacturers look to replace metal interconnects with optical ones. This would allow for a higher density of component connections on a printed wiring board due to the elimination of cross-talk between metal contacts and overall faster information transfer rates from an increase in transmission speed (Kash et al., 2009; Immonen, 2013). Removing the metal content from printed wiring boards is a positive development for manufacturing costs, and in terms of social and environmental impacts, but one that could have significant ramifications for EEE recycling business models that depend on material recovery value.

Also of note are developments in display technology. For televisions, this has been seen in the progression of technology from the CRT tube to flat panel liquid crystal displays (LCDs) with cold cathode fluorescent lamps (CCFLs) for backlight, which have since been eclipsed by light-emitting diode (LED) technology. CCFLs have not gone away entirely, though, due to the fact that the color coverage and brightness possible for CCFL-backlit displays is still better than that produced by LEDs (Simmons, 2015a). Improving this situation is a priority for display manufacturers such as Samsung and LG.

New display technologies are also coming forward to further improve the viewing experience. Organic LED technology (OLED) replace the liquid crystals and the backlights currently used in displays with a layer of organic molecules that emit light of different colors when placed in an electric field. While offering superior clarity and contrast, OLED integration presents a couple of significant challenges. First, they need to be entirely sealed into a display so they are not exposed to moisture, which would degrade their performance. Second, the molecules used degrade over time, which will, in turn, degrade the display performance. OLED technology is already used in smartphone and tablet displays, where moisture barriers are easier to manage and displays spend the majority of their time in standby mode, where the electric field is turned off, which lengthens the lifespan of the OLEDs. Only a few high-end televisions and monitors with OLED displays are currently available from the major manufacturers due to the additional challenge of manufacturing even, consistent arrays of the organic molecules over the display areas required (Simmons, 2015b).

A second emerging display technology that received attention at the Consumer Electronics Show in 2015 is quantum dot technology, or QLED (Perry, 2015a; Simmons, 2015b). Here, tiny semiconductor crystals, or quantum dots, emit light of one specific color, so an array of these tiny dots can be used as pixels to make a display. Superior color contrast and a broad spectrum of colors are possible, since, in theory, each dot in a display can be addressed to produce a specific color. In practice, the reliability and repeatability of the arrays that would be needed to make stand-alone QLED displays has not been achieved. Instead, quantum dots are replacing the LED backlights in standard display configurations to produce the backlight for traditional LCD screens (Perry, 2015a). Samsung shipped the first models to employ this technology in 2015. The downside to this technology is the materials that are required to make quantum dots work. The most common types of dots contain cadmium, a toxic element that has come under regulation in Europe (Perry, 2015b). The material is not a problem during manufacturing, where it can be controlled and managed, but at some point in the future, when these displays reach end of life, workers could be exposed to it. Questions regarding the safety of recycling processes for nanoscale material remain uninvestigated. Alternative dot chemistries include indium, while not as toxic, may be supply-constrained in the future, making the technology economically infeasible (Harper, 2015).

A final emerging display technology that could influence the recovery landscape is flexible electronics. Flexibility is clearly desirable in the large-format smartphones common on the market today, but also for enabling flexible, even foldable, displays in new products (Nathan et al., 2012). One major barrier to flexible electronics has been the battery. Flexible batteries have been a rich field for research, producing lithium-based cells that incorporate carbon nanotubes or graphite or other novel materials as anodes, and batteries with new chemistries not currently available on the market that incorporate elements such as cobalt, vanadium, and zinc (Zhou, Li, & Feng, 2015). Until recently, flexible batteries were only a concept, but recently both Samsung and LG released prototype flexible battery cells demonstrated in wearable devices (Mlot, 2015; Purcher, 2015). These technologies will soon be available in devices available to the consumer, and, with an assumed lifespan of two years or less, will be in the recycling stream in less than five. This will introduce not only new materials to the stream but a significant new form factor that will need to be managed.

Critical Minerals and Rare Earth Elements

Functionality, especially in mobile devices, depends on a broad profile of elements that have not traditionally been part of manufacturing processes. For the United States, critical minerals are identified by the Department of Energy based on the importance of the mineral to clean energy technologies and the level of supply-chain disruption risk, as well as political or regulatory risks, lack of producer and supplier diversity, limited substitution options, and competing technology demands (CMI, 2015). Five rare earth elements are considered critical—dysprosium (Dy), europium (Eu), neodymium (Nd), terbium (Tb), and yttrium (Yt). Other minerals classified as critical by the Department of Energy are lithium (Li), indium (In), and gallium (Ga) (DOE, 2011).

Critical minerals are most notably found in lighting phosphors, batteries, and magnets used in wind turbines and electric vehicles (DOE, 2011). Within consumer electronics, rare earth elements are found in flat panel displays and permanent magnets. Eu, Yt, and Tb are used in flat panel displays to create the “trichromatic” (blue, green, red) light that combines to create images, and Nd and Dy are used to create the permanent magnets found in hard disc drives, amplifiers, and speakers in consumer electronics (Tasman Metals, 2015).

While there are in-ground reserves of rare earth elements in almost every country in the world, approximately 90% of current supplies are produced in China, where the social and political landscape may be more of a factor in the continued availability of these materials than any real scarcity (Nassar, Du, & Graedel, 2015). The challenge is that rare earth minerals are not scarce, so there is more than adequate supply on the market, when the market is not being manipulated (Bradsher, 2010; Stupples & DeSousa, 2015). This means that there is little incentive to develop these streams through material recovery without external support; the processes that exist today are not economically viable considering the market price of these materials (Nassar et al., 2015; Tsmis & Coyne, 2015). Long-term, there will certainly be a need for these materials, but justifying investment in secondary recovery technology today is challenging.

In a recent series of papers, Graedel and colleagues have assessed all technologically relevant elements for criticality using the same analysis process (Graedel, Harper, Nassar, Nuss, & Reck, 2015; Harper et al., 2015; Nassar et al., 2015; Nassar et al., 2012; Nuss, Harper, Nassar, Reck, & Graedel, 2014). They assessed the supply risk, environmental implications of extraction and processing, vulnerability to supply restriction, and impact of uncertainty in data sources. This series of papers addresses the fact that, globally, there are a wide variety of studies trying to address element supply criticality using a wide range of methods, and the results have not been consistent. The variability across these studies has prevented a clear picture of what elements society should truly be worried about from emerging, preventing government and other entities from clearly defining element-related risks. With respect to rare earth elements in particular, this team found that rare earths were one of the least likely to become critical along the four dimensions analyzed, in large part due to their relative geologic abundance. The authors do note that their results differ from other results in part due to the 10-100 year time horizon they used for analysis. Other studies use a much shorter time horizon such as 5 years, so the impact of the Chinese restriction on rare earth exports in 2010 have greater influence in those studies (Nassar et al., 2015). However, the authors do note that other technologically relevant metals do face some level of scarcity risk. Silver and arsenic (Nassar et al., 2012), indium (Harper et al. 2015), and niobium, manganese, and chromium (Nuss et al. 2014) were identified as causing significant levels of concern across these studies.

The challenge in recovering critical minerals is twofold. First, unlike precious metals that are found concentrated on the circuit board, these minerals are scattered across a wide range of components at very low concentrations, usually less than a gram per device for the most prevalent metals. To recover usable amounts, a very large number of devices is needed. Second, as discussed previously, there is no market for recycled REEs and critical minerals, so there is no immediate economic driver for improving recovery processes. Even though the economic drive may not be significant, the environmental and social impact of the mining operations to produce these metals is. The damage induced by rare earth mining and refining has already become evident in some regions in China (Maughan, 2015).

Because of the breadth of industries potentially impacted, the Critical Minerals Institute (CMI) was founded to develop cost-effective recovery methods and create the market for these materials (CMI, 2015). The mission of CMI is to assure supply chains of minerals that are essential to clean energy technologies in particular, which are also critical to the operation of modern electronic devices. The technologies researched and developed under the Institute are designed from the start to be commercially viable, so funding is focused on those solutions most likely to be adopted by the market. Of particular interest for the electronics industry is their focus on reducing waste through manufacturing process optimization and recycling and recovery technology development.

Electronics and the Circular Economy

The circular economy has emerged in recent years as a disruptive approach to innovation in product design and manufacturing that attempts to produce more sustainable supply chains. The circular economy has been defined by the Ellen MacArthur Foundation as:

> *"[The circular economy is] restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times."*

While not a new concept, interest in circular economy concepts was reenergized by the Ellen MacArthur Foundation in 2012, with the publication of their first economic report on the circular economy (Ellen MacArthur Foundation, 2012). This report is the first in a series that outlines the business case for the adoption of circular economy models across a wide range of product types and industries, including electrical and electronic equipment. Their most recent study estimates that in Europe alone, there is a potential resource benefit of €1.8 trillion ($1.98 trillion) achievable by the year 2030 through the implementation of circular economy models (Ellen MacArthur Foundation, 2015).

The need to consider the full lifecycle of EEE devices is underscored by the results of life cycle analysis (LCA) work completed for a range of devices (Ciroth & Franze, 2011; Kahhat & Williams, 2012; Lam, Lim, & Schoenung, 2013; Meyer & Katz, 2015; Scharnhorst, 2008). Not surprisingly, energy consumption of EEE during manufacturing and use and the environmental impacts related to power generation are routinely cited as major life cycle impacts. Beyond energy and related greenhouse gas impacts, resource depletion from metal mining, precious metals in particular, is also a significant source of impact. Resource depletion is accompanied by environmental and human health impacts from the processes required to mine and refine ores into materials that can be used in manufacturing. Reuse and recycling play a key role in offsetting resource-related impacts by keeping the products and materials they contain in the manufacturing system as long as possible. Impacts related to end-of-life activities for EEE have traditionally been harder to assess, as these processes are poorly understood within the context of life cycle analysis, and the data required for analysis are not readily available. This lack of information has led to disregard of end of product life considerations. This situation has improved in recent years, with studies illustrating the benefits used EEE management can have for global warming and resource recovery, as well as the opportunities for improved life cycle performance (Menikpura, Santo, & Hotta, 2014; Oguchi, Murakmi, Sakanakura, Kida, & Kameya; 2011; Wagner & Hischier, 2015; Williams et al., 2008; Xue, Kendall, & Schoenung, 2015; Zink, Maker, Geyer, Amirtharaja, & Akella, 2015).

In spite of the general sense that the electronics industry should be a leader in the goal of realizing a circular economy, electronic devices are some of the most difficult product types for which to achieve a circular economy. It is important to recognize the special challenges for electronics in reaching a fully circular system: the great diversity of materials in each product, the fact that some valuable materials, or even critical materials, occur in very small quantities per product (even if the number of units produced makes their recovery important), and the complexities of separating components and materials from each other for effective recovery. A case study presented by the Ellen MacArthur Foundation shows how simple design considerations, such as changing the composition of a product's external housing, can improve the overall performance of a product by keeping available resources in play. A recent example of a device entering the market with a circular manufacturing model is the Dell Optiplex 3030 all-in-one system. Dell has incorporated recycled plastics from electronics back into their products through collaboration with one of their specialty plastics providers, Wistron GreenTech, using materials collected through their Reconnect program with Goodwill (Dell, 2015; Clancy, 2014). This success involved many years of work and coordination efforts throughout the entire supply chain, but has produced a product that decreases embedded energy, decreases carbon emissions, and provides a market use for recycled electronic plastics. It provides a real example of the gains that can be made for both the environment and a better economic bottom line through implementing circular economy principles (Clancy, 2014; Gonzalez, 2015). While circular economy models may not be feasible for entire devices in the near term, special opportunities to achieve a circular economy with certain products or materials should be pursued, and those efforts made visible. Creating successful circular economy systems for EEE may entail coordinated initiatives in both product design and recovery system development, which could make new models and opportunities possible that otherwise may not be.

Electronics Reuse and Recycling Industries

Used electronics management starts with collecting devices that have reached the end of their first useful lives. Ideally, used electronics will be collected close enough to the time of their sale to be reused or refurbished for two or more lifecycles. Otherwise, devices move straight into the materials collection phase, where they are pre-treated to remove hazardous materials, then further reduced in size either through additional hand disassembly or mechanical separation and size reduction (i.e., shredding).

The materials recovered during the treatment step can then be sent to appropriate commodity recovery facilities, such as smelters. Figure 1 provides an overview of this process.

Table 4 provides an indication of the value of different products and the cost to manage them. The “refurbished” and “used” columns show the average price of a device on the current secondary market; the recycled column shows what the materials themselves may be worth; and the “labor” column indicates the cost of the work required to minimally disassemble a device (i.e., remove hazardous or high-value components) in preparation for recycling. Small appliances have not been included because of the wide variety of products that are included in that categorization. Transport of devices and materials from collection to final disposal has also not been included because of the high variability in paths and distances devices travel, as well as the difficulty of allocating transportation costs on a per-device bases. Further details on these calculations can be found in Annex C.

Overall, the resale value of devices is considerably higher than the material value alone. Refurbishing a device can provide a premium, if the consumer is confident that the refurbishment process adds value. The recycled material value comes from Sage BlueBook, an online resource for determining the value of used electronics and recovered materials (bluebook.sagese.com). In addition to the per-unit material value, there are bulk scrap values for some devices. Of note is the bulk scrap value for printers of \$0.04/lbs, which is also the scrap value attached to consumer electronics accessories and peripherals such as mice, keyboards, and speakers. This is the value for mixed plastics, one of the lowest and least valuable of materials categories, and one of the most common materials streams derived from EEE. The incredibly low value of this material underscores the challenges in assuming profitable recycling for all devices, when coupled to the impacts that factors such as labor and logistics can have on an organization's bottom line, may drive decisions that have poor outcomes for both communities and the environment.

TABLE 4: Average reuse and recycling prices for selected product categories

	FORMAT	REFURBISHED	USED	RECYCLED (PER UNIT)	LABOR COST (PER UNIT)
MOBILE DEVICES (2011)	ANDROID	$145	$122	< $2	-$0.07
	iOS	$180	$203	$1 ($3.30/lb scrap)	
TABLETS (2013)	ANDROID				
	iOS				
LAPTOPS (2010)					
PC	15"	$450	$359	$17	-$0.42
APPLE	15"	$700	$600	$18 ($2-3/unit for non-functioning units)	
FLAT PANEL DISPLAY TELEVISIONS (2015)	1080P				
	32"	$260	$214	$5	-$2.11
	55"	$650	$600	< $10 (scrap LC display $3)	
CRT TELEVISIONS	ANY SIZE	N/A	$5	-$15 or higher depending on size and weight of display	-$0.98 (Excluding glass handling)
PRINTERS	LASER & INKJET	NONE LISTED	$60	< $1 ($0.04/lb scrap)	-$0.14

[1] From GEC, 2014. This reference cites the material value of a tablet as a sum of its component materials, which totaled $0.24.

Reuse and Refurbishment

Using the term "electronics recycling" as a way to describe the entire used electronics management space is misleading. The actual action commonly associated with recycling is materials recovery: Bottles or cardboard boxes are taken to a recycling facility and turned back into raw materials that can be made into new products. There is no space in this flow for reuse or refurbishment, as these actions are not common or profitable for materials that are essentially already commodities.

For electronics, reuse and refurbishment are a very important pieces of the puzzle. Reuse and refurbishment represent the greatest value recovery opportunity from used devices, as well as the most environmentally friendly step, which allows the material resources in the device and the embedded energy from manufacturing processes to be captured and reused. Interviewees from all stakeholder groups identified reuse and refurbishment to be significant opportunities for used electronics management in the near term, and necessary for the industry in the long term, as the devices reaching end of life become smaller and lighter and therefore less valuable for materials recovery. To capitalize on this opportunity, though, a better approach to device collection is required. Figure 8 shows the decrease in the retained value of laptop computers and mobile phones. Further details on this analysis can be found in Annex C. The percentages represent the loss of value in a given device between its original MSRP (manufacturer suggested retail price) and today's retail price. Mobile phones have lost 50% of their value in two years, whereas laptops will hold their value for three to four years. While none drops to zero value, this only reflects that there are used devices available for sale, not that there is an active market for older devices. This rather clearly shows that for a robust reuse market, devices need to be recovered as soon as their first useful life ends, rather than losing significant value while sitting in a drawer or closet.

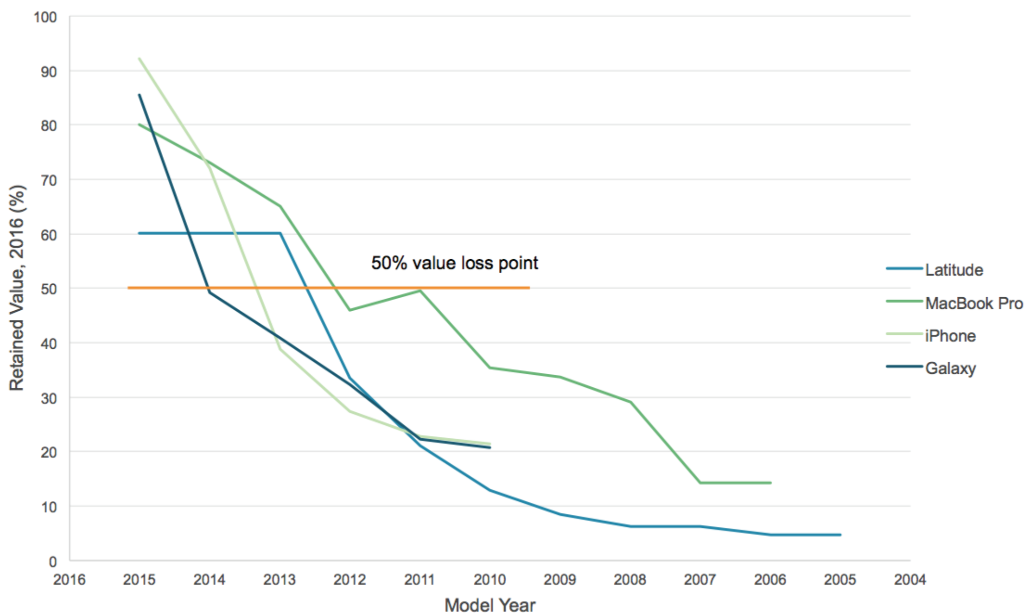


FIGURE 8: Retained value of select laptop computers and mobile phones in 2016

While cited as a significant opportunity, the obstacles facing the repair community today make the repair industry forecast hazy. The data security issues for phone and computers will only continue as devices become smaller and more interconnected. Any device that transmits data is capable of storing data on some level. This means personally identifiable information is now contained on unexpected devices such as printers and in Bluetooth devices in automobiles (Bhalla, 2015; FTC, 2015; Zimmerman, 2015). Complete data destruction is challenging, even when the location of the data is known, and the feasibility of installing a new version of the operating system if it is damaged or removed during the data destruction process is still unknown. An emerging issue that could further complicate device reuse is how intellectual property concerns (transferring ownership, manufacture of replacement parts) will intersect with reuse activities. These issues will continue to evolve in relation to the evolving electronics landscape, and will in part determine how successful device reuse and repair can be in the future.

One of the biggest barriers today to more device reuse and refurbishment is the lack of information that would enable better repair of used electronics and electrical equipment. In order to build a robust reuse and refurbishment system, greater accesses is needed to: schematics, material lists, and diagnostic tools for new products; repair manuals for independent refurbishers; and parts and firmware to ensure quality repairs (Digital Right To Repair, 2015). Manufacturers are not comfortable with releasing this information because of potential liability if someone is injured during repair or brand damage from poorly or improperly repaired products on the market. How to enable a robust refurbishment and repair community while addressing concerns regarding the quality of those activities is an ongoing conversation that will shape the role of reuse.

One example of how repair can work to everyone's advantage is the Microsoft Registered Refurbisher and Authorized Refurbisher programs. These programs are designed to enable refurbishers of all sizes to reimage hard drives (the firmware) and install the latest Microsoft software (Microsoft, 2015). The consumer receives a refurbished product with the latest software, the refurbisher is compensated for this service, and Microsoft receives a software licensing fee. As the market for refurbished devices includes individuals who do not have the resources to buy products new, this system also helps bridge the digital divide and enables students to succeed in an education system now geared to online learning. While the Microsoft program has not scaled beyond computers, this model is a strong and economically sound proof of concept that manufacturers and the repair community can successfully collaborate.

Industry's working with independent repair shops to provide standardized diagnostic tools is not unprecedented either. In 2014, the automotive industry settled with independent repair shops to provide diagnostic software and other tools for the consumer market (Nelson, 2014). In 2015, manufacturers of trucks and other heavy-duty equipment have come to a similar deal. Ironically, the patchwork of legislation that exists for electronics recycling was cited by the automotive industry as the reason why they decided to accept the laws passed in Massachusetts as a national standard (Nelson, 2014).

Challenges & Costs

For true product end of life electronics recyclers--those who focus on material recovery and whose business models are in-part or wholly dependent on the commodity markets--a convergence of factors has created an extremely challenging business environment today. From the stakeholder interviews, descriptions of the following challenges emerged: Record low commodity prices: The severe decline in commodity prices, especially for precious metals, has made many product streams cost-negative to recycle (i.e., it costs more to disassemble devices and transport the commodity materials than can be made selling them). This, in turn, has led to stockpiling of these materials, notably CRT monitors and televisions.

Transportation: As mentioned previously, extensive logistics may be necessary for material management and moving material around is very expensive. When a quantity of used EEE has been collected, it has to be moved multiple times before reaching material recovery. Considering that many end markets for recovered materials are international, these costs can be significant.

Wide variety of product types: In the consumer electronics space, the variety of product types available on the market today translates to a challenge for recyclers to collect enough material of one type that it can be managed efficiently and made profitable in the commodity markets. This is in contrast to the business-to-business space, where there is still a large number of the same type of product being recovered together, which makes sale on the commodity markets more profitable.

Speed of technological change: The speed with which electronic devices evolve challenges the ability of recyclers to understand what will be reaching their organizations in the near future. Smaller organizations may not have the bandwidth to research what materials are in devices on the market today and, therefore, coming into their facilities in two to fiveyears. This is further compounded by the lack of medium- to long-term investments in equipment and process research and development as there is no reliable forecasting method to understand generation of used electronics and the volatile nature of the commodities market.

Old and obsolete equipment: When consumer products are collected, there is often little value in reuse or repair because the equipment is so old that there is no market for the refurbished device. They do not cost less to recycle, but value in reuse or repair that could offset some of the costs is no longer available.

The most notable legacy equipment are CRT displays. The challenges with these devices have been well-documented, as discussed previously, but the impact they have had on the industry cannot be overstated. The cost to manage these materials is much greater than the commodity value the displays contain. Both capacity and cost factor into this issue -- cost, because some organizations who were accepting CRTs did not plan for adequate compensation for responsible disposal of these materials, and capacity to manage the glass, especially with respect to treatment in preparation for grinding and shipping to downstream glass recycling facilities. Multiple stakeholders did, however, point out that the capacity issue is not a roadblock if there is funding to cover the considerable cost of management. Lead smelters that incorporate heavily-leaded funnel glass into their processes in place of sand or other fluxing agents were frequently cited as a key part of the downstream solution, with one stakeholder recommending that some sort of incentive or positive recognition be provided to the smelters to encourage them taking on more glass.

Low barrier to entry: Anyone who wishes to start a shop and collect material for recycling is able to do so (Peters & Chaplin, 2015), with or without any certifications or partners for downstream material management. This creates a situation where manufacturers can opt for the lowest rate quoted by recyclers, whether or not this rate adequately covers the real cost of material management. This is particularly noticeable in the run-up to and first year of new EPR regulations, where individuals will enter a market on the expectation of reimbursement, collect material, and then be responsible for the cost of disposal if not compensated through the state program/obligated manufacturers.

Labor market: Today, all material recovery requires some basic level of manual labor to depollute devices. Batteries, lamps, toner cartridges, and other potentially dangerous materials cannot be introduced into mechanical reduction systems such as shredders and must be removed by hand prior to reduction. Mechanical solutions are under development, but have not really reached a point where they are economically feasible to operate in most organizations. In some areas, such as Seattle, Washington, there have also been significant increases in the minimum wage, the effect of which on an already-tight labor market, has yet to be understood.

A related issue to the cost of labor is the challenge that it presents to effective material separation. To develop new markets that would provide the economic incentive for new material streams, effective recovery technology for the elements is needed, but so is technology that will enable cost-effective isolation of the components. For example, technology developed at the Critical Minerals Institute to recover heavy rare earth elements such as neodymium (Nd) from permanent magnets has recently entered a commercial pilot with U.S. Metals in Dallas, TX, but the small magnets found in speakers, smart phones, and hard disc drives still have to be separated out, usually by hand, at the same labor costs as for other materials.

Free-to-consumer recycling: In many of the state programs in effect, the consumer can drop off any equipment free-of-charge, whether or not the product is covered under the EPR regulation. Since manufacturer obligations are based only on covered products, this can leave recyclers responsible for the additional cost of managing collected equipment not covered by regulation. The uncertainty in what will be received coupled to the lack of robust forecasting models greatly inhibits the ability of recyclers to plan accordingly and ensure responsible management routes are available for this material.

Impact of EPR laws: While the state EPR laws were established to provide varying levels of consumer collection, the impact on the recycling industry has not always been positive. Before the implementation of the laws, recyclers would focus on local governments and others as their customer base and set fee levels for their services based on the expected volumes. Those collectors could then choose to charge fees to offset the costs or pay them from other funds. In many cases, this option is no longer available to recyclers and other organizations handling non-covered products as regulations restrict what organizations can do.

The outcome of these forces has been a high number of mergers, acquisitions, and bankruptcies in this industry, a trend most expect to continue. Some organizations have opted to stop taking consumer electronics and focus only on business asset management programs. Unfortunately, the bankruptcies often leave stockpiles of cost-neutral or cost–negative equipment, CRT displays in particular, that then need to be managed by someone else.

Material Challenges

Due to the focus on commodity value for electronics recycling, the material profile of devices and how that profile changes over time is very important. One change noted by the majority of stakeholders is the decreasing content of precious metals due to the decrease in size and weight of products. In particular, stakeholders commented on the evolution of printed circuit board technology. Boards in products on the market today have greatly reduced amounts of metal, with gold being replaced by copper in many lower-end applications, which impacts their value for material recovery. Beyond the precious metals, base metals such as copper (from wiring other accessories), steel, and aluminum can be recovered, as well as plastics from the housings of devices.

The hazardous components of electronics that require special handling add additional challenges to responsible recycling. Integrated batteries, most notably in smartphones and tablets, must be removed by hand prior to recycling, which is labor intensive. For example, a generic tablet may take 10 minutes to just disassemble and remove the battery, which leads to a loss of approximately $0.50 per tablet based on commodity pricing and labor required to remove hazardous components (GEC, 2014). The challenges in disassembly of tablets in particular has been studied by Fraunhofer IZM in their 2013 study, *“Disassembly Analysis of Slates: Design for Repair and Recycling Evaluation”* (Schischke et al., 2014).

The plastics, especially those types found in televisions and desktop and laptop computers, contain brominated flame retardants (BFRs). As the name implies, these additives are used to inhibit, suppress, or delay the production of flames, reducing the flammability of materials such as plastics and textiles. Some are considered toxic, with multiple classes of BFRs banned or restricted for use under RoHS or REACH regulations in the European Union (European Chemicals Agency, 2013; RoHS, 2011). Under the bans, plastics with BFRs present a challenge in the recycling stream, since plastics with BFRs should not be re-integrated into new products. This limits the possible product applications for recycled plastics, although some standards, such as EPEAT, have waivers for recycled plastic content up to 25% of the weight of a plastic component, where that plastic contains BFRs from a previous use (EPEAT, 2015). Even without BFRs or other additives, there are still limited commodity market options due to the challenge of recycling rigid plastics (Nnorman & Osibanjo, 2008). One stakeholder noted that the need for flame retardants in electronics in general should be revisited, not just due to toxicity issues, but the fact that the product safety laws driving their inclusion in electronic products were written when high heat generating technologies such as CRT displays were standard. Considering the major advancements made in lowering power consumption and creating electronics assemblies that do not produce large amounts of heat, are BFRs even really needed anymore? The answer isn't clear, but the conversation should happen.

While the heavy metals, PVC, and plastics with brominated flame retardants found in electronics are not of particular concern to the device user, these materials can cause significant harm when devices are treated at end of life (Lim & Schoenung, 2010; Nimpuno, McPhearson, & Sadique, 2009). Treating electronics for material recovery can expose workers to these materials in particles from shredders and in the dust in facilities (Lau, Liang, Man Chung, & Wong, 2014; Tsydenova & Bengtsson, 2011). Exposure to these dusts has been tied to a range of health issue in workers both in developed and developing countries (Perkins, Brund, Nxele, & Sly, 2014). In addition to contamination in facilities that are part of the formal material recovery sector, the informal processes employed in the developing world, such as open-pit burning to liberate metals from electronic components, expose workers to hazardous materials, as well as contaminate the air, land, and water around informal processing sites (Alabi, Bakare, Zu, Li, Zhang, & Huo, 2012; Pradhan & Kumar, 2014). The environmental contamination then creates significant health risks for the surrounding communities (Minh Tue, Takahashi, Subramanian, Sakai, & Tanabe, 2013; Song & Li, 2014).

On the display side, liquid crystal displays (LCDs) using mercury lamps as backlights have started to reach end-of-life processing. The challenge here is disassembling a panel and removing the very thin mercury lamps for separate processing. This process is difficult and time consuming, and has a high risk of exposing workers to mercury if a lamp is broken. Flat panel display technology has evolved significantly since its introduction, and mercury lamps have largely been phased out of current television and monitor models. In recycling, however, the mercury lamps are expected to be part of the landscape for at least the next decade (Huisman et al., 2008; Boni & Widmer, 2011).

CRT legacy materials are of particular concern in the current market. There are two toxicity-related issues with CRT displays. First, the phosphors that coat the inside of the tube itself can be quite hazardous. Second, the lead content of the glass itself is above US EPA thresholds for hazardous materials, requiring any material not recycled to be sent to hazardous waste landfills rather than regular municipal ones. Improper storage that may cause the CRTs to break, as well as the actual process of separating the different parts of these displays, can expose workers to both the phosphors and the lead. While the processes used in the US to separate and treat CRT glass are highly automated, significantly limiting worker exposure, lead exposure in processing facilities is still a concern that needs to be managed by these organizations. A 2014 study conducted by the National Institute of Occupational Safety and Health (NIOSH) highlighted the extent of contamination of facilities in the U.S., by lead in particular, due to CRT treatment, showing clearly that this is an issue that all organizations need to address (Ceballos et al., 2014).

As noted earlier, roughly 6 billion pounds of CRT displays were left in households in 2015 (NCER, 2015). A study by Transparent Planet has estimated that an additional 333,000 tons of material were already stockpiled by recycling facilities in the United States due to the cost of responsible transport and treatment of this material (Roman, 2012). How these numbers have shifted from displays stored in residences to those treated or stockpiled have not been published. It is clear, however, that this material will be in the system for many years to come. As of 2013, there was only an estimated 128,000 tons per year of processing capacity in North America, located primarily in Canada or Mexico (Shaw, 2013), well below what would be needed to manage the volume of displays ready for treatment on an annual basis. Compounding the lack of domestic options for management and an increasing number of businesses closing and abandoning stockpiled material, 2015 saw volatility and uncertainty in the export market due to Videocon's ceasing to accept shipments of CRTs or CRT glass (Elliott, 2015b). Videocon is the only remaining smelter for leaded glass in the world. While closures and stockpile discoveries are expected to continue in 2016, Videocon has begun to accept material from select vendors again and additional treatment capacity is being found. Camacho, a glass tile manufacturer in Spain, has been approved to accept shipments of glass from the United States, and new domestic options may provide some easing of the situation (Elliot, 2015a).

Looking forward, there will be increased uncertainty in the materials profile of devices. New engineering materials such as nanocomposites, the plastics in flexible displays, and smart textiles embedded with electronic components have not yet worked their way into the recycling streams, so the handling and treatment options are still unknown (US EPA, 2013; Caballero-Guzman, Sun, & Nowack, 2015). They also bring unknown health risks with them as human exposure has not been assessed with respect to end-of-life treatment of devices incorporating these materials.

Role of export

Contention surrounding the transboundary movement of used electronics highlight the strong divisions in used electronics management philosophies. Recovered devices and materials flow to where the most value can be gained with the least cost, including locations that may not have facilities or processes to protect workers and the environment. In the past, this movement has been dominated by the flow of material from developed countries in the northern hemisphere to developing countries in the southern hemisphere, but recent work indicates that this may not be a fully accurate description of how used electronics and e-waste are moving today (Basel Convention, 1989; Lepawsky, 2015). Export has played, and will continue to play, an important role in the movement of used equipment because it provides a route for materials to move to where value can be extracted for the least economic costs, whether the material is whole units or components for reuse or refurbishment, non-working material shipped under questionable circumstances, or recovered materials from recycling operations headed to end-use markets.

For the purposes of this work, the legality of transboundary movement of electronics is not explicitly considered. Export is certainly a large part of the economic equation for used electronics reuse and recycling, and the damage improperly handled materials causes both to people and the environment in countries where material recovery is taking place is significant as well. This work does not take a stance on whether this would be improved by banning all export of equipment. The recommendations developed here are focused on solutions that can be implemented domestically to improve system performance and prevent exports in the first place.

Opportunities

While there are significant challenges around used electronics management, especially under the current market conditions, there are also significant opportunities. Stakeholders identified a series of opportunities open to organizations recycling electronics, as summarized below.

Broaden scope of products routinely collected: One path to increasing material available for recyclers is to develop effective ways to manage a larger array of used EEE. One approach would be to expand the scope of product types covered in U.S. state programs for electronics recycling. Recyclers are only reimbursed or contracted to handle covered electronic products, so they must find other routes to handle non-covered products. Printers, small appliances, and accessories, such as mice and keyboards, fall into this category. Further development of affordable and cost-effective disassembly and sorting equipment that would allow for the maximum recovery value of materials from used EEE types would also help broaden collection programs. Automating these processes would also create flexibility for managing new device types, especially if the new technology is designed to handle the smaller devices entering the consumer electronics market today.

Improve logistics and decrease the distances traveled: Create more efficient handling and transport systems of materials to maximize commodity value, or increase the number of treatment facilities in underserved regions. One stakeholder suggested that having at least a secondary smelter for circuit boards and other metal streams in each region, rather than relying on facilities on either coast. A second recommendation was to have pre-treatment and treatment facilities located close to major population centers to decrease distances material must travel, much like regional distribution centers are located for retail operations today.

Over the course of the interview process, a few participants provided potential improvement models to decrease the costs of logistics, which are presented in the recommendation section of this report.

Diversify operations: To improve resiliency to market forces, an organization can diversify by working with both business-to-business and business-to-consumer models, or include some repair or component harvesting along with traditional material recovery operations. As noted by Willie Cade of PCRR, “repair is a diversification strategy.” Regardless of whether an organization opts to diversify or stay focused on one part of the system, they need to understand the market and the business model before jumping into the business. As multiple interview participants pointed out, a good business is going to be successful without subsidies or high commodity prices because these organizations will be able to adapt to changing market conditions to ensure profitability while managing material responsibly.

Landfill ban: While all interview participants expressed dissatisfaction with the existing state laws and a desire for some sort of national (but not necessarily governmental) system, a national landfill ban was mentioned by multiple stakeholders as a way to get material flowing into the system and leveling the playing field as well as increasing material recovery. National legislation at this level and on this topic is highly unlikely, but such a change would serve as a significant disruptor in the recycling industry.

Invest in R&D: Currently, research and development of new processes and technologies is not common in the electronics recycling industry. Recyclers tend to focus on the material arriving on their dock today, rather than trying to understand what is coming in two years and what processes and technology they would need in place to maximize value recovery from future material. Reuse and refurbishment operations tend to be more tuned into changes in the market because they work with a much newer mix of devices. Since there is a lag between products entering the market and reaching material recovery, forecasting is possible, but having the bandwidth to synthesize this information and develop technology to address new materials and processes is beyond the capability of the vast majority of recyclers. Even where bandwidth exists, the long-term investment needed to see through the deployment of new technologies does not exist.

Comparison with other recycling streams

There is a tendency to compare electronics recycling with other types of recycling, such as municipal waste management systems. This oversimplifies the picture and gives the impression that similar interventions will work on all the different material streams. Municipal recycling tends to address materials such as plastic packaging, cardboard, and newspaper (US EPA, 2015). The flow of material is fairly linear with few, if any, hazardous materials present, and significantly larger volumes of these materials are collected. More challenging streams, such as mattresses or tires, are sometimes covered by producer responsibility laws so that they can be collected and managed rather than landfilled (Moore, 2012; CPSC, 2103).

Electronics are different from the other streams in their individual product complexity, the amount of personally identifiable information present on used devices, the potential for hazardous materials to be present, and a traditionally high commodity value due to the precious metals used in a variety of components. How these devices are handled may differ from other material streams because of the interaction of these different factors. There are also a greater variety of actors, especially at the collection and pre-treatment stages, and management stages, because of device complexity and potential residual value.

Clothing and textile recycling combines aspects of both the municipal recycling systems and electronics recycling. There is a very active secondary market in and informal exchange of used clothing that is similar to that found for some electronic products. Clothing and textiles also do not have organized municipal collection, although drop-off locations co-located with other recycling drop-off points are becoming more common (SMART, 2015; CTR, 2015). There is also an active commodity market for these materials, whether they are repurposed (e.g., T-shirts to industrial rags) or recycled and sold into fiber markets. The most notable differences between recycling clothing and electronics are that clothing and textiles are not considered hazardous materials and do not store personal information that must be handled responsibly at the end of their useful lives.

A final difference between EEE and other recycling streams is that EEE is not collected curbside as part of municipal waste collection. The larger appliances, such as televisions, may be collected as part of special heavy or bulky collection days, but this varies by community. Otherwise, electronics and sometimes small appliances are collected as part of annual or semi-annual household hazardous waste collection events or are accepted at the same drop-off points where other hazardous wastes are collected. Rather than handling electronics themselves or through centralized material recovery facilities, municipalities will most likely contract with recyclers to manage this material, whether or not a given area is under a state-run EPR program. How the costs for recycling are handled is then up to each municipality. This complicates intervention because of the variability in management programs based on local and regional preferences, funding models, and availability of treatment facilities. It also raises the question of ownership: Do the collectors own the devices and other materials even if they are collected under schemes paid for by the manufacturers? This distinction is not spelled out in existing legislation and can drive up the costs for manufacturers under regulatory obligations.

Used Electronics Management System

One of the very few things all stakeholders agreed on during the interview process is that the U.S. system—if what is in place today can be considered a 'system'—is broken.

In non-regulating states in particular, some stakeholders felt that no working system was in place at all. As expressed in the previous sections, the issues highlighted ranged from the high degree of program variability between states to inadequate funding mechanisms to offset the true costs of recycling to the rapid evolution of the products themselves.

A "Working" Used Electronics Management System

While stakeholders readily agreed that the existing system is broken, they had a more difficult time describing a working system. Each participant was asked, "Please describe your idea of a "working" (if not ideal) electronics management system", to which they were able to respond as they felt appropriate. Figure 9 provides an overview of the different types of models discussed by participants and the differences in what constitutes

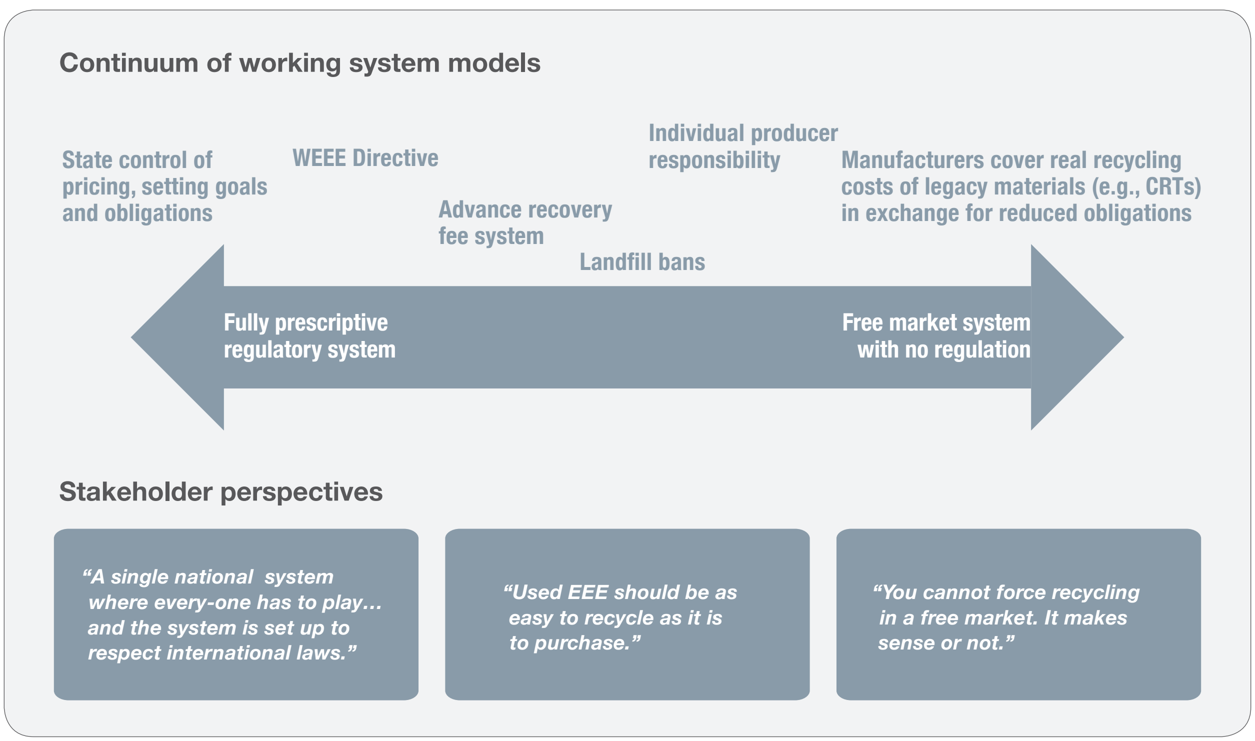


FIGURE 9: Perception of working systems by stakeholders

"working". One participant pointed out that whether a system is working depends on the goals. If the goal is to divert material from landfill, the system does that pretty well. If the goal extends to include minimizing human health and environment risks or maximizing value recovery or resource recovery, system performance was debatable and very dependent on which path through the system one considers.

Multiple definitions surfaced for what constituted a "working" system, such as:

- A working system is one where it is as easy to recycle devices as it is to buy them.
- A working system is one where the manufacturers cover the true costs of recycling with no cost to consumers at the time of recycling.
- A working system is one that is cost-neutral to the local governments managing collection and provides for responsible material handling.
- A working system is one where the costs of recycling are managed up-front with a recovery fee to ensure funds are available for proper material handling when products are returned.
- A working system is a single national system where everyone participates on a level playing field.

A more specific definition was provided by Basel Action Network (BAN):

"A 'working system' across the country would include federal regulations creating a level playing field for all recyclers/refurbishers, requiring them to meet a minimum high standard for responsible recycling and reuse. Waste generators of any kind would pay a reasonable price to recyclers/refurbishers to provide these environmental and data security services. The US will have ratified both the Basel Convention and the Basel Ban Amendment, keeping US hazardous waste in developed countries for recycling and disposal."

As is readily apparent from the range of answers, the perception of what works is not unanimously shared. Only a handful of stakeholders considered any of the state programs as "working", and many found different aspects of the programs to be desirable, even if the full regulations were problematic. One point on which everyone agreed, though, was that the patchwork of state programs created inefficiencies due to the inability to coordinate resources across state lines and that they created unnecessary confusion and costs for compliance for both manufacturers and recyclers.

Program effectiveness assessments are also hindered by the lack of a single definition of success for voluntary or regulatory programs. No two state-legislated electronics recycling programs use the same set of equations to determine targets or goals or even how collection volumes should be measured, if such reporting is even required. Some states also factor in “convenience” by requiring a specific distribution of collection sites based on the population of the state, which adds further confusion and variability to evaluating success. A more holistic approach to assessment that includes a broader set of indicators to describe the performance of an entire program would enable measurement of not only volumes or units received but of how effective a program is in managing used electronics from collection through to final disposal. Without a more objective way to determine performance, assessing “working” is difficult and very little progress can be made to improve the system.

Other Industries

When discussing what constitutes a working recycling system, systems developed in other industries were cited. Call2Recycle, a battery stewardship program in North America, was frequently cited as how a manufacturer-funded effort should work (Call2Recycle, 2015). Its success is attributed in large part to the fact that it is an industry-led and industry-funded group, that “got out in front” of legislation on battery recycling and was able to work with states and local governments to create programs that, while not identical, are far more aligned than electronics recycling programs. This program had very specific success criteria that were called out in the battery legislation in California, the first state to institute a program, which were then incorporated into the Call2Recycle efforts. Other programs noted were those led by the paint industry and tire industry.

On the market-driven side, the lead-acid battery recycling system was highlighted as an ideal system. Here, the industry collects 98% of the batteries put into the market for recycling and returns the recovered material back to the battery manufacturing process in a closed loop system. While market driven, organizations recovering lead-acid batteries have an advantage in that these batteries tend to be replaced in independent or manufacturer automotive repair shops or purchased for replacement by the automobile owner at an auto parts store. A close relationship between the battery manufacturers and the repair shops and automotive part dealers helps ensure the batteries are recovered. One example of such a program is run by Johnson Controls; further information on their process can be found on their website: http://www.johnsoncontrols.com/content/us/en/products/power-solutions/responsible-recycling/how.html.

Policy Landscape

The electronics recycling landscape in the US has been significantly shaped over the last 10 to 15 years by policies adopted to address concerns over improper management and lack of recycling opportunities. Beginning in 2000 with the first regulation to ban households from disposing CRTs in landfills in Massachusetts, state policies have created market responses with both intended and unintended impacts. Beyond Massachusetts, state-level policy activity began around 2004 with California implementing the first statewide electronics recycling program based on a consumer fee at the time of sale.

This followed the end of a national dialogue convened by U.S. EPA that occurred for several years between 2001 and 2004 to develop a national approach for recycling programs. Once it was clear that this group, known as the National Electronic Product Stewardship Initiative (NEPSI), was not going to agree on a common approach, state legislatures looked at how to address consumer demands for recycling programs at their level.

California's response was to implement a law that required the retailer to collect on certain electronic devices a fee that would be remitted to a state agency, who would later review and approve claims for payment from collection and recycling activities. Despite the fact the largest state in the U.S. adopted the first legislative approach based on an advanced recycling fee like this, no other state after California took that same route. Beginning with the Maine law passed in 2004, other state laws used a version of producer responsibility, where manufacturers/brand owners were required to physically and/or financially support a statewide recycling program. After passing one new state law per year until 2006, there was a flurry of activity in 2007-2010, resulting in 24 state laws by the end of 2010. After the final law was passed in Utah in 2011, half of the U.S. states, representing two-thirds of the U.S. population, had some type of program law in place. The only new regulation related to electronics recycling was in the District of Columbia, who passed an ordinance to establish a manufacturer responsibility program in 2014 that will be fully implemented in 2017 (ERCC, 2015). Further details on how different states have chosen to implement producer responsibility laws can be found on the website for the National Center for Electronics Recycling: http://www.electronicsrecycling.org/.

During the stakeholder interviews, many participants expressed that a national system would be ideal, but felt that the opportunity to do so had passed. They did not feel that the challenges faced by NEPSI had changed, especially with respect to disagreements among the different stakeholders, and the existence of the state programs made national-level legislation even more difficult. Any national program strong enough to be effective would have to preempt these programs, which was not seen as politically likely or feasible. Participants were slightly more optimistic about the chances that a national framework could be developed, possibly as an industry-led initiative that could better coordinate at the national level and work with the different state agencies that have regulatory flexibility to adjust their program parameters to more effectively harmonize with other state programs (NCER, 2015b).

One additional theme that emerged with respect to the state programs was the challenges related to enforcement of the laws. Many states lack the support or resources to enforce the laws they have on the books, so there are no consequences for illegal activity. Improving enforcement was cited as an additional need for improved system performance (E-scrap News, 2015).

Role of Certifications

Within the U.S., the two primary recycling certifications are R2 (https://sustainableelectronics.org/r2-standard) and e-Stewards (http://e-stewards.org/).

In August 2015, Chaplin and Peters conducted a survey to explore perceptions of end of life electronics, the results of which were presented at the 2015 E-Scrap Conference (Peters & Chaplin, 2015). The survey garnered 213 respondents--52% from the electronics reuse/recycling industry, and 48% from government, NGOs, and other interested groups--and focused on the overall business climate, the perception of certifications, and the auditing processes that accompany them. Overall, 57% of respondents felt that certifications added value to their business, and 59% felt they added value to the industry as a whole. The two greatest company-level impacts of certification were improved reputation (51%) and reduced risk (42%). The R2 standard was seen as the better of the two for encouraging reuse, even though neither standard was considered great for this purpose, and e-Stewards was seen as more effective in encouraging export controls.

The results of this survey align closely with those of the interviews conducted in support of this work. Interview participants felt that certifications had been successful in establishing a “floor” for the industry, and that certification was becoming necessary to be in the business, but that which certification an organization carried did not matter as much as having one at all. While the cost of certification and the burden this can place on small-to-medium businesses was noted, many participants felt that if an organization wasn’t able to afford certification, it shouldn’t be in the business anyway.

Role of the Retailer

The retailer does not have a particular role to play in the collection of used electronics under state law in the United States, with the exception of certain requirements to educate consumers on recycling options at point of sale in some states. Participation in collection activities is voluntary and subject to the same types of economic forces that drive other aspects of electronics collection and recycling. In comparison, the provincial programs in Canada define obligations across a much broader set of stakeholders, including wholesalers, retailers, and brand owners, so retailers are required to be involved in the collection and management of covered electronics products.

Retailers have an advantage over other organizations for education and collection of used electronics, especially with respect to collection, because they interact directly with consumers. At point of sale, consumers are focused on the device they are about to get, creating an opening to engage them about discarding the device being replaced. Telecommunication companies, in particular have capitalized on this opportunity and run trade-in programs, such as Sprint’s BuyBack program, where consumers are given a credit to their account or other incentive to turn over their old device when getting a new one (Sprint, 2015a). Not only is this a service to the consumer, but provides the carriers with a supply of newer devices they can refurbish and resell to maximize use of embedded resources for as long as possible. They are also able to ensure that broken or obsolete devices are managed responsibly.

Retailers may also choose to engage with their customers on used electronics as a service provided to the customer. Bringing products back to a store, and therefore a customer into the store, is a convenient option for used electronics collection. This can also provide a crucial outlet for material when other options are no longer available in a particular area (Weislow, 2015).

Product Collection Considerations

There is no shortage of consumer electronics and electrical equipment available for end-of-use management based on the predictions for used electronics generation presented earlier in this report. Getting these devices into existing management systems to enable value recovery, however, relies on motivating the individual who owns the device to return it in a timely fashion and not store it in a drawer or closet. A small majority of consumers do know where to take electronics to be recycled. According to the "2014 Consumer Electronic Recycling and Reuse Study" conducted by the Consumer Technology Association, 50%-60% of consumers know where and how to recycle their used devices (CTA, 2014). The same survey found that the main reason that consumers did not recycle was lack of perceived convenience of the sites they knew were available. Anecdotal evidence routinely supports the position that if you educate the population and provide a place for equipment to be recycled, they will come, so developing a more robust collection infrastructure would help increase electronics recovery rates.

Further challenging collection schemes is the consumer expectation that all equipment should be recycled free-of-charge. As discussed in the previous section, there are significant costs related to used electronics management, and these costs may not be covered in full by manufacturer obligations in those states where legislation exists. Multiple survey participants highlighted that the funding challenges faced by the state programs are due to manufacturers' not paying fair and reasonable prices for product recycling, which creates a "race to the bottom" for recycling contracts. This can force recyclers to choose between managing material responsibly and staying in business. Also cited was the fact that many state programs do not allow recyclers to charge additional fees for managing returned devices that are not covered by the state programs.

One common answer to the question, "how do you improve recovery rates?" is that collection sites need to be convenient. Unfortunately, convenience is in the mind of the user, and not even experts in the industry can define a convenient program. In 2013, The Sustainability Consortium ran a stakeholder survey using the Delphi panel methodology to develop a definition for an ideal used electronics management program. Multiple attributes relating to the convenience of an ideal program were identified, but when the panel, consisting of 20 stakeholders from the same stakeholder groups convened for this work, was asked to recommend measures of convenience tied to the attributes identified, no two participants provided the same response (Mars, Mangold, & Hutchins, 2014). Additionally, convenience needs to be defined at a local level, since every community approaches recycling differently. Collection schemes that may work under state laws will not necessarily translate to other states, and rural communities have different needs and challenges than urban communities. Developing a methodology to identify factors that create a locally-relevant, convenient management program was also undertaken by The Sustainability Consortium (Nafe & Mars, 2014).

Retailer Programs – Best Buy

As the largest retail collection program in the United States, Best Buy's Electronics and Appliances Recycling program has accepted more than 1 billion pounds of electronics and appliances since its inception in 2009 (Best Buy, n.d). The program accepts most electronic equipment at the customer service desk, and provides recycling kiosks for rechargeable batteries, cables, cords wires, ink and toner cartridges, and gift cards. Currently, small appliances are not accepted as part of the program, and large appliances (including televisions 32" and larger) are only accepted with the delivery of a new product or for an additional handling fee. Devices collected are assessed for reuse and refurbishment potential and are recycled responsibly if not able to be resold.

While retail outlets certainly provide an attractive way to increase collection sites, this does not make the system behind the collection any more efficient. The retailer still needs to cover the cost of managing the devices and manage the liability related to electronics collection and storage. Due to variations in laws and hazardous waste definitions at the local, regional, state, and national level, electronics may be considered hazardous and have to be handled accordingly, creating additional challenges for these types of programs. This may also limit the volumes of products that can be accepted at any given location. There are also limits to how much a retailer can recover due to the willingness of the consumer to work with them. They are still dependent on individuals' bringing equipment to their stores and will never be able to replace collection sites and events run by state and local governments.

Scaling Used Electronics Management Programs

Used electronics and electrical equipment recycling options are already available nationally, and the value chains downstream of collection are already global. The key questions are not ones of scale but ones of efficiency and capacity. How do we get more material of value into the system? How do we better utilize the infrastructure and resources already in place? Increasing collection is certainly a place to start, but the variability in types and quantities of devices returned by consumers requires careful consideration of the business model used by collectors and recyclers, and a robust downstream is necessary to ensure that responsible management of all materials takes place. Just increasing collection without addressing the lack of infrastructure to manage the additional materials collected, though, can make an already stressed system fail, as witnessed with CRTs.

One of the largest barriers to increased capacity suggested by stakeholders was the patchwork of state laws described above. The inability to institute a program at a national level because of discrepancies in the state EPR programs prevents scale. A national system, whether developed by the government, created through an electronics industry-led initiative, or some other approach, would be a great enabler of system scale.

System Solution Opportunities

The system in place today evolved with little coordination or consideration between actors across used device collection and treatment stages, or even between actors in the same stage. Potential interventions to improve the outcomes in the used electronics management systems in the U.S. require a holistic view of the entire product life cycle, and should be product agnostic, where solutions are flexible with respect to products managed or have the planned ability to evolve with changing device form factors.

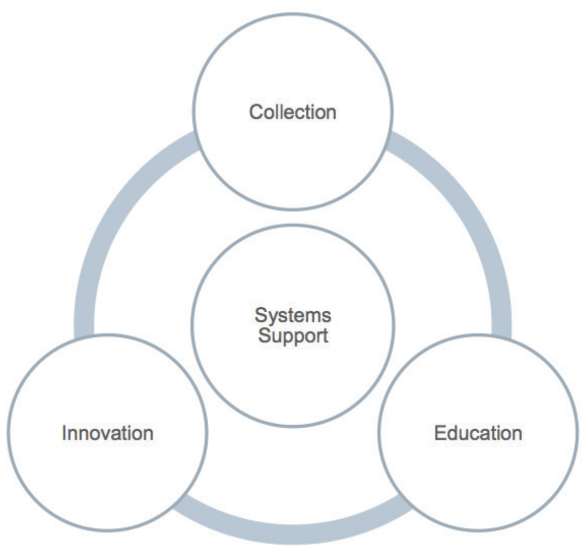


FIGURE 10: Solution set themes

Opportunities to minimize uncertainty and maximize the adaptability of all downstream actors, from refurbishers to smelters, to the rapidly evolving EEE product stream should be prioritized.

From the stakeholder surveys, three major, interrelated interventions were recommended:

Education

Stakeholders highlighted the need to educate all actors involved in managing used electronics. Table 5 summarizes points where education is needed. For consumers, there is a need to learn about the real value, and devaluation over time, of used electronics, and about what equipment to turn in where. For policy makers, education on the challenges and barriers to reuse and repair, the reality of the electronics recycling industry, and the real costs of responsible recycling would help inform future program revision or development. For designers, an understanding of how their design decisions impact device end of life is necessary if design for reuse and recycling is to take root and evolve so that circular economy models can be realized across a broad range of new devices.

A more hands-on need that was identified in one interview is that for better education of collectors on best practices for managing a collection event or collection site. Practices vary widely and are based only on anecdotal collector accounts. Mishandled material that is damaged at the point of collection not only loses value, but possibly exposes workers to hazardous materials, such as mercury from LCD backlight lamps. Proper sorting at the collection site saves time and labor costs as the material proceeds through the system because recyclers no longer have to sort through large, heterogeneous piles of material to figure out what is there and where it should go. One stakeholder also mentioned that manufacturers could do a better job of communicating to consumers about their programs and program successes by committing a greater percentage (>20%) of funds dedicated to used electronics management programs to marketing and communications activities, rather than the <1% currently invested in these activities.

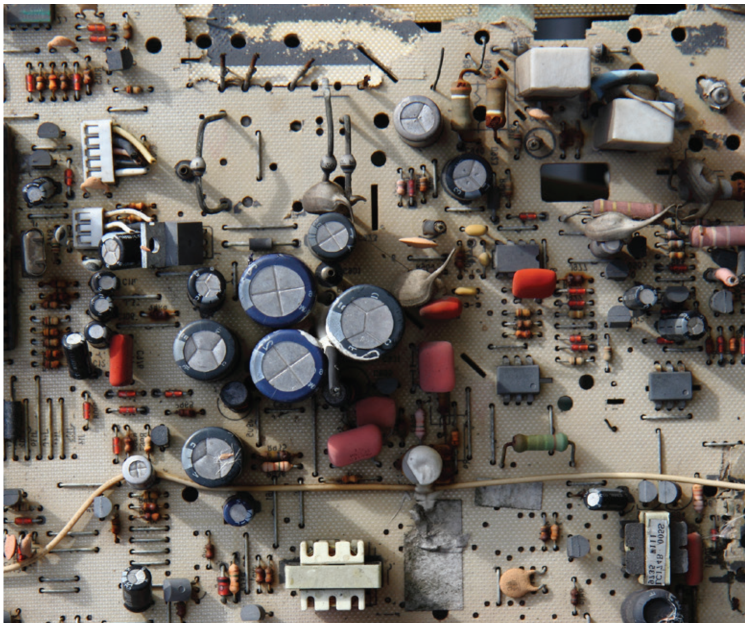
TABLE 5: Summary of Education-Related Opportunities

OUTCOME	BENEFIT	TRADE-OFF/ CHALLENGE	IDEAS
Consumer education - reuse/repair/recycling	Get material back into the system for management	Need convenient locations, places to send individuals	Add information to e-commerce apps for point-of-sale information, reminders to return old equipment
Consumer education - product value	Return products with reuse/ repair value earlier	No objective resale values set; devaluation rate over time not clear	Potential resource: Sage Electronics online pricing guide
Consumer education – EPR program funding	Use portion of funds from OEM-sponsored EPR programs	Regulations already set; would need a way to track spend	Emphasis on marketing and communications
Policy makers – recycling industry reality	Where possible, better align regulations with what recyclers experience	Current OEM obligations are not aligned with real costs of recycling	Align contracts going forward; educate policy makers on the real costs of recycling
Collectors – proper material management	Improve the value of materials collected and reduce worker exposure by proper handling	Individual outreach in regionally appropriate ways is necessary	Leverage best practices collected through states (e.g., AZ) and other organizations already doing this
Collectors – sorting and triage	Further improve the value of material collected by communicating proper sorting and triage methodologies	Individual outreach appropriate to the collector situation needed; supplying materials and collection bins to support proper handling	Leverage best practices and existing literature to develop materials for collectors; work with recyclers to support their collection partners
Designers – implications of design choices	Creation of products better suited to reuse or material recovery; enabling circular economy models.	Reaching designers – product end of life management is usually centralized in compliance, and designers may never be exposed to what happens at this point in a product's life cycle	Enable designers to think about the complete life cycle from the very start (e.g., Dell's "Design for Recycling" program)

Collection

As the first step in the system, the effectiveness of collection impacts material flow and is dependent upon education. A successful consumer education program without convenient collection points may do more to discourage electronics recycling than no education at all. An additional idea is to encourage engagement and collaboration for collection through locally relevant charities or non-profits that can work with recyclers for collection. Research shows consumers are more willing to give used electronics to a non-profit or charity organization that can use devices for societal benefit (Saphores et al., 2009; CTA, 2014). Examples of this type of model are the Dell-Goodwill Reconnect partnership and Blue Star Recyclers, who focus on "recycling electronics and other materials to create local jobs for people with autism and other disabilities" (Dell, 2015; Blue Star, 2014).

More systematic collection (e.g., permanent collection points rather than events) coupled to consumer education should also help reduce the uncertainty of product volumes and product mix, not necessarily by increasing the inherent value of products collected, but by allowing better profiling of collection to inform basic forecasting models. There is currently no standard model available for forecasting or a concerted effort to create one, although successful recyclers already have some forecasting proficiency as part of their business model. In order to support such modeling efforts, better tracking and measurement of products received is necessary as well. One stakeholder also noted that the industry will need to move to counting collections by units rather than weight because the intact device or recovered components will hold the value of the product, and with smaller and lighter products, weight provides less meaningful information.



Bringing in more devices is necessary to justify investments in capital equipment or other process improvements, whether for reuse, repair, or materials recovery. The trade-off is that increasing supplies of materials that already pose treatment challenges, such as CRTs, may make a bad situation worse. Increasing collection of consumer electronics is needed but needs to be done in such a way that does not encourage or initiate irresponsible handling of the equipment. Identifying and engaging responsible partners and a robust downstream treatment process are musts before starting collection. Finally, there is a risk in expanding collection efforts in the hopes of capturing more valuable materials that may otherwise be diverted elsewhere. Some programs established under state laws have witnessed low return rates of more valuable devices, or "cherry-picking", at the collection point. These devices can be diverted to other informal recyclers and markets where a consumer or collector may receive a higher return than through the regulated recycling system. This can undermine the ability of some state programs to continue to fund recycling, as a portion of the value of materials collected is not seen by the program operators.

Innovation

Right now, electronics recycling is primarily driven by the value of the precious metals that can be recovered from printed wiring boards and other metals that can be extracted from the products. Plastics, while plentiful, introduce their own set of challenges, from the sheer variety of plastics used in products to additives like BFRs that decrease the value of the resin, if it can be recycled and used at all.

> *Infrastructure:* The extent of the opportunity in improving the infrastructure related to handling used electronics was not clear, as the participants in the interviews had mixed opinions on whether there was capacity in the U.S. to manage increased non-CRT display consumer EEE. Optimizing the movement of material did surface as an

opportunity, especially with respect to transportation and logistics, which was seen as one of the highest costs in the system. The cost of logistics ties closely to the lack of regional infrastructure, which was identified as an intervention point - capacity may exist to manage equipment and materials, but requires traveling significant distances to reach.

Innovation opportunities: Innovation in the way used devices can be re-purposed, reused, or repaired and related business models is needed to support the reuse market. One example of supporting innovation comes from Sprint. In partnership with Net Impact, Brightstar, and HOBI, Sprint hosts the Smartphone Encore Challenge, a competition for novel business models to repurpose used mobile devices. Even if no longer useful as a consumer mobile phone, the array of sensors and other components that come standard can be redeployed for new uses (Sprint, 2015b).

Technology opportunities: There is a need to develop cost-effective, automated materials handling and treatment systems that can produce purer streams of materials, which can reap higher prices in the commodity markets. Some commercial systems exist today that address plastics-sorting issues and mechanical disassembly, but they are economically beyond the reach of most recyclers and are still in the early stages of development. Technology advances to date tend to be proprietary systems or commercial systems optimized in-house to meet specific material flow needs, but these solutions may not be appropriate for the industry as a whole.

Recovery of REE has captured headlines and has become a focus of recovery research. The Critical Minerals Institute leads this effort in the United States. Recovery of critical elements, such as indium, would also be a good target for technology development. Overcoming some of the technical difficulties in recovering trace materials from a wide range of components may open up these commodity markets to include recycled content.

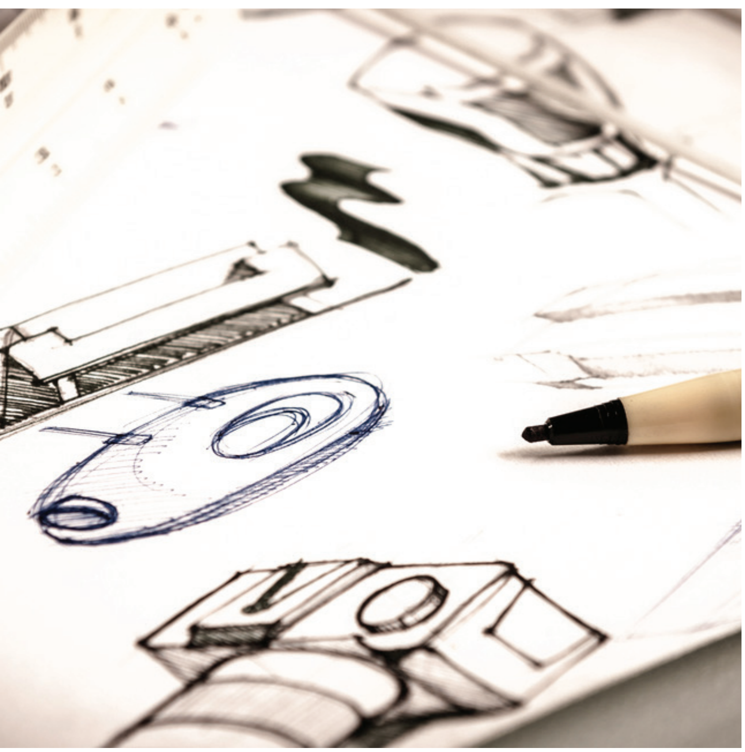
Solution Set Support

Beyond the three themes identified for direct system intervention, two additional themes were brought forward by stakeholders. These two additional themes, design for reuse and support system design, do not directly impact the flow of materials through the used electronics system, but would enable the used devices and recovered components and materials to flow more efficiently to their final disposition point.

Design for Reuse/End-of-Life

While product design activities aren't explicitly part of the used electronics management landscape, they have a significant impact on the options available when devices are at the end of their first useful life. The impact of design on used electronics management will become more noticeable as refurbishers and recyclers look to reuse and repair as an important part of their business model. Design for Reuse (DfR) or Design for End of Life (DfEOL) initiatives have been slow to develop, even though requirements around design can be found in voluntary certifications such as EPEAT and eco-friendly rating systems or labels used by telecommunications companies (AT&T, 2015; EPEAT, 2015; Sprint, 2015c).

Also noted by stakeholders is that designers are a missing voice in the conversation about used electronics management. The design community does not typically participate in discussions about the current issues surrounding used electronics or the future of used electronics management, nor are there widely-available tools that can be used during the design phase to improve outcomes at device end-of-use. Improving awareness among designers may also contribute to better recovery options, as they begin to consider how best to incorporate recycled material into their designs or select recoverable materials. For plastics, in particular, this could be a significant improvement since most emerging technologies rely on plastic materials instead of metals for different aspects of functionality. A strong need for better integration of DfR and DfEOL into the design process was highlighted during interviews.



One effort to support the development of tools that would enable designers to better assess the impact of their decisions on device end-of-life is the Repair and Recycling Metrics Project at iNEMI. The first project phase, completed in July 2015, focused on evaluating existing practices, tools, and specifications for their usefulness in assessing the reusability, remanufacturability, repairability, and true recyclability of electronics and identifying where existing methodologies require further work to support quantification of these design attributes (Dender et al., 2015). The second project phase, currently in development, will build on the results of this work to provide metrics and tools that can be used by designers and other stakeholders to assess product design related to DfR and DfEOL. Further information can be found at the iNEMI website: http://www.inemi.org/repair-recycling.

Support Systems

A final set of ideas emerged during the interview process about activities and initiatives that are necessary to support system improvements, with an emphasis on tools and metrics to empower the industry to improve performance. The challenge to developing a robust tool to forecast what material is going to be available when and in what volumes is accessing the data needed. This is not a simple task considering the data collection infrastructure is not in place, and there is no strong imperative for organizations to add data collection to their processes. One approach has been proposed by the United Nations University in their publication, “E-waste statistics: Guidelines on classification, reporting and indicators” (Balde et al., 2015). While not easily applicable in the United States at this time due to the data gaps, the methodology has been developed for global applications. Consideration of how to make this approach feasible in the United States would be greatly beneficial as e-waste is an international system. A second resource available that allows organizations to understand how different business scenarios can impact their business models has been developed under the Step Initiative. Relevant for organizations looking to enter the collection and pre-treatment space, the Business Plan Calculation Tool for Manual E-waste Dismantling Facilities is available through the Step website (http://www.step-initiative.org/business-plan-calculation-tool-for-manual-e-waste-dismantling-facilities.html). The current model is based on business conditions in Europe, so those using the tool outside the European market may need to adjust some of the data accordingly.

Another perceived hindrance to an effective system is that there is no clear definition of success, and therefore no metrics to assess the system. Developing holistic metrics that assess not only how much a program collects, by both units and weight, but how the program is created and executed would allow for better measures of success and progress among different program approaches. One example of how this may be approached is outlined in the *Definition of an Ideal Used Electronics Management Program*, published by The Sustainability Consortium (Mars et al., 2014). During the development of the definition, stakeholders were asked to provide metrics they considered appropriate and feasible for the program attributes of an ideal program. The identified metrics will be assessed for their usefulness in measuring ideal program attributes in the second stage of this work.

Recommendations

The recommendations presented here are not perfect solutions, but that should not be used as an excuse for inaction. New processes and innovative approaches need to be encouraged and supported; taking even small actions that move toward a more robust and adaptable system will improve the overall effectiveness of used electronics management.

Considering the systems issues that already exist, investments in single point solutions without consideration of implications for the broader system face a higher risk of failure. Rather than providing just a list of actions, solutions are presented below that, if at least planned together, would support each other to improve used electronics management to the benefit of all actors. Figure 11summarizes the recommendations for this report.

FIGURE 11: Recommendation summary

Collection Solutions

The goal of the collection solutions focus area is to enable organizations to collect and handle more equipment effectively and consolidate equipment to minimize logistics costs. Education initiatives focused on improved collection should also be considered. The solutions presented here are considered the most impactful and immediately accessible of collection solutions proposed:

- Develop training materials based on existing work for collection sites. This may not decrease the variability of products turned in, but would help an organization get more recovery value from what it receives.
- Support development of networks of small-to-medium sized collectors that can leverage each other to create steady volumes of used devices and enable them to work directly with recyclers.

System Redesign Concepts: Rather than just expanding a system that already has significant challenges, a couple of stakeholders looked to ways that would disrupt the system and create a more efficient way to manage collection.

The first idea was to leverage delivery systems in place for online retailers by collecting used devices when new products are delivered. This would be similar to some of the mail-back programs already run by manufacturers, but would need to be deployed on a much larger scale. Another approach would leverage emerging service economy and ride-sharing business models for the same type of reverse logistics. One example of the latter approach was run by Uber in Beirut, Lebanon. On Earth Day 2016, users were able to request free pickup of used electronics through the Uber app, which was then taken to a local NGO collection and recycling point (Masi, 2016). Either approach creates a highly individualized type of collection system that looks much more like the door-to-door collection that happens in developing countries, which has been acknowledged as the most efficient collection system model globally.

The second idea is more specific and proposes a system redesign to minimize the movement of equipment destined for materials recovery by moving the pre-treatment steps to the collection sites and putting collectors in direct contact with material recovery facilities. Instead of travelling through multiple stops from collector to material recovery, the collected equipment would go through a triage process at or near (<10 miles) the collection point, where devices destined for reuse or refurbishment would be separated, then hazardous materials would be removed, and plastics, metals, and circuit boards would be sorted and sent directly to the appropriate materials recovery facility. The collector would ideally be a non-profit with strong support from its community, as this is expected to bring in more material. If the non-profit focuses on job creation, this allows them to fund their mission while providing opportunities to the underserved populations they engage. This would disrupt the current system by consolidating the activities that currently take place across multiple points into the collector facility, with the benefit of significantly decreasing the cost of logistics related to materials management.

Innovation Solutions

The goal of these activities would be to produce both new technologies that address current issues related to sorting and disassembly of products and new business models for reuse and refurbishment. Investors can no longer rely on commodity prices to cover the costs of investments; even if the commodity markets recover to ‘normal’ levels, smaller and lighter products will still have less inherent value. Enabling solutions that create reuse and refurbishment may require investment that does not see immediate returns, as multiple models, such as those bulleted below, may need to be tested before breakthrough models are discovered.

- Refurbisher “bounty” on devices designed for reuse or end of life: collaboration among stakeholders (e.g., trade groups, refurbishers, recyclers, retailers, telecomm companies) to offer some award or reward to brand manufacturers creating devices using DfR or DfEOL principles.

- X-prize-style competition or event, modeled on Recycling Innovators Forum (http://www.recyclinginnovators.com/), specifically for new technologies that address deficiencies in current processes (e.g., mechanical separation, optical plastics sort) or issues on the near horizon (e.g., mercury lamp removal, REE recovery, value recovery from small devices).

- Incubators to enable entrepreneurs to experiment with new business models and technologies for reuse, refurbishment, and materials recovery of devices streams or pilot projects for technology currently under development in universities.

System Support Solutions

System support solutions are crucial to developing a robust system that has the information and stakeholder support it needs to be successful. Actions focus on collaborative initiatives aimed at creating better tools and processes across the electronics supply chain:

- Convene the full value chain to facilitate conversations around design and more effective cost-sharing mechanisms and to collaborate on best practices and tool development. This would be especially effective if retailers or other entities with market influence led the effort.

- Support development of holistic metric sets that better assess the effectiveness of management programs in dealing with the smaller and lighter products entering the recycling stream; forecasting tools for the industry to predict material stream composition and timing; or recyclability calculators that account for the economic reality of material recovery and the time and labor required for disassembly.

Conclusions

Used electronics will continue to be a challenge and opportunity for a wide range of players as the electronics industry evolves. Unfortunately, the used electrical and electronic equipment management systems in place today in the United States are widely seen as broken, with few if any opportunities identified by stakeholders to improve the situation.

There is no question that costs are involved in responsible materials management. The current CRT management crisis underscores this cost and identifies the potential for used EEE to harm both human health and the environment. Unfortunately, without leadership or initiative from key parties, the path to a more sustainable solution appears far away from what is possible today. Stakeholders appear to agree on what the issues are, so there is potential for conversation, but no one is willing to take the first step as they do not view the issue as their problem. There are pockets of good ideas and effective processes in place today, but the forum to scale these ideas just does not exist.

The costs of not developing an effective solution stretch well beyond those related to merely sustaining an inefficient status quo. Devices will continue to be replaced at an increasingly rapid rate, and used devices will still be generated. Without an outlet, they will stockpile in residences, where they provide no further value to anyone, or find their way into the waste stream. Equipment will still be collected, with or without state-mandated programs, and disposal will still cost money and resources, whether disposal is by recycling or landfill. In some cases, such as with televisions and larger equipment, taxpayers foot the bill when government agencies have to clean up equipment that has been illegally dumped. Coupled to this loss of material into closets and landfills is the continued toll on the environment, workers, and communities that house used electronics processing facilities. These individuals and their environment, both domestically and internationally, bear the brunt of impacts from illegally or improperly handled equipment as these materials find their way to the lowest-cost methods of disposal. The very technology that has enabled a standard of living beyond that imagined by previous generations will be dumped, legally in landfills or illegally elsewhere, and its legacy will be one of lost opportunity, waste, and environmental degradation.

This vision of waste is avoidable. Today, many organizations are successfully navigating this continually changing space, and many examples of innovative management models exist. This point is also underscored in the current CRT display crisis—with good management practices, this material is being handled responsibly as part of profitable business. This is the story that does not make headlines. Great strides have also been made in the last decade to improve responsible management of used EEE in the United

States. Market acceptance of certifications has led to improved working conditions and greater transparency in downstream material management. New emphasis on data security is enabling new models where used EEE management becomes a service to the consumer, addressing their need for efficient and responsible device and data management, and not just a one-way materials treatment system. With some innovation, creativity, and a continued drive to handle used EEE the right way, not just the cheapest way, the industry will be able to meet the challenges facing it and continue to thrive.

Moving forward, EEE will continue to become smaller and lighter as technology evolves, and the system that manages them at the end of their first useful lives will also need to evolve to make the most of the opportunities presented by these devices. Getting the right tools, metrics, and processes to those who are committed to responsible materials management will ensure there is resiliency in the system for the next wave of devices that will arrive on loading docks. Engaging designers together with individuals responsible for product end-of-life management will help create devices that can be kept in use longer and enable efficient material recovery at the end of the device's useful life. Support is also needed for innovative, cost-effective technologies to improve material recovery processes. Working together, across organizations and industries, we can provide our best technology another legacy—one that continues to improve the standard of living of consumers, workers, and the environment long after reaching the end of its first useful life.

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Survey Participants

An important part of accurately representing the used electronics management and electronics recycling landscape is to accurately represent the range of opinions and perspectives that intersect and interact on that landscape. The stakeholder interviews took the shape of one-hour interviews over the phone or in person. The questions focused on:

1. significant trends in the electronics and electronics recycling industries over the next five years;
2. how well the current used electronics management systems in the United States are incentivized, and how this could be improved; and
3. disruptive developments (positive or negative) that might impact the used electronics management system over the next five years.

The full set of questions is provided in Annex B.

Stakeholders were drawn from the following groups: (Figure A-1)

Original Equipment Manufacturers (OEMs): Organizations that manufacture electronics and electrical equipment.

Recyclers: Organizations that are primarily concerned with the disassembly and material recovery or the treatment of electronic equipment or materials derived from recycled equipment. These organizations may also collect and refurbish equipment, but their primary business model is material recovery.

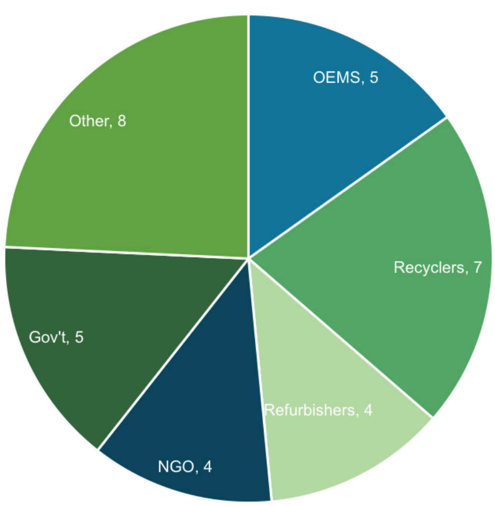

FIGURE A-1: Participants by stakeholder group

Refurbishers: Organizations that take in and refurbish used equipment for resale. These organizations may be for-profit or non-profit and act as collectors of equipment. Organizations that specialize in IT Asset Disposal (ITAD) are included in this designation.

NGOs: Non-governmental organizations concerned with and active in electronics recycling and/or used electronics programs.

Government: Federal, state, and local government agencies that work with electronics recycling and/or used electronics management programs.

Other Interested Parties: Organizations with a stake in this life cycle phase that do not clearly fit into one of the other four categories. If fewer than three organizations of a class participated in the work, that class was not identified separately.

Participating Organizations

Arizona Department of Environmental Quality (AzDEQ)
Basel Action Network (BAN)
BestBuy
Broadway Metals
Cisco
Consumer Electronics Association (CEA)
Dell
Dynamic Recycling
eGreenIT
EPRA
ER2
Electronics Recyclers International (ERI)
eStewards
Electronics Takeback Coalition
Green Electronics Council
iFixit
Independent
iNEMI
Lenovo
Minnesota Pollution Control Agency
MRM
Panasonic
PCRR
Product Stewardship Institute
Resource Recycling
Samsung
Sustainable Electronics Recycling International
SIMS
Sprint
State of Maine
Total Reclaim
Umicore
URT
US EPA /ENERGY STAR
US EPA Office of Resource Conservation and Recovery
Vintage Tech
Westech

Stakeholder Interview Questions

1. Do you understand your rights as a participant in this study, and do you consent to continuing the interview?
2. How do you see the electronics industry evolving in the next 5-10 years, and how is this expected to change the current e-waste landscape?
3. In your opinion, what are the current challenges facing the electronics recycling industry?
    a. What materials in particular are difficult to work with and why?
    b. Where do you see new challenges emerging, and how do you expect them to be met?

Considering the used electronics management system in place in the United States today:

4. Please describe your idea of a "working" (if not ideal) electronics management system.
    a. How does this compare/contrast with what you see in the marketplace today?
    b. Where do you see barriers in the system, and how would you prioritize them?
    c. What do you see as emerging or new business models that have the potential to change how current management programs work?
5. Beyond funding your specific organization, where do you see potential points where some type of incentive could be applied to improve the overall functioning of the system?
    a. What do you constitute as effective incentives?
    b. Do you feel the market today is incentivized correctly? Why or why not?
6. What do you feel are key changes needed to support the system and what are the current barriers to these changes?
7. Closing Remarks:
    a. Can you recommend additional resources that would be beneficial to this work?
    b. Can you recommend other individuals or organizations to interview?
    c. Would you like to receive a copy of the final report for this research effort?
    d. Do you have any further questions for me before we conclude?

Fate of Used Electronics

The routes that used electronics take through the current management system is illustrated in Figure 1 at the beginning of this report. This Annex covers the processes and basic economics of electronics recycling in the United States. The flow and outcomes from each step along the journey of different devices from final use to final disposal are described first. Then, the refurbished, resold, and recycled material values for a selection of representative devices are presented, as well as how the prices of these devices varies with age, which underscores the importance of timely device return. Finally, a note on labor costs is included.

Small appliances are excluded from the economic analysis portions, as there is little data on the value of recycling, and the range of possible products within this category make determining a meaningful average secondary market value difficult. Transport and logistics costs have also been excluded due to the high dependency on route and business model and contracts for any given organization. These costs are also very difficult to allocate on a per-device basis.

Device Flow

To provide more detail about what each step of the process entails, and how that varies with product type, Table C-1 has been assembled from information collected during the stakeholder interviews. This table summarizes the steps needed to move a used device through the system to materials recovery. Different types of products have different routes through the system, depending on the nature of the secondary market for whole devices or components. The high level descriptions have been generalized to give an idea of the steps, but the actual actions corresponding to each step have not been included. These actions would be optimized by each collector, refurbisher, or recycler based on their individual business model.

TABLE C-1: Summary of device flow through the used EEE system

PRODUCT	COLLECTION	REUSE/RESALE	PARTS REUSE/ RECOVERY	TREATMENT	RECOVERY VALUE
Mobile Phones/ Tablets	High number of routes and trade in programs available; leasing programs with telecoms and active resale market; not part of state EPR programs	6-12 months from release; ~90% should be in secondary market	Model-dependent; popular lines will have parts value	Hand disassemble (e.g., battery removal); shred	Market value for common and precious metals (PWBs);
Computers	High number of routes and trade-in programs available; active resale market; laptops included in all state EPR programs, desktop included in most.	Strong markets, especially used devices from business	Strong market for components	Hand disassemble (e.g., battery, Hg lamps); degree of disassembly will vary with organization;	Market value for PWBs; value of material increases with level of hand disassembly;small amount of metal; little to no value for mixed plastics
Monitors **CRT** **Flat Panel**	Accepted where electronics recycled; covered under most EPR programs; CRTs share issues with TVs	Limited; some overseas markets can convert and use as TV with board added.	Undamaged LC displays	Hand disassemble (e.g., lamps, CRT funnel tubes and metal components); shred	Market value for common and precious metals (PWBs) – medium to low grade boards; little to no value otherwise (mixed plastics, glass)
Televisions **CRT Flat Panel**	Accepted where electronics recycled; covered under most EPR programs; CRTs problematic – negative value, uncertain and limited market for leaded glass	Very limited	Very limited	Hand disassemble (e.g., mercury lamps, CRT funnel tubes and metal components); shred	Market value for common and precious metals (PWBs) – medium to low grade boards; little to no value otherwise (mixed plastics, glass)
Printers	Accepted where electronics recycled; covered under some state EPR programs	Used models widely available; market for high-end units	None (toners/ ink cartridge maybe)	Hand disassemble (e.g., Hg lamps); shred	Little to no value – metal very small portion of product and large number of low-end mixed plastics
Video Game Systems	High number of routes and other programs to collect; not covered under state EPR programs	Very strong secondary markets for functioning units; rarely seen in recycling streams unless broken beyond repair	Value for parts due to popularity of models regardless of age	Hand disassemble (e.g., battery removal); shred	Market value for PWBs; value of material increases with level of hand disassembly; small amount of metal; little to no value for mixed plastics
Accessories/ Peripherals (Keyboards, Mice, Etc.)	Accepted where electronics are recycled; covered under only a few state EPR programs	Used models available; high end keyboards and mice, especially with gaming features, have value on secondary market	None	Hand disassemble hazardous materials (e.g., batteries); shred	Little to no value – metal very small portion of product and large number of low-end mixed plastics similar to printers
Misc Consumer Electronics (Set-top Boxes, Audio Equipment, Etc.)	Accepted where electronics are recycled; covered under only a few state EPR programs	Used models available; unclear market value	Minimal except for cases of high-value products	Hand-disassemble for hazardous material; shred	Market value for PWBs; value of material increases with level of hand disassembly; small amount of metal; little to no value for mixed plastics
Small Appliances	No formal collection; many recyclers will accept as part of events or other municipal collection routes	High secondary market through both direct reuse and refurbishment through warranty programs	None	Hand-disassemble for hazardous material; shred	Market value for PWBs; value of material increases with level of hand disassembly; small amount of metal; little to no value for mixed plastics
Wearables	Unknown	TBD	TBD	TBD	Little to no value for mixed plastics

Product Value

TABLE C-2: Average reuse and recycling prices for selected product categories

	FORMAT	REFURBISHED[1]	USED[2]	RECYCLED (PER UNIT)[3]
Mobile Devices[4] 2011	Android	$145	$122	<$2
	iOS	$180	$203	$1
				($3.30/lb scrap)
Tablets[5] (2013)	Android	$286	$225	$5
	iOS	$335	$315	$4
Laptops (2010)[6]				
PC	15”	$450	$359	$17
Apple	15”	$700	$600	$18
				($2-3/unit for non-functioning units)
Televisions[7] (2015)	1080p			
LED	32”	$260	$214	$5
	55”	$650	$600	<$10
CRT		N/A	$5	(scrap LC display = $3)
				-$15 or higher, depending on size and weight of display
Printers[8]	Laser and inkjet	None listed	$60	<$1
				($0.04/lb scrap)

1 Refurbished = professionally restored to working order to meet manufacturer specifications
2 Used = fully functional products that may show signs of previous use. “Very Good” and “Good” conditions from Amazon.com used to calculate used prices.
3 Recycled = raw material value only. Excludes labor and transportation costs.
4 For mobile phones, Android operating systems are represented by Samsung Galaxy SII and iOS by Apple iPhone 4s, unlocked.
5 For tablets, Samsung Galaxy Tab S and Apple iPad Air were used as proxies for their respective operating systems.
6 Laptops explicitly exclude gaming systems, netbooks, Chromebooks, and 2-in-1 systems. Models released in 2010 were used to determine list price, refurbished and used values. Three PC manufacturers and Apple MacBook were considered.
7 LED Televisions analyzed were 32” and 55” display models with LED backlighting for LCD displays. Models released in 2015 were used to determine list price, refurbished, and used values as older models are no longer easily available. Five manufacturers considered.
8 Printers analyzed explicitly excludes compact mobile printers, printers designed for commercial offices, and those models marketed as “photo printers”. All-in-one personal printers were considered, including monotone laser models and standard color inkjet models. Five manufacturers considered, and model year was not tracked explicitly as new models are not regularly released.

Determining fair market value for used devices is extremely challenging and requires understanding of a wide range of products, product configurations, and material values. Table C-2 shows average values for a selection of refurbished, used, and recycled devices. The values listed were retrieved from Amazon.com between March 7 and 10, 2016. The same model-year products were used to determine average values within a category, but different models years were used between categories to ensure products had a representative number of values to average (two or more listings with used and refurbished values). The value of materials recovered during recycling will vary with the size of the device – larger devices have more materials and larger circuit boards, so have more value. In some categories, additional bulk-scrap values are listed for products. While these values are representative of where the market is today, most organizations who are moving scrap material optimize their returns through contracts and other negotiation routes, and the return on used equipment can be better than the numbers cited here. The values cited in Table C-2 are for the unit or material contained within, and do not account for labor or transportation costs related to collection, testing, repair, disassembly, or materials disposal.

The numbers listed below represent averages for the products. The refurbished and used numbers do not take into account product configuration beyond high-level hardware configurations as listed in Table C-2. Configuration details such as processors, graphics coprocessors, operating system, screen resolution, software and app compatibility, and memory size can significantly influence the desirability and, therefore, the resale price of a given device. For recycled materials, the amount per device was taken from Sage BlueBook values as available for a given type of product. This value is calculated based on the weights of raw materials included in a product and does not include the labor cost to disassemble a product or transportation costs. Further information on labor costs can be found below.

Values for mobile devices are for representative products running the listed operating system. The models investigated were unlocked by the manufacturers. In this way, variations in models and prices among telecom companies was not factored into the numbers. Apple products running the iOS system tend to be worth more on the secondary market than most Android phones. The representative Samsung Android phone used in this analysis tends to have higher resale values than other Android models due to quality and name recognition.

The model refresh frequency executed by mobile phone manufacturers increases the complexity of pricing devices. When a new device model is release, there is a decrease in the value of the older model numbers. This is particularly noticeable with iPhones. For example, the market value of an iPhone 5c dropped 40% when the iPhone 6 as launched (Berezny, 2014). On older devices, operating systems may not be able to run, or the system version already on the device may not be compatible with new apps and other support software. If no upgrade is available, then the usefulness of the device is limited. These factors are drivers for why mobile devices, in particular, should be collected as early as possible and not stored by consumers.

Mobile device and tablet material prices also show the pressures that arise with smaller and lighter devices. To get one ton of mobile phones, a recycler would need to collect approximately 6,200 devices, compared to approximately 20 29” CRT televisions necessary to reach the same weight. The sheer volume required for profitable recycling as devices get smaller and lighter becomes a serious issue. This emphasizes the conclusions that more effective collection is absolutely necessary and that focus should be placed on reuse and refurbishment and, therefore, product design and information accessibility, to maximize the economic value and keep the materials in the products in the market for as long as possible.

Laptop computers are an interesting counterpoint to their smaller mobile counterparts. Consumers tend to hold onto their computers longer than their mobile phones since models do not change as dramatically year-to-year, and the older equipment is able to run newer software for a longer time. One interesting note is that, in terms of reuse, Apple products keep their value longer than PCs, but, when recycled for materials, the values are the same. Recycled value is equivalent because the bulk of material value in laptops is found in the precious metals found on the motherboard. The computer boards used in laptops are the highest grade of boards that are used in electronics and drive the value of products.

Desktop computers follow similar trend as laptops. There is a very active secondary market for quality systems, especially in the non-profit sector. Desktops can easily be refurbished and updated for new software so that they are more than adequate for schools or other household uses. Refurbished, they are also much more affordable for those who cannot afford the latest and greatest in technology, so they help bridge the digital divide within both developed and developing countries.

Televisions lose their value quite quickly after their release. They tend to not even be available on the secondary market within two to three years of model release. This is not a function of the televisions not working – most models have an expected lifespan of at least five years and usually closer to 10 years for established technology. CRT displays were expected to last 30+ years. With changes in software and the advent of new services integrated into televisions, older models age out of the usability window faster, so they go into materials recycling rather than onto the secondary market. Note that the cost of materials recycling for CRTs is negative. This means that recyclers experience a cost to manage the materials, the leaded glass in particular, which is not recovered in the value of other materials, such as copper, that can be recovered from the displays.

Monitors are not treated separately here as they follow the same trends as televisions. The difference is that monitors can be found in the secondary market for as long as the displays are still sharp, since they tend not to come with the range of compatibility options common to televisions and are also frequently purchased as part of business computing systems. Because they are office equipment, monitors are bought and replaced on a similar schedule to desktop and laptop computers, and there are a greater number of relatively new models available in good condition to support an active secondary market. The fate of all-in-one systems, where the computer is integrated directly into the monitor, is still to be determined.

Printers are included as an example product category for products that have little value in the secondary market or the materials recovery market. Printers are predominantly PC-ABS and mixed with other plastics and metals in such a way that they cannot be separated into individual streams. This greatly degrades the value of the recovered materials in the commodities markets. There is not a particularly robust parts market, as it is rarely worth the time to repair these devices. The caveats here are for high-end models designed for businesses or with advanced graphics capabilities, where the new price is prohibitive and a gently used model works just as well. This holds true for most electronics peripherals and accessories, which also quickly find their way to the shredder where they are sold as bulk, mixed plastics.

Product Depreciation

To maximize the reuse of a device and the price for which it can be sold, it should enter the secondary market as close to the release date as possible, not be stored in a drawer or closet until some later time. This is particularly true for products that have an active secondary market. Figures C-1 and C-2 chart the resale values as of March 13, 2016, for laptops and mobile phone models of different. Prices were taken from Amazon.com, and averaged over the devices available for sale. The year is the model-release year for the product model cited. Table C-4 and C-5 in the Reference Data section present the models used for this analysis for laptops and mobile phones. Dell Latitude and Apple MacBook Pro are shown for laptops. Laptops are 15” models with the processor held constant, where applicable. When multiple models of a given product line were released in a given year, the devices chosen for inclusion were the ones with sequential serial numbers.

Apple iPhones and Samsung Galaxy S series models are shown for mobile phones. When multiple models were released in a given calendar year, models with sequential model numbers were selected. For the Galaxy series, this means base models of the S series (S, S2, S3, etc.). For iPhones, this follows the primary iPhone line and excludes product variations, such as those marked with the designator c (i.e. iPhone 5c). All models were unlocked or international-release models to remove the variations in price between telecom carrier contracts. Prices are averaged across the 16GB and 32GB memory sizes. The Samsung Galaxy S7 was released in March 2016 (Dolcourt, 2016). The factory-unlocked version of the Galaxy S7 retails for $670. Table C-3 shows the impact of the S7 on the retail prices of the S6. The change in price drops the retained value of an S6 from 85% to 80%. The iPhone 7 is rumored to be scheduled for release in September 2016, with no estimate on price given (Jaffe, 2016).

TABLE C-3: Impact of Galaxy S7 release on Galaxy S6 value

	NEW MSRP
Pre-S7 release	$600
Post-S7 release	$480

Model Samsung Galaxy S6 SM-G920F unlocked
Pre-S7 release values from Amazon.com, March 7-10, 2016
Post-S7 release values from Amazon.com. May 22, 2016

Figure 8 in this report shows the retained value of the four products described above, calculated from the data presented in Tables C-4 and C-5. The older the product, the less value it has on the current market. For both products, a majority of value is lost over the first two to three years. Prices for laptops fall off more gradually than for mobile phones. For the Dell Latitude laptop, there are plateaus in the price change that represent years where the models did not change significantly enough to generate either a new model number or separate listings for used devices. Price decreases are more pronounced for mobile phones, due in large part to the yearly release of a newer model. As noted earlier, this phenomenon has been well documented for the iPhone (Berenzy, 2014).

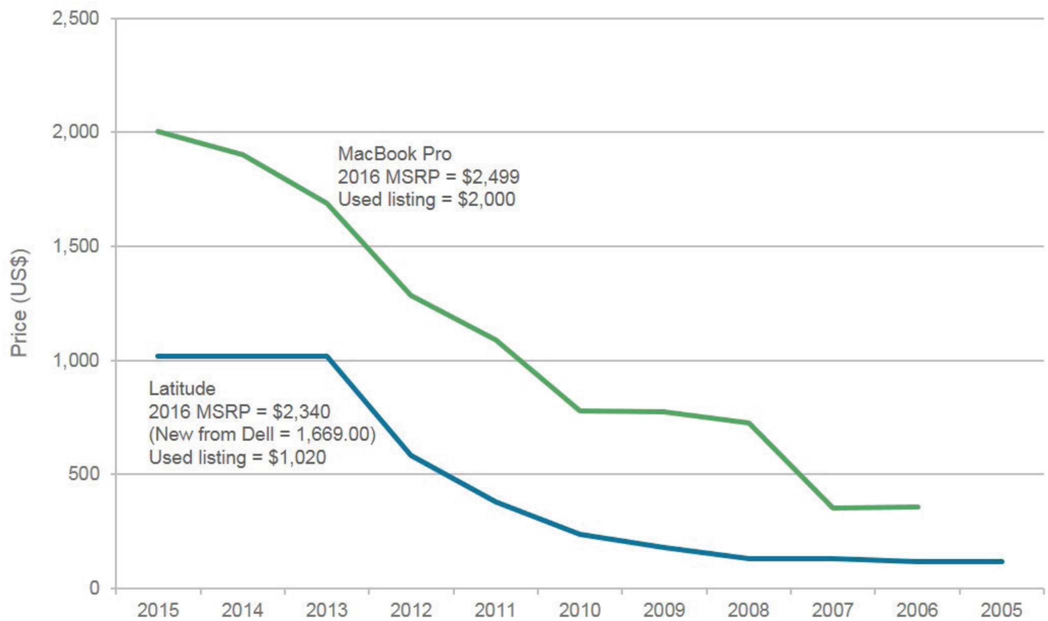

FIGURE C-1: March 2016 pricing for used laptops

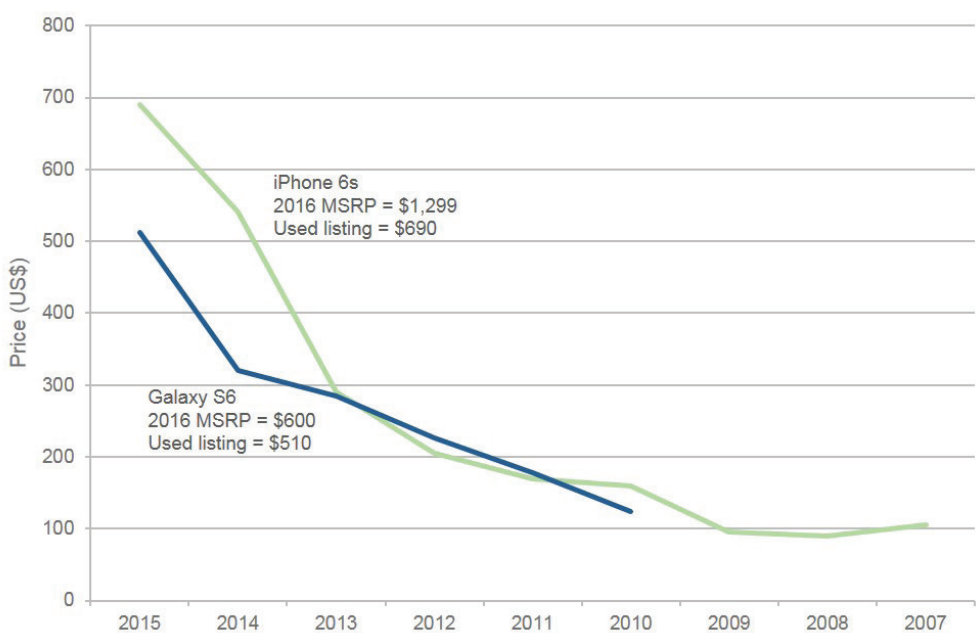

FIGURE C-2: March 2016 prices for mobile phones

Labor Costs

With the current emphasis on repair and refurbishment and the desire to gain the maximum price for recycled materials, consideration of the costs of labor is necessary. For repair and refurbishment, skilled labor is needed to be able to assess, diagnose, and repair devices. Materials recovery also involves manual labor – hazardous materials such as batteries and lamps must be removed before a device can be shredded to avoid contamination of all material and the equipment itself. Batteries are at risk of exploding in the shredder, and the lamps in flat panel displays on laptops, televisions, and monitors contain mercury, which, once released, can become airborne and pose a hazard to workers. CRT displays present for workers problems too. In addition to handling devices that can be 50 pounds or more, workers must cut from the glass tube metal pieces, such as copper wires, and the electron gun inside the display for recycling. Then, the panel glass (where the picture was viewed) needs to be separated from the funnel glass (the rest of the tube), and the two pieces must be sent to separate treatment facilities due to the dramatically different lead levels in them. There are a greater number of recycling options for the panel glass than the funnel glass, as the former has much less lead content (Shaw, 2013).

Figure C-3 shows the relative costs to disassemble various devices under three treatment scenarios. Tables C-6 and C-7 in the Reference Data section provide detail on the calculation of these numbers. The values are listed per device and represents the cost to the recycler for the manual work necessary to safely and responsibly prepare devices for mechanical treatment. The three scenarios presented correlate to three different levels of disassembly:

Scenario A: Bare minimum effort – only hazardous materials and high-value components (e.g., printed circuit boards) are removed prior to mechanical separation.

Scenario B: Medium level labor – in addition to A, components of some value are removed and remaining material dismantled to easily accessible pure materials and recyclable fractions.

Scenario C: In-depth disassembly – devices are disassembled to a point where no further separation into pure material fractions is possible without mechanical shredding.

A full description of the scenarios and how dismantling times were determined can be found on the *Business Plan Calculation Tool for Manual E-waste Dismantling Facilities webpage from Step* (http://www.step-initiative.org/business-plan-calculation-tool-for-manual-e-waste-dismantling-facilities.html).

The labor cost for Scenario C for CRT displays includes the effort necessary to separate panel glass from funnel glass. The labor costs related to flat panel displays (FPD) is primarily related to the removal of mercury lamps from some liquid crystal display models. Beyond removing the display itself from the housing, there is very little additional value in disassembling FPDs further, so Scenarios B and C are the same. The dramatic increase in the cost of disassembling a laptop in Scenario C is due to the additional value that can be gained from components that can be scavenged for parts and the general feasibility of disassembly into single-material fractions.

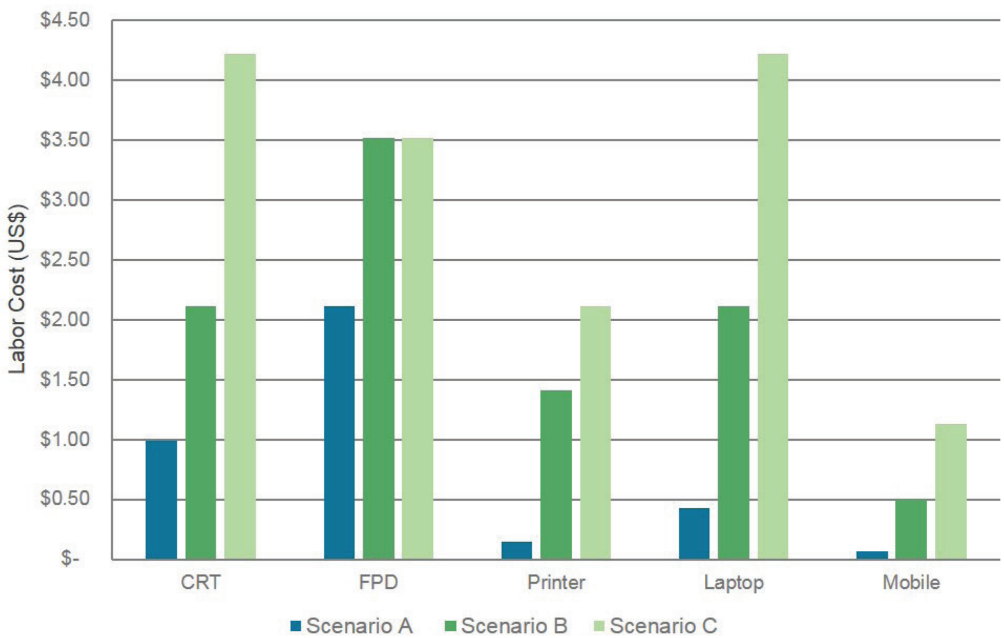

FIGURE C-3: Relative costs of labor for three scenarios of device dismantling (US$/device)
FPD =-Flat Panel Display
A, B, and C refer to Scenarios A, B and C described in the text.
Scenario C for CRTs includes the time and labor necessary for CRT glass separation.

Reference Data

Data Sources - Table C-2

Accessed March 7-10, 2016:

Amazon –refurbished, used.
Sage BlueBook – used for product recycled materials value (bluebook.sagese.com)
Walmart.com – list price, refurbished and used
Best Buy – list price, refurbished and used
Scrap Monster.com – bulk material value (www.scrapmonster.com)
CashforComputerScrap.com – bulk material value (www.cashforcomputerscrap.com)

Laptop Models

Model reference data:

Latitude: https://engineering.purdue.edu/ECN/Support/KB/Docs/DellModelYears

MacBook Pro: http://www.everymac.com/systems/apple/macbook_pro/index-macbookpro.html

TABLE C-4: Laptop models, March 2016

MODEL YEAR	DELL LATITUDE			APPLE MACBOOK PRO[1]		
	Model	Original MSRP	Current Market Value	Model	Original MSRP	Current Market Value
2005	D810	$2,519	$118	*		
2006				A1211	$2,499	$356
2007	D830[2]	$2,117	$133	A1226	$2,499	$725
2008				A1286/ MC026[5]		
2009	E6500	$2,117	$180	A1286/ MC118	$2,299	$775
2010	E65103	$1,854	$240	A1286/ MC371[3]	$2,199	$780
2011	E65204	$1,804	$380	A1286/ MC322[4]	$2,199	$1,090
2012	E6530	$1,746	$585	A1286/ MC831[6]	$2,199	$1,285
2013	E6540	$1,699	$1,020	A1398/ ME874	$2,799	$1,690
2014				A1398/ MGXC2	$2,599	$1,900
2015				A1398/MJLT2	$2,599	$2,000

*MacBook Pro was initially released in 2006.

1 Order numbers are provided for MacBooks referenced where the model number did not change year-over-year. All orders end in 'LL/A' when referenced online.

2 Models use Intel Core 2 Duo processors

3 Introduction of Intel i5 processor models

4 Introduction of Intel i7 processor models

5 Introduction of unibody configuration for MacBooks

6 Introduction of Retina displays for MacBooks

Mobile Phone Models

Model reference data:

Galaxy: https://en.wikipedia.org/wiki/Samsung_Galaxy

iPhone: https://www.theiphonewiki.com/wiki/Models

TABLE C-5: Mobile phone models, March 2016

MODEL YEAR	SAMSUN GALAXY			APPLE iPHONE		
	Model	Original MSRP	Current Market Value	Model	Original MSRP	Current Market Value
2007				iPhone A1203	$499	$105
2008				3S A1241	$199	$90
2009	*			3GS A1303	$199	$95
2010	S GT-I9000	$599	$124	4 A1332	$749	$160
2011	SII GT-I9100	$799	$178	4s A1387	$749	$170
2012	S3 GT-I9300	$699	$226	5 A1428	$749	$205
2013	S4 GT-I9505	$699	$285	5s A1533	$749	$290
2014	S5 SM-G900F	$650	$320	6 A1549	$749	$540
2015	S6 SM-G920F	$599	$512	6s A1688	$749	$690
2016	S7 SM G930F	$670	$670	7s	TBD (release 9/2016)	

*Samsung Galaxy S series first released in 2010, so no data are available for comparison 2007-2009

Device Dismantling Times

Data from Business Plan Calculation Tool, Step Initiative (Step, 2016)

TABLE C-6: Dismantling times for three scenarios

	Scenario A	Scenario B	Scenario C
CRT TVs	7	15	30
FPD TVs[1]	15	25	25
Printer	1	10	15
Laptop	3	15	30
Mobile Phone	0.5	3.5	8

Scenario A: Removal of hazardous materials and high value components before mechanical shredding. This scenario corresponds to the material value reported in Table C-2.

Scenario B: In addition to A, removal of components with reuse market value and pure materials that can be removed with reasonable effort.

Scenario C: In addition to B, disassembly of a device into pure materials as possible prior to mechanical shredding.

[1] FPD = Flat Panel Displays

Device Dismantling Times

TABLE C-7: Labor costs per device for disassembly under three scenarios in US$/device

	Scenario A		Scenario B		Scenario C	
Minimum Wage Level	Low[1]	High[2]	Low[1]	High[2]	Low[1]	High[2]
CRT TVs	$0.85	$1.12	$1.81	$2.40	$3.63	$4.80
FPD TVs[3]	$1.81	$2.40	$3.02	$4.00	$3.02	$4.00
Printer	$0.12	$0.16	$1.21	$1.60	$1.81	$2.40
Laptop	$0.36	$0.48	$1.81	$2.40	$3.63	$4.80
Mobile Phone	$0.06	$0.08	$0.42	$0.56	$0.97	$1.28

[1] Low minimum wage corresponds to $7.25/hr, standard in OK, NM, NC, ND, OH, OK, PA, TX, UT, VA, WI, Puerto Rico, and the US Virgin Islands. The lowest labor rate in states with mandates is $5.15/hr in WY and GA.

[2] High minimum wage corresponds to $9.60/hr, found in CT, RI, and VT. The highest labor rates in the US can be found in CA ($10.00/hr) and Washington, D.C. ($10.50/hr). Both low and high wage rates were taken from The State Minimum Wages Table at the National Conference of State Legislatures (http://www.ncsl.org/research/labor-and-employment/state-minimum-wage-chart.aspx#1).

[3] FPD = Flat Panel Display

Market Statistics

To understand the order of magnitude of the challenge faced by used electrical and electronic equipment (EEE) management systems, an estimate of how many devices have been sold and how many are ready for end-of-life treatment is useful. Ideally, forecasted volumes of used EEE generated in a given time frame would be extrapolated from actual collection numbers of different types of devices over time. The data set that would be necessary for this calculation, especially at a national level in the United States, does not exist at this time. There is no national data collection effort in the United States to capture volumes of EEE recycled, state regulations do not capture comparable data on device recycling rates, and the myriad routes devices may travel into the recycling stream do not allow for a straightforward determination of how many devices are recovered and recycled in the United States in a given year. The US EPA does publish estimates of products that are landfilled or recycled as part of their annual municipal solid waste studies, but only a select set of consumer electronics plus small appliances are considered under the "Durable Goods" category (US EPA, 2015). Reused and refurbished products are not part of this data set either. The US EPA has recently launched a research effort to address this data gap, but so far has not published results (E. Resek, personal communication, Sept 30, 2015). This lack of information is one of the greatest challenges for long-term planning for recyclers and other related organizations, since judging what types of materials in what volumes will be available in the future is necessary for new technology and process development and capital equipment investments.

This Annex presents the methodology used to estimate the units and weight of end-of-life products generated in the United States in the target years of 2015 and 2020. This method uses sales data for the various product categories coupled with the estimated lifespan for the products to determine when a product would theoretically be available for end-of-life treatment. Equipment that has been sold but has not reached its average life span is assumed to either be in use or in storage by the consumer and is represented by the "in-home storage" values presented below.

Products Ready for End-of-Life Treatment

Figure D-1 provides an overview of retail volumes and trends from the previous 15 years for consumer electronics in the United States (Euromonitor, 2015a). The charts also include the retail volume forecast by Euromonitor from 2015 to 2018.

The product categories listed in Figure D-1 are aggregated at the product category level or higher, and illustrate macroscale trends in the electronics market. An example of how newer technology replaces older technology is seen in the increase of mobile devices sold and a corresponding decrease in imaging equipment (including cameras and camcorders) and portable media players (including e-readers, MP3 units, other portable media devices). Many technologies such as cameras or desktop computers are not expected to trend to zero sales, as has happened with the obsoleted cathode ray tube (CRT) display technology, for example, because niche needs will persist for these products.

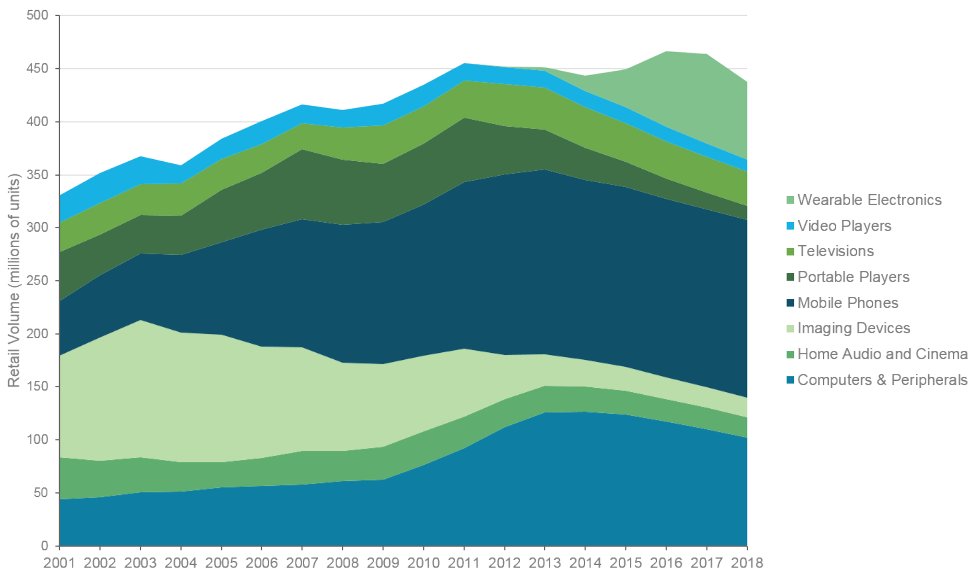

FIGURE D-1: Consumer electronics retail volumes, 2001-2014
Forecast Retail Volumes 2015-2018 (Euromonitor, 2015)

In Figure D-1, the Computer & Peripherals category encompasses laptop and desktop computers, tablets, printers, and monitors. This rather large grouping of products represents a significant portion of the current used electronics space, so Figure D-2 provides a more detailed look at the products in this category. IDC sales data provided to the National Center for Electronics Recycling (NCER) covers the years 2005-2013 for the listed product categories (NCER, 2015). Mobile phone sales dominate other product categories, as was seen in the category-level data in Figure D-1, but here, the impact over time of technology changes, such as the increase in laptop sales and decrease in desktop sales, is clear. Tablets, relative newcomers to this space, show a strong increase in sales over this time period. The volumes of tablets sold are expected to decrease due to consumers' either moving back to a more powerful laptop format or migrating to a large-format phone, or phablet, for their mobile device. Phablets can perform all the functions of a tablet as well cellular communications (CTA, 2015). The impact of increased market penetration by wearable devices on the overall market shares of existing products is somewhat unknown, since these are not currently stand-alone devices but require another device to store and display data collected.

The evolving software platforms for content delivery are changing consumer behavior by enabling every device with a display to stream programming. This trend is making a traditional television set less of a necessity that it has been in the past and more of a luxury for those who can afford the space (Williams, 2014). This has already impacted television sales over the last two to three years, shrinking nearly 10% in 2013 alone (Mearian, 2014). This trend is expected to continue with sales remaining flat or decreasing, as is seen in the forecasts to 2018 in Figure D-1.

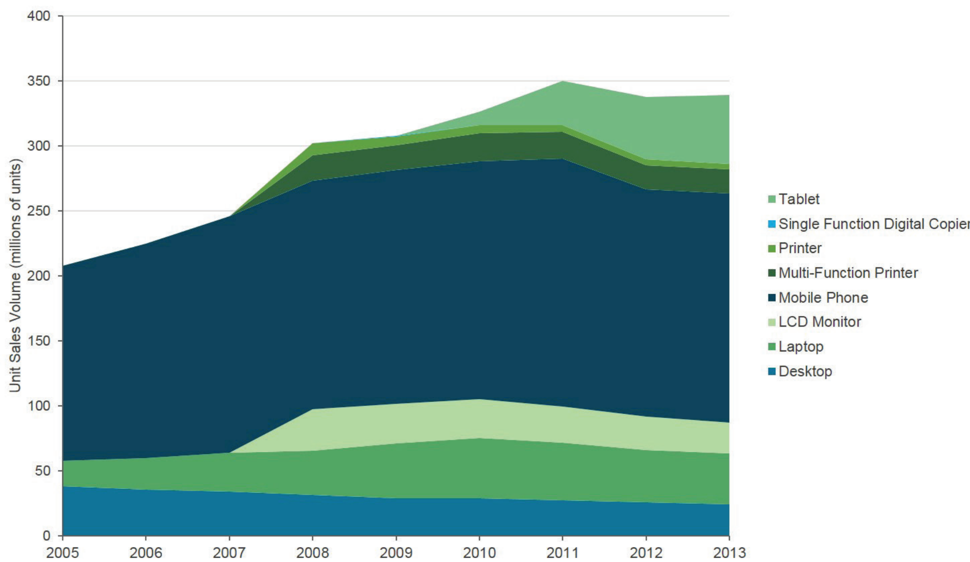

FIGURE D-2: Unit sales for a selected set of consumer electronics, 2005-2013 (NCER, 2015)

Figure D-3 provides retail volume data for consumer appliance categories. Steady growth is anticipated in the personal care and small cooking appliances categories, with sales for product categories such as vacuum cleaners and irons holding steady over the forecast time range. The data, however, do not provide a view on the emerging category of smart appliances. These devices have the function of traditional appliances, such as a coffee maker, but with added electronics that allow them to be connected to household networks as part of the emerging Internet of Things. Currently, small electrical equipment tend not to have the toxicity issues or material value in recycling that electronic products do, so they have largely been excluded from consideration as part of the used electronics and e-waste conversation in the United States, outside of a limited reuse market tied to the resale of refurbished warranty returns. The addition of electronics to these products to enable connectivity means that they will have material profiles similar to consumer electronics and should be handled in a similar fashion. In the European Union, these products are already managed this way, as the Waste Electronic and Electrical Equipment (WEEE) Directive includes the majority products powered by electricity (WEEE, 2012).

Forecasting WEEE Generation

Multiple approaches to calculating the volume of EEE that would be ready for end-of-life handling have emerged due to the desire to understand what amount of material may be available for treatment at any given time (Lam et al., 2013; Ryen et al., 2015). All approaches require estimates of product sales over the time frame of interest and the expected lifespan of a given type of product. In a study conducted by Duan, Reed, Gregory, Kirchain, and Linnell (2013) for the Solving the E-waste Problem (Step) initiative, both a generation model that estimates when products sold in a given year would be available for end-of-life management and a stock model that estimates the number of products still in use or stored in households were used to analyze the EEE market in the US (Duan, Reed, Gregory, Kirchain, & Linnell, 2013).

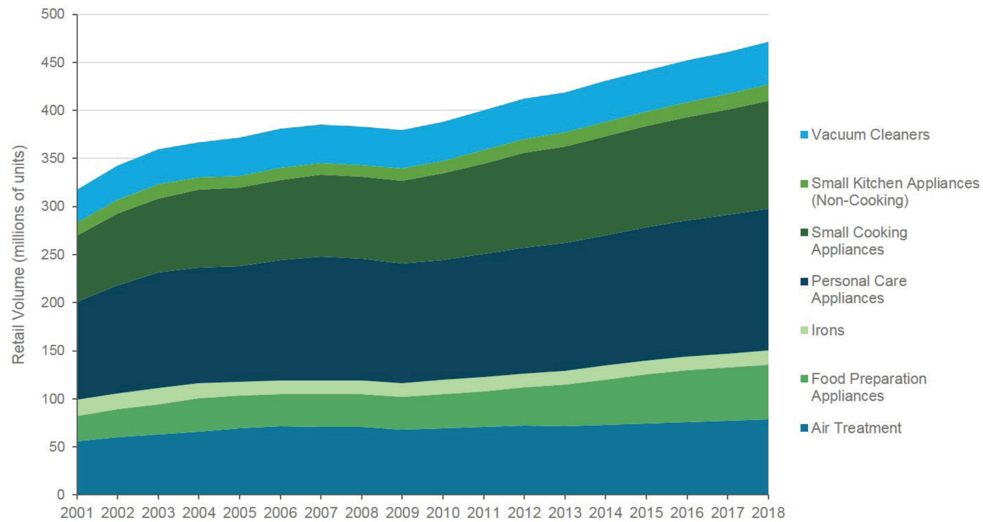

FIGURE D-3: Consumer appliance retail volume data 2001-2014
Forecast Retail Volumes 2015-2018 (Euromonitor, 2015)

Product lifespan was estimated through a review of recent literature with an emphasis on nationally representative surveys and empirical studies, as well as the distribution of products ready for management over time modeled using the Weibull distribution. In some cases, such as small appliances or keyboards and mice, reliable life span data is not available, so an estimated minimum and maximum lifespan is used instead. Figure D-4 shows lifespan distribution estimates for smart devices and accessories, TVs, and small appliances (Duan et al., 2013; Miller, 2015). Each bar represents the first, second and third quartile of data, with the line representing the median lifespan of a given product type. The range represents the 95th confidence interval for the data set.

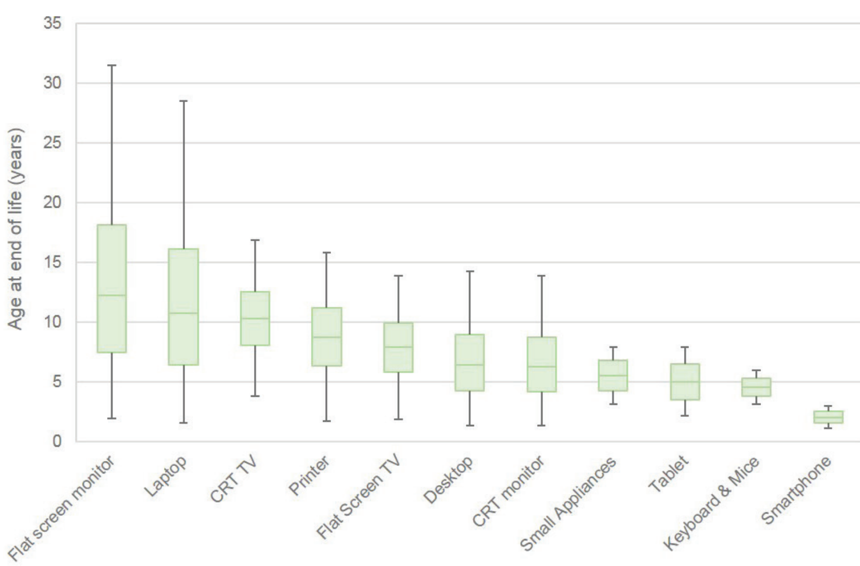

TABLE D-4: Lifespan estimates

Based on comments left on blogs and other forums where consumers compare lifespans of their products, personal care appliances, such as hair dryers and curling irons, are perceived as having short lifespans (two to three years) due to heavy, daily usage, whereas products used less frequently, such as vacuum cleaners, have longer lifespans (up to 10 years). The two-to-eight year range used in this study matches the consumer experience. In all categories, commenters noted that the life of a product can be extended with simple maintenance and repairs, such as keeping vents clean and changing belts regularly, which adds an additional uncertainty to this calculation.

Using forecasted sales, actual sales data or backcasted yearly sales data for the time span 1980-2020 alongside the lifespans shown above, two calculations were made, based on the method published by Duan et al. and from the data sources listed in Tables D-5 and D-6. First, the number of units that would be generated for end-of-life management were estimated. This value represents, for a given year, the number of products that reached their average life span from the original date of sale, and are assumed to be ready for end of life management. Second, in-home stocks can be estimated, which represent the number of products in use or stored in a household that have not yet reached their average expected lifespan.

Data for the product categories under consideration are shown in Figure D-5 (Miller, 2015). Figure D-5A and B present the number of devices that would be available for end-of-life treatment in 2015 and 2020 based on cumulative sales data starting in 1980. Similarly, Figure D-5C and D present the number of devices that are assumed to be either in use or stored in the average household for the same years. This number represents the total cumulative sales to the year in question (2015 or 2020), minus the number of devices that have been generated for end-of-life treatment. Tables D-1 and D-2 also present this information.

The difference in the absolute values of products generated and products in home in a given year reflects the fact that generation numbers are for the cited year (2015 or 2020), while the in-home volume is cumulative over time up to the cited year. A used product is generated only in one year, but is assumed to be in the home and counted in each year between the date of purchase and the date of generation.

This analysis shows that the greatest number of devices ready for treatment are in the tablet and mobile device category, which reflects not only the large number of products sold, but the comparatively short lifespan of these products. The high numbers of smartphones and tablets in-home implies a high potential for reuse and refurbishment if products enter the used electronics management stream while there is still market demand for them. Otherwise, these products would move directly to materials recovery, the challenges of which are covered in previous sections.

When considering the weight of devices, televisions dominate. In 2015, the weight of CRT

[1] Survey of blog sites conducted through Google search using the question, “How long should my [appliance] last?” Small appliances searched included hair dryers, toasters, coffee makers, curling irons, clothes irons, and vacuum cleaners.

televisions anticipated to be ready for end-of-life management is almost double the weight of all other devices combined, excluding small appliances. The number of used CRT televisions, both generated and present in-home, is expected to decrease dramatically by 2020. Note, however, the volumes of CRT televisions do not disappear entirely -- these devices are expected to play a significant role in the used electronics stream for at least another five years. Flat panel televisions are second in total weight, and show an increase in the number of units ready for end-of-life treatment in 2020. This jibes well with the fact that flat panel displays are relatively new in the market, so they have not yet served out their first useful life cycle. There is little change seen between the number of flat panel displays in-home in 2015 and 2020, which is consistent with the projections that new television demand will remain the same or contract slightly over the next five years. In categories where product sales are already in decline, such as desktop computers and accessories, the amounts of these products generated are estimated to be less in 2020 than in 2015.

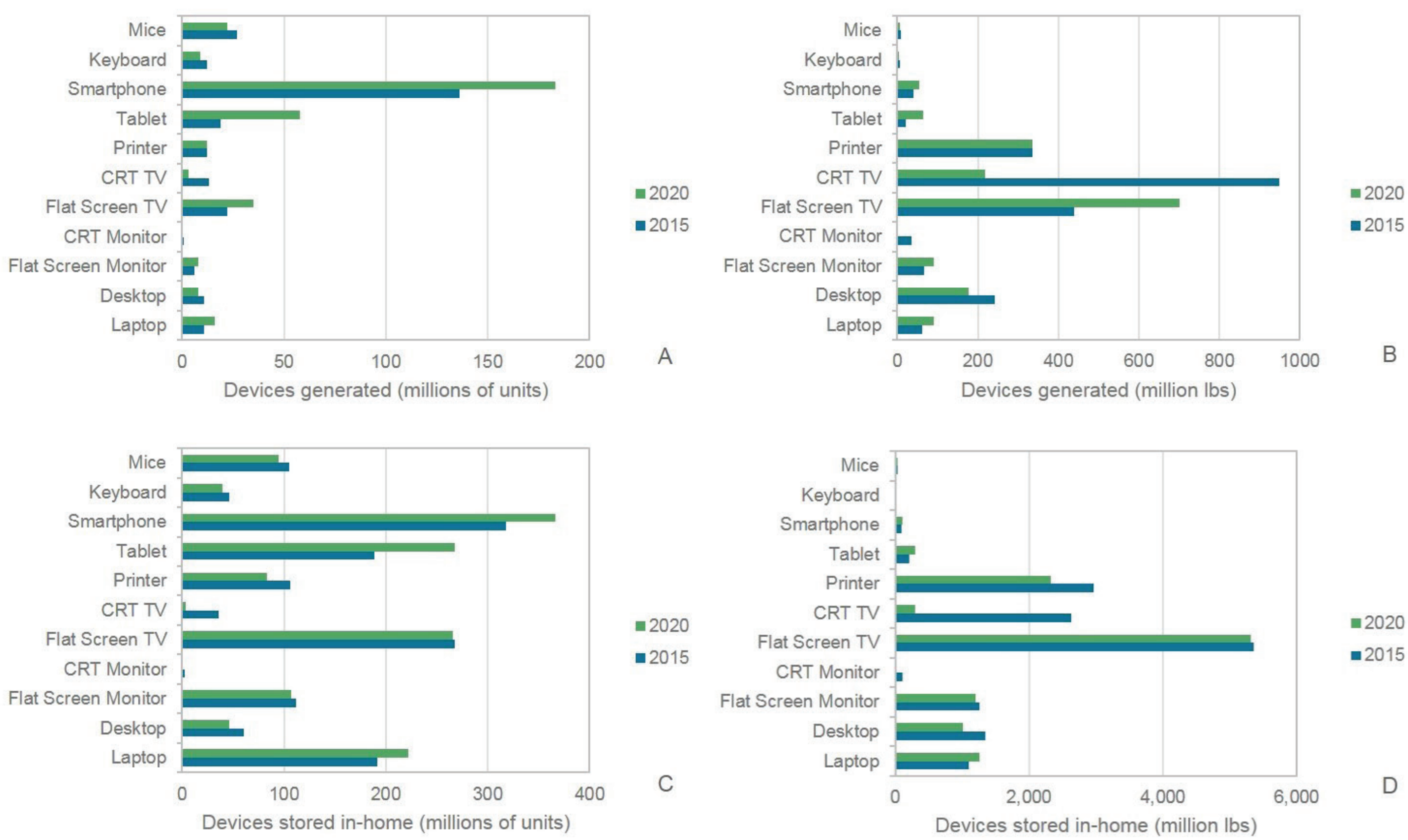

FIGURE D-5: Estimated volumes and weights of devices generated and stored in-home in 2015 and 2020
A: Number of Devices Generated; B: Weight of devices generated; C: Number of devices in- home; D: Weight of devices in-home

The estimations of generation and in-home numbers of small appliances in 2015 and 2020 are presented in Figure D-6 and are also notable. While it's not surprising that there would be a greater number of these products in use or stored, since many have longer lifespans than other categories of consumer electronics, the fact that so many products are stored may imply that people don't know what to do with them when they are no longer useful. A second implication is that there is a high potential for a great number of small appliances to move from use or storage into the used electronics management system. This is problematic because the current system is not equipped to handle these types of products efficiently, which may lead to a great loss of resources and potential environmental and community impacts when less-than-ideal treatment methods are used.

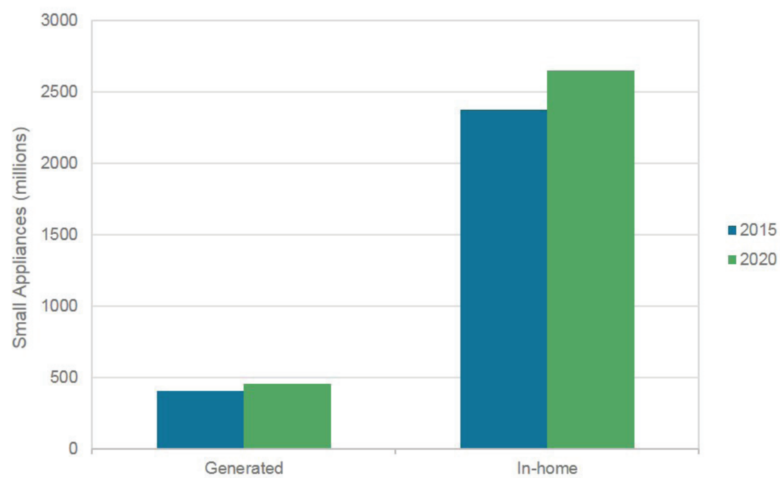

FIGURE D-6: Small appliances generated and stored in-home in 2015 and 2020

The one caveat to this discussion is that these numbers do not provide information on the actual fate of products. The estimated generation number assumes that devices that reach their calculated lifespan are removed from the home at that point. It does not account for devices remaining in a household after reaching their assumed lifespan, nor does it provide insight on where devices go next. As mentioned at the start of this Annex, reuse and recycling rates for the product categories under consideration are not available for the US market. At the end of this section, Tables D-3 and D-4 present recycling rates calculated by two different methodologies. The recycling rates from 2009come from a US EPA report that used a methodology developed in-house to determine the reported end-of-life electronics generation and recycling rates (US EPA, 2011). A second set of recycling rate estimates was presented by Duan et al. in their paper, which bases calculations on consumer behavior survey data and state program recycling rates where this information is available (Duan et al., 2010). This value has been updated for 2015 based on the latest recycling rates returned by state programs (Miller, 2015). In this second approach, collection rate is the fraction of the used electronics that are collected for processing out of those going toward collection or landfill. It is applied to the quantity generated that same year to estimate the collected quantity.

The recycling rates per category vary quite a bit between the two methods. US EPA Office of Resource Conservation and Recovery used data available from states with used electronics recycling programs to estimate the share of residential generated electronics that are collected for processing versus disposal (US EPA, 2011). Low collection rates (one pound collected per capita) were assumed for states without programs, and does not account for other collection routes such as voluntary takeback programs or municipal collections. To further refine the data set, a survey of recyclers conducted for this report suggested that two-thirds of collected electronics originated from commercial sources. In states like California, where the state program includes commercial collection, the residential figures were adjusted from total collection volumes based on this two-thirds figure. An overall generated electronics recycling rate of 27% (by weight) is projected for 2010; the projected generated computer recycling rate is 40%.

The second approach bases collection estimates on the results of surveys of consumer behavior with respect to used electronics management and disposal. For the results presented in Tables D-3 and D-4, several surveys of representative groups of US residential computer owners which took place from 2005 to 2014 were used to estimate national collection rates (Consumer Reports, 2006; CTA, 2012; Williams, Kahhat, & Mattick, 2009). Survey data pertaining only to collection and landfill are used, even though some studies included broader considerations such as reuse. The survey estimates were compiled and analyzed, and the presented forecasted rates in the future are based on the trends resulting from the analysis (Duan et al., 2010; Miller, 2015). The sources for data sets used by these two approaches underpins the differences between these two sets of results, and underscores the challenges of accurate accounting of used electronics flows in the US and reliable used electronics volume forecasting for electronics refurbishers and recyclers.

Figure D-7 shows the average collection volumes, based on the average recycling rate from these two methods, and the ranges of the numbers of units generated for select categories. Not all categories have two different recycling rates, because not all categories of equipment are collected by the states or were included on the consumer surveys used by the study to estimate its numbers. In these categories, only the collection volume derived from US EPA recycling rates are presented. Keyboards and mice are excluded from the figure due to the very low recycling rates (<10%) in comparison to the other categories. CRT monitors are included to show the change over time related to technology that has become obsolete in the marketplace. The reuse and resale of devices, however, and products that are moved to a closet or a drawer rather than recycled are not explicitly accounted for in either method. This is in part due to the underlying data, where there are currently no reliable sales data to underpin generation and in-home use and storage numbers, in addition to the lack of reuse or refurbishment rates.

Product Storage

Storage of devices after the end of their first useful life, whether this is due to the device being replaced by the original owner or the device ceasing to work, complicates the ability

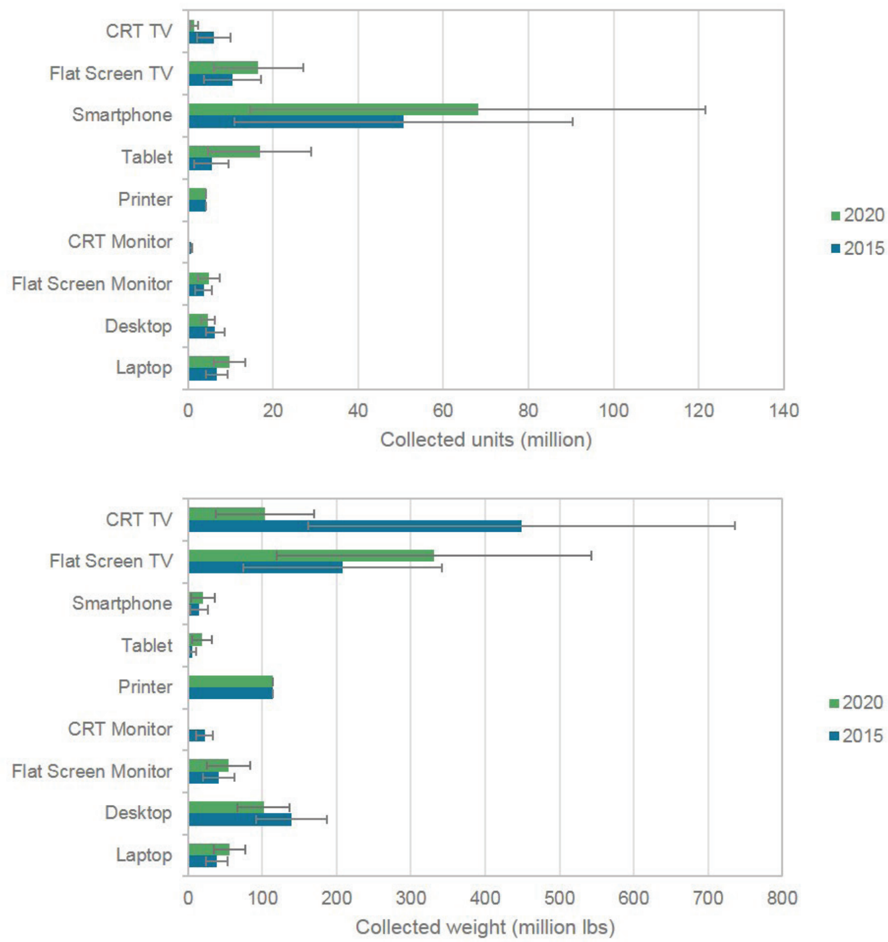

FIGURE D-7: Estimated collection rates for select categories

of industries involved in used electronics management to forecast when material will be available and at what rate it will be available because there is no data set that captures how much potential material is stored in the average household.

Consumers have been surveyed directly how many electronic devices they have in storage. The results of the study, "How much e-waste is there in US basements and attics? Results from a national survey," by Saphores and co-authors indicate that there is a large quantity of still-functional used electronics and e-waste ready for recycling or end-of-life processing stored in homes in the United States (Saphores, Nixon, Ogunseitan, & Shapiro, 2009). The average number of functional electronic devices stored by consumers increased from 10 to 25 items between 1990 and 2007 per the Consumer Technology Association (Saphores et al., 2009). Paired with that increase in electronic devices purchased and used in consumers' homes there has been an increase in the number of both functional and non-functional devices in a given household. Saphores's nationwide survey yielded the results that each US household has an average of four small e-waste items (≤4.5 kg) and 2.4 large e-waste items (>4.5 kg) in storage. Extrapolated over the total number of households in the United States, these estimates represent at least 470 million small and 277 million large e-waste items in storage totaling 747 million items weighing over 1.36 million metric tons (Saphores et al., 2009; Ogunseitan, Schoenung, Saphores, & Shapiro, 2009; US Census Bureau, 2015). The authors indicate that these estimates, completed six years ago, were low because they utilized a narrow definition of e-waste on their surveys that did not include large appliances such as refrigerators, washing machines, and dryers, and because it was time-consuming for their respondents to precisely and accurately inventory stored electronic devices (Saphores et al., 2009).

Other estimates based on alternative calculations do not provide further clarity. Consumer electronic storage estimates have varied tremendously over time depending on the source estimating the number of devices being stored. Kang and Schoenung cite the fact that, per the EPA, more than 70% of retired consumer electronics devices are kept in storage, typically for as many as three to five years (Kang & Schoenung, 2005). Specifically looking at televisions, Linton and Yeomans estimated that between 25% and 35% of televisions are disposed of in the year that they fail, and the rest are disposed of within the following 10 years (Linton & Yeomans, 2003). Greenpeace refers to the flows of used electronics and e-waste that is not collected for reuse and recycling as “hidden flows” (Greenpeace, 2008). They cite several different percentages of used electronics ready for processing by product type, and indicate that between 10-20% of televisions, computers, mobile phones, and peripherals are separated for further processing and recovery, while the remaining 80-90% are “incinerated, sent to landfill, put into ‘storage or reuse’, or exported” (Greenpeace, 2008). The same report indicated that 45% of e-waste hidden flow in the United States is put into storage or reused as of 2005 (Greenpeace, 2008).

The reasons why consumers store devices can vary as much as the predictions. Survey studies indicate that consumers store products as backups to newer devices, because they feel the devices are still functional and, therefore, not to be disposed of, and because they are uniformed about disposal options (Saphores et al., 2009). A second opinion is that consumers think that stored consumer electronic devices have some value that they don’t wish to surrender (Kang & Schoenung, 2005). Unfortunately, the residual value of outdated electronic devices plummets as the recovery value of parts and device resale value drop rapidly with device age.

The conclusion to be drawn from the wide-ranging information available is that the aggregate amount of used electronics and e-waste being stored residentially is greater than most of the estimates and past projections. The result of device storage could be increased flows that stress local recycling infrastructures, currently unequipped to process older or low value materials, and a system unable to absorb increased e-waste recycling flows due to inaccurately low estimates on what facilities are needed (and their capabilities).

TABLE D-1: Estimated product volumes by units (millions of units)
Miller, 2015

	LIFESPAN	WEIGHT	SOLD		GENERATED		STOCKPILED	
	years	pounds	2015	2020	2015	2020	2015	2020
LAPTOP	11.8	5.7	20	20	11	16	192	222
DESKTOP	6.7	22	6	6	11	8	61	46
FLAT SCREEN MONITOR	13.3	11.2	8	6	6	8	112	107
CRT MONITOR	6.6	36	0	0	1	0	3	0
KEYBOARD	4.5	0.5	9	9	12	9	46	40
MOUSE	4.5	0.3	21	21	27	22	105	95
PRINTER	8.7	28	9	7	12	12	106	83
TABLET	5.0	1.1	49	58	19	49	189	268
SMARTPHONE	2.0	0.3	171	183	136	183	318	366
FLAT SCREEN TV	7.9	20	35	28	22	35	268	266
CRT TV	10.3	73	0	0	13	3	36	4
SMALL APPLIANCES	5.5	6.5	459	505	409	453	2,378	2,651
WEARABLES	1.5	0.2	24	42	6	39	28	62
			811	884	685	846	3,842	4,210

TABLE D-2: Estimated product volumes, by weight (million pounds)
Miller, 2015

	LIFESPAN	WEIGHT	SOLD		GENERATED		STOCKPILED	
	years	pounds	2015	2020	2015	2020	2015	2020
LAPTOP	11.8	7	115	112	63	91	1,094	1,265
DESKTOP	6.7	22	140	130	242	176	1,342	1,012
FLAT SCREEN MONITOR	13.3	11.2	84	66	67	90	1,254	1,198
CRT MONITOR	6.6	36	0	0	36	0	108	0
KEYBOARD	4.5	0.5	5	4	6	5	23	20
MOUSE	4.5	0.3	6	6	8	7	32	29
PRINTER	8.7	28	245	189	336	336	2,968	2,324
TABLET	5.0	1.1	54	64	21	64	208	295
SMARTPHONE	1.5	.3	15	17	41	55	95	110
FLAT SCREEN TV	8	20	760	566	440	700	5,360	5,320
CRT TV	10	73	0	0	949	219	2,628	292
SMALL APPLIANCES	5	3, 10	3,055	3,283	2,659	2,945	15,457	17,232
WEARABLES	1.5	.2	7.2	14.5	1	8	6	12
			4,487	4,461	4,868	4,694	30,576	29,108

TABLE D-3: Recycling rates and collection volumes by units (millions)

			US EPA (2011)[2]			Miller (2015)[3]		
	GENERATED[1]		RECYCLE RATES	COLLECTION ESTIMATES		RECYCLE RATES	COLLECTION ESTIMATES	
	2015	2020	2009	2015	2020	2015	2015	2020
LAPTOP	11	16	38	4	6	84	9	13
DESKTOP	11	8	38	4	3	77	9	6
FLAT SCREEN MONITOR	6	8	29	2	2	94	6	8
CRT MONITOR	1	0	29	0	0	94	1	0
PRINTER	12	12	34	4	4	34	4	4
TABLET	19	49	8	1	4	50	10	29
SMARTPHONE	136	183	8	11	15	66	90	122
FLAT SCREEN TV	22	35	17	4	6	78	17	27
CRT TV	13	3	17	2	0	78	10	2
KEYBOARD	12	9	8	1	1	8	1	1
MOUSE	27	22	8	2	2	8	2	2
SMALL APPLIANCES	409	453	No data	No data		No data	No data	
WEARABLES	No data currently available for wearable devices							

1 Miller, 2015
2 US EPA, 2011
3 Miller, 2015; methodology Duan et al., 2010

TABLE D-4: Recycling rates and collection volumes by weight (million pounds)

			US EPA (2011)[2]			Miller (2015)[3]		
	GENERATED[1]		RECYCLE RATES	COLLECTION ESTIMATES		RECYCLE RATES	COLLECTION ESTIMATES	
	2015	2020	2009	2015	2020	2015	2015	2020
LAPTOP	61	90	38	23	34	84	23	34
DESKTOP	242	173	38	92	66	77	145	105
FLAT SCREEN MONITOR	72	88	29	21	25	94	56	75
CRT MONITOR	49	4	29	14	1	94	31	0
PRINTER	342	324	34	116	110	34	116	110
TABLET	21	64	8	36	403	50	10	32
SMARTPHONE	41	55	8	11	12	66	27	37
FLAT SCREEN TV	440	700	17	75	119	78	341	543
CRT TV	949	219	17	161	37	78	736	170
MICE	27	22	8	2	2	8	2	2
KEYBOARDS	12	9	8	1	1	8	1	1
SMALL APPLIANCES	2,659	2,945	No data	No data		No data	No data	
WEARABLES	No data currently available for wearable devices							

1 Miller, 2015
2 US EPA, 2011
3 Miller, 2015; methodology Duan et al., 2010

Table D-5 lists the data sources that were referenced to determine the volume of sales for each product category for the set of the years 1980-2015. The referenced time series sales data were used to estimate the generation and in-home storage quantities. Table D-6 provides the reference for each source.

Note that consumer sales data were needed for this analysis. In the case of computer peripherals, if the sales data were not disaggregated by sector, the percentage of consumer computer sales out of all computer sales in a given year was multiplied by total sales of the peripheral product to estimate the consumer peripheral sales. For the specific case of keyboards and mice, sources that provided the ratio of keyboard and mice sales to computer sales were used in combination with computer sales data to estimate volumes of keyboards and mice sold, which could then be used to estimate generation and in-home storage quantities. This was not an issue for non-computer related products.

TABLE D-5: Consumer product sales data sources by product type

PRODUCT	SOURCE AND APPLICABLE YEARS
LAPTOP	IDC 1992+
DESKTOP	US EPA 1980-1992, IDC 1993+
FLAT SCREEN MONITOR	US EPA 1980-2005, IDC 2006+
CRT MONITOR	US EPA 1980-2010
KEYBOARD	Trade Data 1996-2010, Logitech and IDC Survey 1980-1995 and 2011-2015. Percentages of device ownership inferred from these two datasets were combined with PC sales data to arrive at device sales.
MICE	Logitech and IDC Survey 1980+. Percentages of device ownership inferred from these two datasets were combined with PC sales data to arrive at device sales.
PRINTER	Snapshots 1997-2002, Estimated 2003-2007, IDC 2008+
TABLET	IDC 2009+
SMARTPHONE	Comscore 2003-2006, BMI 2007-2010, IDC 2011+
FLAT SCREEN TV	US EPA 1980-1999, CEA 2000-2010, NPD and IHS 2011+
CRT TV	US EPA 1980-1999, CEA 2000+
SMALL APPLIANCE	Backcast 1980-2000, Euromonitor 2000+
WEARABLES	Euromonitor 1999-2013, IDC 2014+

TABLE D-6: References for consumer product sales data sources

SOURCE	REFERENCE
US EPA	United States Environmental Protection Agency. (US EPA, 2011). Electronics Waste Management in the United States through 2009. US Environmental Protection Agency, Office of Resource Conservation and Recovery, EPA 530-R-11-002. Retrieved from http://www.epa.gov/waste/conserve/materials/ecycling/docs/fullbaselinereport2011.pdf.
IDC	IDC Trackers. http://www.idc.com/tracker/showtrackerhome.jsp Various press releases with forecasts about market changes were also incorporated.
Logitech	Labrousse, Junien. "The Fuel of Growth". Logitech Investor Day New York. November 1, 2007.
IDC Survey	Gaw, Jonathan. "IDC's 2015 Consumer Devices Survey, Part 1: US PC-Related Results." (Percentages of device ownership inferred from this survey were combined with PC sales data to arrive at device sales).
Trade Data	USA Trade Online. https://usatrade.census.gov/ (HS Code 8471602000 Keyboard Units).
BMI	BMI research. "United States: Consumer Electronics: Domestic smartphone sales, '000."
Comscore	Comscore. "Mobile Future in Focus 2013". February 2013.
CEA	CEA. 2010. "12th Annual household CE ownership and market potential." CEA Market Research Report. Consumer Electronics Association.
NPD	NPD Tracking Services. https://www.npd.com/wps/portal/npd/us/solutions/tracking-services/
IHS	IHS. 2012. "US Flat-Panel TV Shipments Projected to Fall for First Time Ever This Year" https://technology.ihs.com/389507/us-flat-panel-tv-shipments-projected-to-fall-for-first-time-ever-this-year and Mearian, L. 2014. "US TV sales shrink nearly 10%". Computerworld. http://www.computerworld.com/article/2487530/personal-technology/u-s--tv-sales-shrink-nearly-10-.html
Snapshots	Snapshots International. "US COMPUTER PRINTER REPORT 2002."
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