Life Extension of Electronic Products: A Case Study of Smartphones

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ABSTRACT Smartphones account for a large and growing portion of global electronic waste, and the life extension of electronic systems—particularly by refurbishment—is a viable solution for reducing this waste stream. In some secondary markets, sales of refurbished smartphones have begun to outpace sales of new smartphones. However, there are concerns over the resulting reliability and, in some cases, the safety of such products. This paper explores the environmental, reliability, and safety impact of extending the life of electronic systems, with a focus on smartphones. We find that smartphones undergo varying levels of refurbishment that consumers are often not aware of, the environmental advantages of refurbished devices are often outweighed by the disadvantages, and that refurbished electronics will never be as reliable as new products. It is thus necessary to create standards for smartphone refurbishment and to capture and analyze lifetime environmental and usage data to enable the assessment and prediction of the reliability of refurbished devices and their components.

INDEX TERMS Refurbishment, smartphone, reliability, degradation, electronics-waste, e-waste, like-new.

I. INTRODUCTION

The circular economy concept, as explored by Kirchherr et al. [1], covers the reduction, reuse, recycling, and recovery of materials framework of a circular process of production and consumption. In the reuse stage of a circular economy, reverse supply chain logistics must be considered when returning products for reuse processes. Reverse logistics for the reuse stage are described by Zarbakhshnia et al. as “the scheduling and planning for the backward flow of products, to be more specific second-hand goods, from customers and consumers to suppliers and manufacturers for the purpose of several activities such as repairing, remanufacturing, recycling, disposal and so on” [2].

The inherent value of a product is realized in the materials and components that comprise the product. Smartphones use materials such as gold and rare earth elements, that require environmentally damaging mining and refining processes to obtain. For example, to mine an ounce of gold, 30 tons of waste are produced, including mercury, cyanide, lead, and arsenic [3]. Mining at one of the world’s largest rare earth deposits in Baotou, Inner Mongolia has created a highly toxic artificial lake of ore processing tailings over 3,000 meters wide. Many more examples of the need to extend the life of the device as long as possible through processes such as refurbishment, and/or to have a resource-effective means to salvage the useful components and materials in a recycling process can be found in [4].

Smartphones’ diminutive size, sensitivity to environmental conditions, precise physical tolerances, and fragile electronic components makes them difficult to repair and/or refurbish. Design choices such as case adhesives, bonded glass displays, non-removable batteries, the need to remove and replace soldered components, non-standard fasteners, and the low level of component modularity in many devices, all contribute to complex refurbishment processes that require specialized tools and knowledge [5]. Additionally, these devices are constructed to resist the intrusion of dust and water into the internal electronics. The use of moisture-resistant seals and gaskets between the case and the display increase the complexity of disassembly and reassembly for third-party refurbishers wishing to retain water resistance ratings [6].
This paper focuses on reuse, repair, and remanufacturing as processes under the broader umbrella of refurbishment with an emphasis on smartphones. The refurbishment of smartphones can run the gamut from returned “new” products that can be reused without undergoing further processing to significantly repaired and/or remanufactured products. Various terms (e.g., refurbishing, remanufacturing, renewed, reuse, recycling) describe the process of providing further utilization of electronic products beyond their initial usage period.

The term “refurbishing” refers to the process by which used products are restored to a defined working condition in form and function. In refurbishing, any parts that are damaged, that have failed, or that are prone to failure may be replaced, but the device’s composition and design are not significantly changed from the original [7]. “Remanufacturing” is defined as the process of disassembling a used product, repairing and/or replacing any failed, worn, or outdated components, and bringing the product back to, or in some cases exceeding, as-new performance (e.g., when more reliable parts replace older parts) [8]. “Reconditioning” is a similar term used interchangeably to describe the process of remanufacturing products [9]. “Renewed” describes “pre-owned, refurbished and open-box products” according to one vendor [10]. These products include smartphones and other electronics that undergo unspecified processes in order to be returned to a saleable condition and offered again to consumers. “Reuse” refers to the secondary use of a functional electronic device after the previous owner has discontinued its use, avoiding landfilling or recycling processes [11]. Electronic devices that are “reused” may or may not undergo processing that could include refurbishment, remanufacturing, or simply cosmetic changes before they reach their next user. “Recycling” is the process by which materials or components are removed or recovered from the product, then processed and put back into productive use as a material or component [12]. For smartphones, this process involves either the complete disassembly of the device into components and/or physical processing of the device into individual materials such as metals, plastics, and glass [13]. Recycling is the final step in a product’s life-cycle, and should not be confused with refurbishment.

The terms listed above overlap and can be incorporated in various aspects of the circular economy [14]. Regardless, as the rising cost of higher-end smartphones has resulted in slowed or even negative growth in new smartphone markets, with consumer upgrade cycles growing longer each year [15], the refurbished smartphone market has experienced extraordinary growth over the last decade. As consumers search for more budget-friendly choices and original equipment manufacturers (OEMs) see an opportunity for another revenue stream.

Aside from their new product sales, many OEMs now sell their refurbished devices directly to consumers. Smartphone manufacturers Apple and Samsung entered the marketplace for “certified” refurbished smartphones in 2016 [16],[17]. The reuse of electronic devices and their components is intended to generate revenue and contribute to the protection of the environment by producing less waste and avoiding the use of new materials in production. Turki, et al. found that as carbon emission caps are lowered and carbon trading prices rise, the economic viability of refurbishment improves [18]. Further improvements may be found by alignment of equipment manufacturers and third party refurbishers through certification of refurbished products [19].

The objective of this paper is to explore the refurbishment of electronic products in today’s mainstream marketplaces by OEMs, communications companies, and independent third-party organizations. Smartphones were selected as representative of electronic devices as they are abundant and being actively refurbished in large quantities. This paper discusses the size and scope of the refurbished smartphone market and explores various refurbishment processes. The benefits of smartphone refurbishment for both companies and consumers are discussed, as well as the drawbacks and concerns with refurbished devices. In particular, the paper addresses the reliability declarations of refurbished products from major reputable companies, including claims from two leading smartphone companies that their refurbished products are “equivalent to new” (Apple) [20] and “remanufactured to original condition” (Samsung) [21]. Approaches by Samsung and Apple, as well as U.S. companies providing communications services and devices—Verizon, AT&T, Sprint, and T-Mobile—are discussed. Finally, suggestions are offered to increase both the use and efficiency of refurbishment.

II. REFURBISHED SMARTPHONE MARKET

SCOPE AND SIZE

Purchasing a refurbished smartphone can result in substantial savings to the consumer. According to the websites of the majority of companies engaged in refurbishment, consumers receive what is described as a fully functional unit that meets quality standards set by the refurbisher. Refurbished devices are offered by major smartphone manufacturers, telecommunications companies, and a wide variety of third parties. Table 1 provides a sampling of the companies involved in smartphone refurbishment and resale. Warranty periods are listed for refurbished devices, as well as each company’s language regarding the level of device testing undertaken in the refurbishment process, with significant variance in their descriptions.

Sales of refurbished smartphones worldwide have increased dramatically since 2010. In 2014, 56 million refurbished smartphones were sold to end-users globally, the equivalent of $7 billion in wholesale revenue [22]. Counterpoint Research reported that refurbished smartphone sales grew to 140 million units in 2017, with an equivalent of $14 billion in wholesale revenue, more than doubling in three years [23]. International Data Corporation (IDC) predicted that the global market for refurbished smartphone sales would grow from 225.5 million devices in 2020 to 351.6 million...
Despite refurbished smartphones offering significant cost savings compared to a new smartphone, the majority of US consumers appeared to prefer a new device. In a survey of U.S. smartphone users undertaken by IDC, only 26% of the respondents said they were “somewhat likely” to buy a well-maintained one-year-old phone if the price were lower; another 14% said they were “highly likely” to do so. Among iPhone owners specifically, the responses were even lower at 25% and 9%, respectively [26].

III. SOURCES FOR REFURBISHED SMARTPHONES

There are three main sources for smartphones that enter OEM refurbishment processes. The first is comprised of new devices that are returned by customers, either directly to manufacturers or through retailers, within the OEM’s or retailer’s allowable return period. In the United States, according to Federal Trade Commission (FTC) rules, even when a customer returns an opened but unused product, it cannot be resold as new [27]. Thus, the device must go through a “refurbishment process” before being resold.

The second source includes products from an official manufacturer’s trade-in program. For example, Apple allows end-users to sell back their working used iPhones for credit towards a newer device model. Devices may also be sourced from information technology asset disposition (ITAD) channels, a source of previously used devices that businesses consider to be either obsolete, out of warranty, or otherwise no longer needed. While many of these devices are destroyed to avoid data privacy concerns and possible legal exposure for companies, some may be sent to an OEM for credit on new products. For example, Apple released an environmental responsibility report in which they claimed to have refurbished 7.8 million devices in 2018. The company also claimed that they recycled more than 48,000 metric tons of electronic waste (e.g., e-waste) in the same year, from returned devices that could not be refurbished [28].

A third source includes devices that have been found to have manufacturing defects (cosmetic damage and/or components with defects) and performance problems within the device’s warranty period. When these devices are returned to the OEM, they may go through a refurbishment process or a recycling process. The refurbished devices can then be provided for resale once the company can verify that it meets manufacturer refurbishment standards and should be labeled as refurbished [29].

IV. REFURBISHMENT PROCESSES

The depth of refurbishment processes undertaken on used smartphones for resale has been found to vary significantly depending upon the standards of the organization performing the refurbishment. While some OEMs claim that they undertake a “rigorous” refurbishment process using equipment and replacement parts designed specifically for their devices,
other companies process many brands and lack specialized OEM testing equipment.

Table 1 illustrates that the OEM’s refurbishment process is likely to involve a greater level of testing than is conducted by third parties. However, while basic test descriptions may be listed, the details of these processes are almost never publicly available from refurbishers. Fig. 1 shows a typical refurbishment process followed by OEMs and third parties. These refurbishment processes may include physical device cleaning, data reset, and some basic functional tests. Some refurbishers will simply perform these tests and offer these “refurbished” devices for sale. Others may engage in additional processing, such as battery and/or screen replacement and performance testing. Further processes might include replacement of selected parts and device casing as well as advanced device testing, such as measurement of device radio power levels and speaker and microphone performance [33].

FIGURE 1. A typical smartphone refurbishment process followed by OEMs and third parties.

In 2017, popular used smartphone reseller Gazelle claimed that it had processed 4.1 million phones through its facility. The company described its refurbishment process as “a rigorous inspection process involving a 30-point functional and cosmetic inspection. Additionally, all devices are reset to factory settings prior to shipment” [34]. The company also claimed that for those devices found to have non-working components, their technicians attempt to repair them by replacing the defective parts.

AT&T lists in their AT&T Certified Restored device refurbishment process, “Each device is validated for authentic parts [such as counterfeit parts or parts replaced by a consumer], a robust display, and scrubbed of data security threats...cleaned, polished, and visual details are repaired and refaced as needed...27-point testing phase ensures the device functions perform as expected...A multipoint test verifies the RF signal strength performs to AT&T and FCC specifications...Every restored device gets the latest operating software installed” [35]. Verizon Wireless claims to test the following components in their self-described “thorough quality inspection”—batteries, connectivity, audio, keypad and software, display, and ports [36]. No further details are given for their refurbishment process. T-Mobile’s Certified Devices program lists an 80-point process for their certified smartphones. According to T-Mobile, this includes testing the basic functionality of the battery, display, audio, buttons, ports, camera, software, cellular radios and appearance [37].

In contrast to AT&T, Verizon, and T-Mobile, Amazon.com has an economics-based approach to their “Amazon Renewed” refurbished product program. They do not specify the exact refurbishment procedures required of companies that are certified by Amazon to be part of the Renewed program. Instead, Amazon.com notes that “Products sold by you on Amazon Renewed have been tested and certified to look and work like new. Your refurbishment process typically includes a diagnostic test, replacement of any defective parts, a thorough cleaning and inspection process, and repackaging where applicable” [10]. Further guidance notes a requirement of returns of 0.8% or less and a minimum of 700 orders in the past three months. Amazon states that its products are “inspected and tested to work and look like new by an Amazon qualified and performance managed supplier,” including a “full diagnostic test, replacement of any defective parts, and a thorough cleaning process carried out by the supplier, or by Amazon...batteries tested to have at least 80% capacity relative to new at the time of sale” [10]. Amazon provided no further details, guidance, or requirements for this program.

Refurbished electronics marketplace Back Market reported that they work with 170 refurbishing companies, and claimed that they pay more attention than other companies to supplier refurbishment procedures. Back Market claimed that they visit their refurbishment partners at their factories and “systematically verify their quality control procedures” [38]. The company also makes available a listing of the functionality that has been tested by each refurbisher, but does not describe the specific testing of the components or the device.

Apple Inc.’s website claims that each certified refurbished product undergoes the following process in regards to testing: “Full functionality testing and any defective modules identified in testing are replaced...thorough cleaning process and inspection...repackaged (including appropriate manuals, cables, and new boxes)...Final QA inspection prior to being added to sellable refurbished stock...given a new refurbished
part number and serial number” [39]. The company further claims in the same document that the technical guidelines of their refurbishment procedures are the same as their Finished Goods testing procedures [29].

The lack of transparency and variation in refurbishment procedures between organizations creates significant uncertainty for consumers in determining the quality of a refurbished product in the marketplace. Even the CEO of the major consumer electronics repair company iFixit, Kyle Wiens, believes this variety of companies and refurbishment actions is problematic, stating that “I honestly don’t know a good way to compare refurbishers…” [40]. With such a variety of testing approaches, there is little doubt that devices that undergo refurbishment with all of these organizations emerge in a variety of states of reliability.

V. REFURBISHMENT BENEFITS

Refurbishment of electronics allows a company to profit from products that have been returned owing to cosmetic, performance, and/or reliability problems. Profits on remanufactured products have been reported to be as high as 40% [41]. High profits from refurbished products have led to OEM involvement, as evidenced by Apple joining the growing direct-to-consumer refurbished smartphone market in 2016, followed by Samsung in 2017. Comparative pricing of Apple and Samsung refurbished and new products is shown in Table 2.

The commodity value of a smartphone when sent to recycling processors and shredded is extremely low compared to the resale value of a working device that is refurbished and resold. The value of recovered commodities has fallen significantly over the past decade, making a stronger business case for refurbishing a smartphone, rather than processing it as waste [46]. As a result of this decline in processed material value, most e-waste recyclers, large and small, engage in some form of refurbishment processing and resale of working electronics, in addition to processing for recycling [13]. We toured one of the largest and most modern electronics recycling facilities in the world, Enviroserve’s e-waste processing facility in Dubai Industrial City on the outskirts of Dubai, UAE. The plant manager indicated that a small workshop at the corner of the facility was used to refurbish working computers, due to their higher value as working electronics. In the United States a similar visit to E-End, a small electronics waste processor in Frederick, Maryland, also revealed that the company devoted some of its space to refurbishment of working computers for resale. The financial incentive for both processors was clear—a refurbished functional electronic device possessed significantly greater resale value than the value of the processed materials from which it was comprised [13].

In developing countries, consumers who purchase refurbished devices get access to relatively newer smartphones at more attractive price points. According to Counterpoint Research, as of 2018, India was the fastest-growing market for refurbished smartphones, despite the Indian government having officially restricted imports of refurbished electronics prior to May 2019. Refurbished phone sales were reported to have grown in India by 41% from 2017 to 2018, far exceeding the growth of 10% globally over the same period. Significant growth in the market for refurbished devices was also reported in Thailand, Vietnam, and Africa, described as “price-sensitive economies” for smartphones [47].

Refurbishment can effectively increase the usable lifetime of smartphones, delaying the time when they reach end-of-life and are sent to the materials recycling sector, or to landfill. As a result, fewer heavy metals and other chemicals will leach into the soil from buried electronic waste. Further environmental benefits of greater refurbishment include the prevention of pollution from processing of smartphone waste. Of greatest concern are informal recycling processes undertaken in developing countries by unskilled and unprotected workers, which have been proven to be extremely harmful to human health. In particular, small, difficult-to-disassemble devices such as smartphones may undergo highly toxic processing techniques and introduce significant levels of phthalates and heavy metals into the ground, air, and local water sources [13].

A typical smartphone consists of more than 60 metals and alloys, including all but one of the rare earth metals, many of which are mined in hazardous and unregulated conditions. Table 3 illustrates the quantity of common metals and alloys that can be recovered per 100,000 iPhones and the estimated emissions of greenhouse gases associated with production of the listed weight of these materials. Smartphones contain common metals and alloys that consume energy when mined, and greenhouse gases are produced during that process [48]. As examined by Pecht et al., the negative environmental and human impacts of mining some of these materials can be extraordinary, poisoning workers and the surrounding environment [4].

Apple reportedly sold more than 217 million iPhones in 2018, and each iPhone 8 (64 GB model) produced an

| Refurbished Product Price ($USD) | New Product Price ($USD) | Refurbished Product Price as % of New Product Price |
|----------------------------------|--------------------------|-----------------------------------------------|
| Apple iPhone 8 Plus (256 GB)     | 509.00                   | 699.00                                         | 72.8%                                        |
| Apple iPhone X (64 GB)           | 599.00                   | 899.00                                         | 66.6%                                        |
| Samsung S8 (32 GB)               | 350.00                   | 499.99                                         | 70.1%                                        |
| Samsung Galaxy Note 5 (32 GB)    | 349.99                   | 696.99                                         | 50.2%                                        |
estimated 57 kg of CO\textsubscript{2} in its life-cycle, with approximately 45.6 kg of CO\textsubscript{2} produced during production of the devices [28]. The majority of greenhouse gas emissions from smartphones occur during the material extraction and manufacturing stages of their life-cycle, but it was estimated that approximately one-fifth of the total emissions for smartphones are in the use stage [55]. If smartphones can be reliably and economically refurbished, priced appropriately, and marketed effectively, they can effectively attract price-sensitive consumers away from purchases of new devices. As a result, it may be possible to avoid unnecessary additional greenhouse gas production.

### VI. CHALLENGES FOR REFURBISHED SMARTPHONES

While the process of smartphone refurbishment results in benefits to both resellers and consumers, there are also significant challenges both in the process of refurbishment, and with the devices themselves. In the United States, there are no clear standards that apply to smartphone refurbishment processes. The ANSI/UL 110 Standard for Sustainability for Mobile Phones [56] was approved in 2017 as a joint effort between the UL Environment organization and the Green Electronics Council. It provides rules for manufacturers so that their products that adhere to the standard may be easier to refurbish, but these rules do not define a refurbishment standard. The Green Electronics Council’s Electronic Product Environmental Assessment Tool (EPEAT) registry for mobile phones is provided for consumers as a guide to the environmental impact of various new devices [57]. Manufacturers voluntarily submit their products for the registry. The few products with Gold EPEAT certification, the highest rating, were found to have low scores in categories regarding ease of disassembly, availability of replacement parts, and availability of repair and refurbishment information, all key areas for effective refurbishment.

The R2:2013 electronics recycling standard [58] is similarly voluntary. It was created by Seri, an ANSI accredited standards development nonprofit organization focused on electronics repair and recycling. Companies are R2-certified by following audited best practices in handling used and end-of-life electronics and by paying an annual fee. The standard primarily covers requirements in responsible recycling of electronics but also covers their reuse. A certified company can only provide “ready for resale” electronics if they use effective test methods, have quality assurance and product return plans, maintain records, verify the performance of key functions, and ensure components are cleaned and cosmetically acceptable. The standard does not mention product categories or give specific details because it is primarily aimed at the responsible management of electronic waste items. In February 2017, the ANSI standard RICO01.1-2016: Specifications for the Process of Remanufacturing [59] was approved. This standard was created by the Remanufacturing Industries Council, an alliance of businesses and educational institutions. The scope of the standard was extremely broad for application to any remanufacturing process. No details exist within the standard, which applies specifically to electronics or smartphones, and as the text of the standard notes, “Compliance with this standard is voluntary and the specifications in this standard offer recommended practices for remanufacturing products and should be regarded as advisory only” [59].

The European Union has built consumer protections into the law for used and refurbished devices. According to the 1999 Directive 1999/44/EC Article 7.1 on the sale of consumer goods, refurbished smartphones must come with a minimum one-year warranty, but this directive provides no requirements for refurbishment processes [60]. The United Kingdom’s Department for Business, Innovation and Skills specified certain procedures for the reuse of waste electrical and electronic equipment (WEEE) in their PAS 141:2011 standard [61], later superseded by BS EN 50614:2020 [62]. These were a UK adoption of EN 50614 standards through the CENELC European Committee for Electrotechnical Standardization. The standards covered tools and test equipment, safety, electrical and functionality testing, disassembly, repair and/or replacement, cleaning, and quality assurance processes when preparing waste for reuse. They do not cover items that are accepted for refurbishment outside of the waste stream. In the absence of accepted and enforced standards, electronics refurbishment processes can be arbitrary, resulting in a marketplace of inconsistently refurbished devices at varying quality, performance, and reliability levels. The consumer is left to use qualitative measures such as purchaser reviews or vendor reputations, which are poor indicators of the quality and reliability of the device they will receive.

Besides quality, performance, and reliability problems, there are also safety concerns, particularly in products that use lithium-ion batteries, which can catch fire and explode. While such safety problems can also occur in new phones, Williard et al. noted that in the process of reverse logistics, the storage and transportation for refurbishment can induce problems [63]. Furthermore, the increased use of

### TABLE 3. Quantity of recoverable common metals per 100,000 Apple iPhones, various models.

| Metals/Alloys      | Recoverable Metals (kg) [28] | Metal Production Emissions (kg CO\textsubscript{2}-eq) |
|--------------------|-------------------------------|--------------------------------------------------------|
| Aluminum           | 1,500                         | 21,750 [49]                                            |
| Gold               | 1.1                           | 25,778.5 [48]                                          |
| Silver             | 6.3                           | 693 [50]                                               |
| Rare Earth Metals  | 32                            | 1,035.5 [51]                                           |
| Tungsten           | 83                            | 1,045.8 [52]                                           |
| Copper             | 1,000                         | 3,700 [48]                                             |
| Tin                | 29                            | 500.3 [53]                                             |
| Cobalt             | 790                           | 6,557 [52]                                             |
| Steel              | 1,400                         | 8,610 [54]                                             |
adhesives rather than mechanical fasteners for retaining batteries inside smartphone housings can cause deformation of lithium polymer batteries during removal, which is commonplace in recycling, as observed by Hazelwood et al. [13]. The removal of batteries for replacement during refurbishment also exposes workers to danger, as mechanical damage to a battery can lead to thermal runaway and result in fires. In fact, there are numerous examples of smartphone batteries exploding during refurbishment and recycling processes, such as those reported in the Washington Post [64]. Contributing to battery challenges, some refurbished smartphones are often provided with third-party chargers and cables. The large refurbished device marketplace Back Market notes in their frequently asked questions that “where accessories are included with a product, they are new and compatible but are not (or at least rarely) the original brand, unless otherwise mentioned” [65].

Third-party USB chargers and cables for smartphones can be dangerous if not designed to operate within OEM specifications. They may vary beyond specified limits in voltage or current and can damage charging systems inside phones. This was reported to be the case with the Tristar/U2 chip that was used in the iPhone 5, where the use of third-party chargers and cables resulted in intermittent charging and connection problems that may not have been identified by refurbishers. These damaged chips were on the main circuit board of these phones and were difficult to replace, so battery or charging port replacements performed even by detailed refurbishers would not have solved the issue [66]. Low-quality chargers and batteries that may be used by third-party refurbishers can be extremely dangerous and even pose fire and electrocution hazards to end-users, as noted by Saxena et al. [67]. Counterfeit batteries can also present dangers when used in refurbished smartphones. The Consumer Product Safety Commission (CPSC) has issued multiple product recalls over the use of counterfeit batteries in refurbished products due to the subsequent fire risk. In one instance, 470,000 counterfeit batteries in BlackBerry-branded smartphones were used in devices provided by Asurion through a handset protection program [68]. In another, 10,200 counterfeit batteries were found to have been used in Samsung smartphones refurbished and supplied by the FedEx Supply Chain organization [69].

In the case of Apple’s iPhone devices, third-party refurbishers who are replacing nonfunctional parts often have sourced used parts cannibalized from other iPhones, or used aftermarket parts in place of original parts, as Apple has traditionally only sold OEM parts to third parties who paid to join their authorized service provider program [70]. Apple’s newly established free Independent Repair Provider Program allows independent repair shops to purchase retail priced components, but does not cover a wide variety of parts, and includes specific requirements for applicants [71], [72].

Third-party refurbishment companies may also damage smartphones in their refurbishment process, due to lack of access to the specialized tools and procedures available to OEMs. For example, third-party refurbisher Gazelle claimed to process almost 5 million smartphones per year for resale and reported only a 70–75% rate of success in their repairs. The company admitted that due to a lack of access to service documents for each new iPhone model, they are forced to learn how to repair it without incurring further damage to the device [34].

Apple requires repair centers to return the “core” part in an attempt to control the flow of genuine parts, and for “examination, refurbishment and return to service stock, or both” [73]. The company has been a central figure in “Right to Repair” legislation, lobbying against a variety of bills that have been put forth in many U.S. states to give consumers access to repair information, provide easy access to tools and parts, and maintain warranty status when undertaking repairs through third parties. While this issue has not been resolved in the United States, the European Commission’s March 2020 Circular Economy Action Plan [74] proposed broadening their existing Ecodesign framework for energy devices to include electronics in order to improve product durability, reparability, remanufacturing, and recycling. Included within this plan was a revision of EU consumer law to provide availability of spare parts, repair manuals, information on product lifespans at point of sale, promotion of repair services, and efforts to ensure the reparability of new products.

While some smartphones that are refurbished and resold may stay within their country of origin, companies can refurbish devices in their local markets, then export them to other countries for resale. As a result, environmental conditions experienced by these devices could have been far outside the extremes experienced within the local market. Even in normal usage by consumers, smartphones can experience temperatures that fall outside of manufacturer-recommended operating ranges. Refurbished devices may have experienced such temperature extremes in normal use in some parts of the United States, as well as in other more extreme climates throughout the world. For example, Apple recommends that iPhones are kept between 0°C and 35°C (32°F to 95°F) when being used (the same range suggested by Samsung [75]), and to store the devices in a powered-down state between −20°C and 45°C (−4°F to 113°F). Apple also specifically warns users that excessive temperatures found in parked cars can permanently shorten battery life [76].

Dadour et al. [77] tested vehicle interior temperatures in a variety of vehicles in Western Australia during the summer and recorded temperatures as high as 70°C or 158°F. Even in a laboratory environment with an ambient temperature between 24°C to 28°C, Kang et al. [78] found that processor-intensive applications could push a modern smartphone’s external temperature up to 50°C within 10 min. Extreme temperatures can cause lithium-ion batteries to malfunction, adhesives to soften, materials to fatigue and components to delaminate or separate. These temperature-driven effects can also reduce the device’s ability to repel moisture
and dust over time, and can lead to accelerated failure of internal components. Such environments and operating conditions will accelerate the failures of the electronics and reduce their remaining useful life. If a device experiencing these conditions is then later refurbished without all of the components being replaced with new electronic components, the operating life of the product will be reduced.

The levels of shock and vibration a smartphone has endured during its lifetime prior to undergoing refurbishment will also contribute to subsequent reliability problems if used components, harvested from used smartphones, are placed into refurbished products. For example, the regular usage of a smartphone charging port may leave fractures in the solder connections to the logic board that only fail to work correctly when the charging cable is oriented in a certain direction, or pins may be broken and work intermittently. Apple’s iPhone 6 Plus and, to a lesser extent, iPhone 6, fell victim to a very specific form of mechanical failure where solder ball connections securing the two “Touch IC” chips to the main logic board of many of these phones partially failed. This resulted in what was dubbed “Touch IC disease,” where the touch screen of the devices would undergo intermittent failures. According to a report by Vox, independent repair technicians repeatedly saw this failure in devices and developed methods to correct the problem. Some technicians reported that even official Apple-refurbished devices were being brought into their shops with the problem, and that the boards showed signs of previous repairs [79], [80].

Moisture levels encountered by used devices can also be a reliability concern. While some newer smartphones have been certified as highly water-resistant by standards bodies such as the International Electrotechnical Commission (IEC), these standards dictate specific testing conditions for new phones only. For instance, Apple’s iPhone 11 Pro smartphone is rated IP-68 (Ingress Protection code, IEC standard 60529), which means when new it can be submerged to a depth of 4 m in freshwater for 30 min and continue to operate within original specifications [81]. However, Apple does not cover liquid damages on iPhones under its Apple One-Year Limited Warranty program [82], and most people do not drop their phones in pure water, but rather chlorinated, soapy, or salty water.

Dangerous third-party software can also be introduced by workers during refurbishment processes undertaken by non-OEM refurbishers. According to a representative of storage company G Data in 2015, “Over the past year, we have seen a significant [growth] in devices that are equipped with firmware-level [malware and spyware] out of the box which can take a wide range of unknown and unwanted actions” [83]. Check Point researchers in 2017 found malware in 36 Samsung, Xiaomi, Oppo, Asus, Vivo, LG, Lenovo, and ZTE devices running the Android operating system, and determined that the malware had been introduced in the supply chain between the manufacturer and the end-user. While the malware was discovered in new devices, refurbishers also have complete access to a device, and the device is repackaged before it reaches consumers, providing opportunities for software tampering [84].

Finally, in terms of the environmental concerns, gains from greenhouse gas emissions savings and diversion from recycling processes may be partially lost due to “rebound” effects [85]. These are possible unintended consequences of increased primary production from closing the loop of the circular economy, invalidating expected gains. Makov and Vivanco [86] examined environmental rebound effects in terms of smartphone reuse and greenhouse gas emissions. They concluded that when refurbished smartphones were significantly cheaper than new devices, about 30% of the emissions savings of used vs. new devices was negated. This was due to “re-spending” of financial savings and that not all purchases of refurbished smartphones are in substitution of a purchase of a new device.

VII. WARRANTIES AND RELIABILITY OF REFURBISHED PRODUCTS

A refurbished device cannot be classified as a new device, since it consists of used (salvaged) components. How this is presented to customers varies based on the companies that offer refurbished devices. This section analyzes the warranty documents for refurbished devices from major smartphone companies and carriers.

As of July 2020, Apple’s online warranty stated that customers who had functionality problems with their device within their warranty period would receive either their repaired device with “new or previously used parts that are equivalent to new in performance and reliability,” or a replacement device that is “formed from new and/or previously used parts that are equivalent to new in performance and reliability” [30]. In other words, when one receives a warranty replacement of any failed or broken iPhone, it is likely to be a refurbished device, and it may contain a mix of older (used and salvaged) and newer parts [20]. According to Samsung’s standard limited warranty statement, during the applicable warranty period, Samsung “may use rebuilt, reconditioned, or new parts or components when repairing any Product, or may replace the Product with a rebuilt, reconditioned or new Product” [87]. Samsung’s statement does not, however, mention the expected performance or reliability of its refurbished devices. Chinese smartphone company Huawei also notes in their warranty statement that they “reserve the right to use new or refurbished replacement parts in repair of the Product” [88]. Similar to Samsung, Huawei does not mention the expected performance or reliability of its refurbished devices.

The majority of mobile communications companies in the U.S. have programs that replace broken or defective devices outside of manufacturer warranty periods. These can result in consumers receiving not only a refurbished device, but one that may be much older. As an example, the AT&T Mobile Insurance program provides replacement warranty coverage of one year on refurbished smartphones. These AT&T Certified Restored devices “may be previously opened or used.
devices that undergo a series of rigorous tests and inspections and may be refurbished or remanufactured. Devices in this category...may contain original or non-original replacement parts and may be up to four years old” [35]. Verizon Wireless sells “certified pre-owned” smartphones and offers a replacement device when a device experiences an eligible in-warranty failure through their Certified Like-New Replacement program [89]. According to Verizon, both “certified pre-owned” devices and “certified like-new” devices are refurbished units that have been “thoroughly inspected and reconditioned to manufacturer performance levels” [90]. T-Mobile claims to perform a detailed, top-down inspection of every device feature and function on their certified pre-owned devices. Additionally, the device protection plan offered by T-Mobile states that when a customer files a claim requesting a replacement phone due to accidental damage, loss, or theft, they will be given a reconditioned device of like type and quality. The assumption is that a reconditioned or refurbished phone has the same level of quality and performance as a new device [91], [92].

Since all electronic and electro-mechanical systems decrease in reliability over time, the reliability of a population of refurbished devices cannot be as good as a new device. When a device is used, it is subjected to various kinds of mechanical, electrical, and even chemical degradation resulting from the environment and usage stresses, including temperature, vibration, shock, and moisture, all of which leads to shortening the time to the end of life. Furthermore, the refurbishment process itself can degrade the electronics. For example, failed electronic components often require de-soldering the components with high temperatures, followed by cleaning and then re-soldering, again at temperatures as high as 220°C. As a result, no used electronic product is ever equivalent to a new product. Typical failure mechanisms are listed for smartphone components in Table 4. Additional failure mechanisms can be found in the JEDEC Standards, including JEDEC’s JEP 122G, Failure Mechanisms and Models for Semiconductor Devices [93].

Phones are classified as solid-state devices, but there are many moving parts, such as the actuators in the camera, springs in the contacts for SD cards, as well as some antennas. Microphones and speakers are also constructed with moving parts that deteriorate with time. Heat, moisture, mechanical stresses, and contaminants are some of the detrimental conditions that reduce the reliability of these parts.

Public data is rarely available for device testing outcomes to illustrate component failure rates. Mobile diagnostic provider Blancco collected data from iOS and Android smartphones from testing by mobile carriers and device processors in North America, Europe, Asia and Australia from August 1 to October 30, 2018. Their data, shown in Table 5, show the top five components with the most common performance test failures.

In working with Huawei, Dell, and Samsung, we have been informed that they conduct extensive burn-in and other screens to ensure that infant mortality (early failure) in both their new and refurbished products are negligible. The result is that the remaining useful life is limited since the deterioration of components occurs over time due to the environmental and operating stress on the components. Furthermore, one

| Component | Example Failure Mechanisms |
|-----------|-----------------------------|
| Battery   | The lithium-ion batteries in smartphones degrade from regular usage, charging cycles, temperature extremes, and physical damage [94] [95] [96]. With usage, the screen may start to develop lag and eventually fail. As an exposed component, screens can fail as a result of physical damage to their surfaces. The newer organic light-emitting diode (OLED) technology screens suffer from burn-in with extended usage [97]. |
| Screen    | When third-party chargers are used, smartphones can develop problems in the charging circuitry and experience battery or system failure [67]. Charging ports can also fail and dirt and debris can enter the port [98]. |
| Charging circuit | With age or mishandling, rubber gaskets, tape, films, meshes, and membranes will shift or degrade. This can allow moisture to enter the device, causing corrosion, electromigration, and performance degradation [6], [99]. |
| Waterproofing | Exposure to water, dust, particulate matter, temperature cycles, and shock degrade the micro-electro-mechanical systems (MEMS) speakers and microphones [100], [101]. |
| Speakers and microphone | Exposure to shock and temperature cycling degrades the autofocus actuators in smartphone cameras [102]. |
| Camera    | Exposure to temperature cycling, shock, and liquid intrusion degrade the baseband modem and associated antenna hardware [103]. |
| Radios and antennae | Exposure to temperature, temperature cycles, shock, vibration, moisture, dust, contamination, and liquid intrusion can all degrade the electronic components, solder joints, other interconnections, connectors, and printed circuit boards [104], [105], [106], [107], [108]. |

**TABLE 4.** Examples of common smartphone components and their failure mechanisms.

| Component                           | Example Failure Mechanisms                                      |
|-------------------------------------|-----------------------------------------------------------------|
| Apple Devices                       | Android Devices                                                 |
| Battery (8.6%)                      | Front camera flash (27%)                                        |
| Live calls (cellular modem) (3.5%)  | Android GPS (13%)                                               |
| Headset microphone (2.5%)           | Screen (13%)                                                    |
| Headset (1.8%)                      | Fingerprint sensor (8%)                                         |
| 3D Touch (1.5%)                     | Headset microphone (5%)                                         |

**TABLE 5.** Top 5 diagnostic problems, Blanco Q3 2018 processor data [109].
cannot state where a refurbished product is on a hazard rate curve of failure rates (sometimes assumed to be bathtub curve), because the refurbisher does not collect or have access to time-in-service and stress information for the device or the individual components that comprise the device. Therefore, it is impossible for a refurbisher (or consumer) to know just how far along any of the components are in their lifespan.

VIII. CONSUMER PROTECTION

In the absence of clear standards for the quality of refurbished devices available from organizations, consumers must educate themselves on available information about refurbished devices in the marketplace. Ideally, consumers would first look to purchase from OEMs, where equipment used to refurbish devices and refurbishment processes are expected to be the highest quality available. The website of the manufacturer will typically show the overall steps taken to refurbish the device, albeit without any detail as to the component age or conditions experienced. This is ultimately where a consumer’s efforts come to an end in determining the possible future reliability of their refurbished smartphone.

Consumers could choose to purchase the few smartphones on the market where components are easily replaced, such as the Fairphone, which was designed for maximum repairability, upgradability, and with care taken to responsibly source the materials used. The Dutch company provides spare parts and repair information on their website, and designed the phone so that the supplied screwdriver allows the consumer to easily upgrade components.

Consumer advocacy organizations have attempted to help consumers to make better buying decisions by clarifying which devices are designed to be difficult to repair, and ultimately difficult to refurbish. Popular electronics repair company iFixIt rates new smartphones by first dismantling them, analyzing their construction, and rating them with a score out of 10 as to their repairability. The group also posts repair guides on their website in lieu of official repair documents, and sells parts and tools to undertake repairs [110]. However, the organization has no methodology, nor ability, to rate refurbished smartphones in terms of component age and condition, and future performance. While iFixIt regularly pushes for manufacturers to improve the repairability of their devices, ultimately as shown by continued poor scores on popular devices, the organization has had little observable effect on smartphone design from major manufacturers.

In May 2021, major EU-based communications companies Deutsche Telekom, Orange, Teléfonica, Telia Company and Vodafone Group adopted an ‘Eco Rating’ for new smartphones sold in 24 countries. An overall rating is provided out of a total of 100, giving scores across five measures: durability, repairability, recyclability, climate efficiency, and resource efficiency. Manufacturers included in the rating scheme include the Bullitt Group, Doro, HMD Global, Huawei, MobiWire, Motorola/Lenovo, OnePlus, Oppo, Samsung, TCL/Alcatel, Xiaomi, and ZTE [111].

The most applicable category from this newly developed ‘Eco Rating’ regarding suitability for refurbishment is repairability, described as “the ease with which the device can be repaired, including mobile phone design and supporting activities that could increase the useful life of the product by improving its repairability, reusability and upgradability potential” [111]. The Eco Rating website gives further visibility into the repairability category, but makes clear the process of refurbishment is not included in the determination of the repairability rating.

While this may ultimately become a useful metric with which consumers can judge new smartphones, consumers cannot predict remaining lifetime with this information. Cordella et al. [96] note that smartphone manufacturers still do not collect and provide information to consumers or refurbishers on the history of the battery usage, or extremes undergone by the hardware. While some OEMs may choose to replace the battery in a refurbished phone, most other major components will not be replaced. For third party refurbishers, minimal basic battery health data may be available to guide refurbishment processes, but there is no information on the age and condition of other components beyond a simple pass/fail evaluation.

As a key element for consumer insight into the remaining life of refurbished devices, comprehensive environmental and operating stress data should be collected on each device throughout its use period so that analysis and reasonable estimation of the remaining life of each product could be undertaken. Automated testing applications developed and provided by phone manufacturers could perform simplified system-wide reliability tests, providing a predicted reliability score in concert with analysis of lifetime environmental data recorded either on-device or to a cloud-based service. A simple overall rating system with per-component scores would benefit consumers and refurbishers alike.

IX. CONCLUSION

Electronics refurbishment extends the functional life of used smartphones. The reuse of these devices and/or their components can minimize the millions of pounds of electronic waste every year that are disposed of in landfills, incinerated, or sent to recycling processes. When consumers opt to purchase refurbished devices, they can positively impact the environment by reducing the need to mine and process materials for further new smartphone production. A refurbished smartphone is often environmentally and economically a better choice than a new device, but as discussed throughout this paper, a refurbished product such as a smartphone is not as reliable as a new product. Consumers must be cognizant of the broad spectrum of any refurbished smartphone’s reliability. They should keep in mind that although some manufacturers claim their refurbished products are “like new,” reliability science tells us that the components in the device that were subjected to environmental and operating stresses, and not refurbished, will have a shorter lifespan.
In order to improve consumer confidence in the reliability and safety of refurbished devices, greater transparency is required regarding where companies source their refurbished components, and the specific detail of refurbishment processes they are undertaking. Standards must be created and adopted across the industry that clearly address best practices for refurbishment. This paper showed that third-party refurbishment companies often set their own standards for refurbished products. If these standards are not identical to the original manufacturer’s performance standards, defects can arise. The remaining useful life of an electronics product will be lessened after refurbishment owing to the failure rates of the components that were not refurbished, and any defects introduced in the refurbishing process.

Electronics manufacturers claim that their refurbished smartphones undergo comprehensive reliability testing. Environmental and operating conditions for previously used devices place stresses on all the components of a device, including those components that were not exchanged or refurbished in a refurbished device, so the reliability of any refurbished product cannot be as good as new, and cannot be accurately determined prior to its return to the marketplace. Following its refurbishment, a device and its components could have been subjected to very little total usage over its lifetime, or be near end-of-life. This is indistinguishable to the consumer, and the devices are sold at an identical price.

The only valid approach to undertaking any estimation of the reliability of refurbished devices is to collect lifetime operating conditions data, along with testing data to provide simplified ratings for overall and per-component remaining life. Combined with transparent and universal standards for refurbishment, this market scheme would better accommodate consumers who have varying levels of willingness to pay for refurbished devices, and would increase the sale and reuse rate of used components. However, the ability to utilize current and historical device data to accurately determine refurbished smartphone quality will not appear without a significant evolution of consumer attitudes and subsequent demands of manufacturers, as well as policy changes to regulate refurbishment processes. Until then, consumers will ultimately be left to gamble with their funds and possibly their safety, purchasing devices of unknown quality with no insight as to realistic future reliability expectations.

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