# Economics of End-of-Life Materials Recovery – A Study of Small Appliances and Computer Devices in Portugal

Patrick Ford[1,5], Eduardo Santos[2], Paulo Ferrão[3,5], Fernanda Margarido[3,5], Krystyn J. Van Vliet[1,4,5], and Elsa Olivetti[1,5*]

Departments of [1]Materials Science and Engineering and [4]Biological Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 USA; [2]3Drivers – Engenharia, Inovação e Ambiente, Lda, Lisbon, Portugal; [3]Department of Mechanical Engineering, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal; [5]MIT Portugal Program

[*]*Corresponding Author:* elsao@mit.edu
MIT / Room 8-403
77 Massachusetts Ave.
Cambridge, MA 02139-4307
Tel: (617) 253-0877
Fax: (617) 258-7471

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# Abstract

The challenges brought on by the increasing complexity of electronic products, and the criticality of the materials these devices contain, present an opportunity for maximizing the economic and societal benefits derived from recovery and recycling. Small appliances and computer devices (SACD), including mobile phones, contain significant amounts of precious metals including gold and platinum, the present value of which should serve as a key economic driver for many recycling decisions. However, a detailed analysis is required to estimate the economic value that is unrealized by incomplete recovery of these and other materials, and to ascertain how such value could be reinvested to improve recovery processes. We present a dynamic product flow analysis for SACD throughout Portugal, a European Union member, including annual data detailing product sales and industrial-scale preprocessing data for recovery of specific materials from devices. We employ preprocessing facility and metals pricing data to identify losses, and develop an economic framework around the value of recycling including uncertainty. We show that significant economic losses occur during preprocessing (over $70M USD unrecovered in computers and mobile phones, 2006-2014) due to operations that fail to target high value materials, and characterize preprocessing operations according to material recovery and total costs.

# Introduction

The consumer electronics industry has seen increased adoption rates, device diversification and decreased product lifetimes all resulting in significant product proliferation. Effective disposal of these devices, or management of Waste Electrical and Electronic Equipment (WEEE), has long been a focus of environmental management policy, due primarily to concerns around human health and ecosystem impact.[1-4] More recently, high demand for, and fluctuating supplies of, metals within such devices, the mining and primary processing of which includes additional environmental and geopolitical impact,[5] has renewed interest in the overall flow of these devices at end-of-life. These ongoing efforts aim to discover where materials come to rest within the so-called "urban mine", and to quantify how the embedded value in particular electronic products might drive material recovery.[6-8]

Despite the potential value present within these devices, collection rates for products and materials recovery remains low. Limited materials recovery stems primarily from the lack of actionable information within the recovery network. Simply put, it is often not clear *a priori* whether the recovery of existing materials from used electronic devices is economically competitive with procurement of "new" materials. The composition of the generated waste stream is dynamic and offset in time and geographic location from the sale of the device, such that the available materials for recovery are not considered at the point of recycling system design. More specifically, there are several processes upstream of the actual metal recovery and refinement processes (generally termed preprocessing), which dictate final process yields and resulting value.[9, 10] These combined factors can result in scenarios that are intended to promote effective recycling – e.g., legislated recovery targets, grouping of printed circuit board (PCB) levels upon collection, and recovery facility design – that do not align well with maximizing the value recovered. Even when the amounts and locations of materials within devices are known, it may not be clear whether and to whom the recycling of such materials at end-of-life presents value.[11]

Through dynamic product and material flow analysis, coupled with detailed case data for preprocessing facility performance, this work establishes an economic framework for the value of recycling. Here we focus on the country of Portugal as a data-rich and well-defined recovery network that employs advanced technologies within its facilities, and consider the system from the point of sale to the preprocessing step for a subset of products that we term as small appliances and computer devices (SACD). This categorization is our own term. It is consistent with the classification of recovery data collected in Portugal that was grouped to include small consumer products and industrial equipment that shared electronic components including PCBs, and to exclude large products (including large household appliances and photovoltaic panels). By considering the perspective of the preprocessor facilities within a particular country, we identify losses in material recovery that could be reinvested in the system in that region. Even though a preprocessor does not typically have visibility into the materials-level recovery potential, the decisions at this stage limit maximum efficiency of downstream recovery and refinement steps that define the secondary materials market.

Previous work to understand electronic waste recovery can be grouped into two distinct focus areas: (1) product/material flows and urban mine characterization; and (2) recycling system architecture and performance.

First, understanding overall material and product flows within the current recycling infrastructure informs criticality assessments, access to the urban mine, legislative compliance, and design for materials or product targeting. The foci of these studies have been twofold, to understand the composition and flow of products and materials in the urban mine, and to analyze the losses during the preprocessing and recovery stages of recycling. According to Georgiadis and Besiou, the total amount of WEEE to enter the urban mine was projected to rise by 16-28% annually.[12] Several studies have quantified the materials contained in a variety of electronic devices that make up the urban mine, including but not limited to computers,[7, 13] phones,[14-19] and printers.[7] In 2015, Chancerel et al. examined the quantities of critical metals in consumer equipment, potential pathways for the removal of those metals, and the potential economic impacts of recovery processes.[20]

Our analysis is modelled after work completed by several researchers in the areas of substance and material flows. Navazo et al. used a material flow analysis to study the material and energy impacts of the recovery process for mobile phone materials.[21] Chancerel et al. used a substance flow analysis to explore the flow of precious metals through the preprocessing stage of recycling.[22] Several other researchers have employed varying sets of tools, including system dynamics and agent-based modeling, environmental impact assessments, and life cycle assessments, to explore the recycling system and its impacts.[2, 12, 23, 24]

Second, researchers have investigated system architecture and performance to assess key material losses, legislative costs, and the environmental and economic health of the system. In 2014, Navazo et al. detailed the material losses experienced during the processing and recovery stages of electronic waste recycling.[21] Meskers et al. provided an overview of the recycling and recovery process for WEEE and batteries, which included an analysis of which materials drive the economic argument for recycling, and the barriers to improved best practices.[18] Hageluken discussed the economic, environmental, and resource recovery opportunities surrounding the processing of electronic waste, finding that value-based metrics are needed to supplement the weight-based metrics specified in the WEEE Directive. The author also addressed tradeoffs between manual and mechanical preprocessing, and challenges such as material comingling and process capital costs.[25] In 2009, Chancerel et al. analyzed the flow of one tonne of information technology and telecommunications equipment (WEEE category 3) through the preprocessing stages of recycling, including sorting, manual dismantling, and shredding, focusing on gold, silver, palladium and platinum. This study identified losses at each stage of recycling, and provided recommendations for system improvements.[22] Several other studies have analyzed the preprocessing stage of recycling and quantified key material and economic losses.[19, 26, 27] Further, impact assessments carried out by the United Kingdom's Department for Business, Innovation, and Skills (BIS), in conjunction with others, studied the economic costs and benefits of the most recent WEEE Directive, listing impacts for businesses, government, and recyclers.[28]

Work to date has not emphasized how legislative decisions have influenced the potential economic benefits of materials recovery. These factors could include the implications of how products are categorized and the effectiveness of material mass-based targets. In addition, few reports have analyzed the impact of targeted investments within the recycling system on overall material recovery. Therefore, the work to date has been focused more on materials characterization rather than on the economic viability of the system. The key contributions of the present work include: 1) quantifying the value of potential materials recovery within SACD over time and by material; and 2) informing operational and investment decisions from the perspective of the preprocessor. In particular, we provide a framework for specific recommendations in facility investment and product grouping for preprocessing facilities. Through this analysis, we also support the evidence of the limitations inherent in material mass-based metrics and targets.

The case presented involves materials recovery data specific to Portugal and accompanying legislation within the European Union (EU). However, we provide conclusions as a function of the characteristics in the system, which may be applicable to other EU nations because of Portugal's state-of-the-art technologies and participation in EU wide recycling initiatives.

Portugal has two take-back programs, Associação Portuguesa de Gestão de Resíduos (Amb3e) and Associação Gestora de REEE (ERP Portugal), that organize the collection and treatment of WEEE, and have been licensed by the government since 2006.[29, 30] These organizations participate in the WEEE Forum (the European Association of Electrical and Electronic Waste Take Back Systems), an EU wide sector association that conducts benchmarking analysis of the country-level performance of its members. Since 2006, operators in Portugal have complied with the recycling and recovery targets set in the WEEE Directive, which was updated in 2012 as 2012/19/EU and legislates the treatment of electronic waste.[31, 32]

The following analysis demonstrates that, even with explicit consideration of the uncertainty within the data, current operations include unrealized material recovery and associated economic value. This value may be sufficient for reinvestment in preprocessing operations for the increased recovery of specific SACD subsets, device components, and key materials.

# Methods

The framework presented here identified the material and economic losses experienced throughout the defined electronic waste supply chain, and identified which opportunities existed to maximize the total recovered value for the system.

A dynamic product flow analysis (dPFA) was developed to determine the amount of materials available for recovery using a methodology derived from work of Navazo and Chancerel et al. and combined with a detailed assessment of preprocessing facilities.[21, 22] We used dPFA to track sales of SACD ($S_p$) through their projected lifetimes ($G_p(t)$), collection ($C_p(t)$), and preprocessing ($R_p(t)$). At the point of preprocessing we applied detailed accounting for materials composition by product and over time, preprocessing yields, and economic performance within preprocessing facilities. It was also necessary to calculate the costs associated with each operation within the preprocessing plants in an effort to guide potential investments aimed at reducing widespread losses. An overall schematic of the methodology is provided in Figure 1.

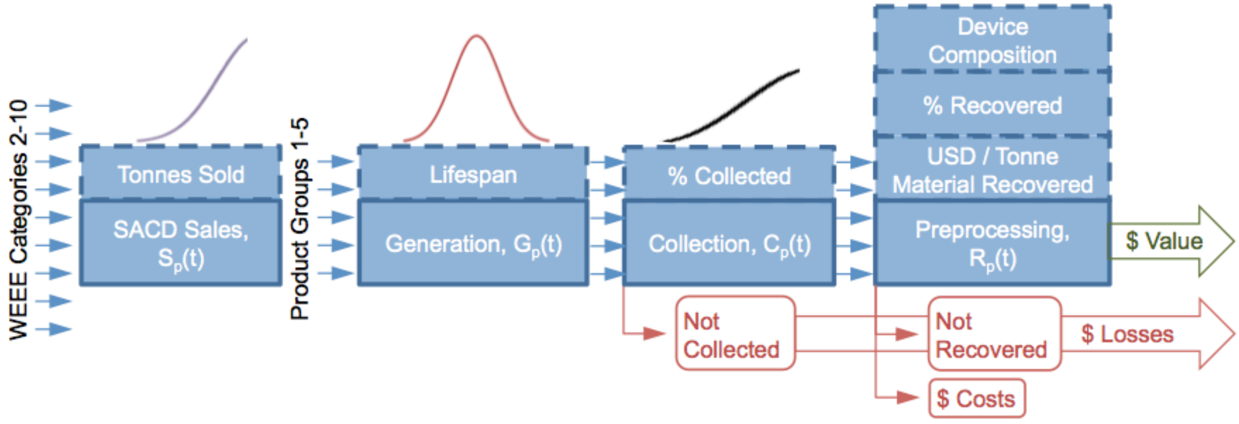

Figure 1. Schematic of overall model methodology

WEEE entering preprocessing stock *R* in each year *t* was tracked by product group *p*, as detailed below. Therefore, the mass (or units) of WEEE into preprocessing year *t*, $R_p(t)$, was the amount of WEEE generated $G_p(t)$ multiplied by the fraction of products collected in that year $C_p(t)$. Thus, $G_p(t)$ equaled the mass (or units) of products sold in the previous year $S_p$ (indexed on s), multiplied by the probability of reaching end-of-life in year *t*, $\lambda_p$, summed over all production years prior to *t*. Therefore, the amount of product in preprocessing was calculated using the following relationship.

$$R_p(t) = \left( \sum_{s=t^0}^{t} S_P\,(s,t) * \lambda_p(s,t) \right) *\ C_p(t)$$

$R_p$ in each year may be manually dismantled or shredded (or a combination of both), and are then sorted into a range of categories based on material composition. Prior to being shredded, the battery is removed from the device in accordance with de-pollution regulations.[33] The non-battery fractions, including components such as the PCB, speaker(s), camera(s), and outside casings are then sent to the appropriate downstream processes within the preprocessing facility. At the preprocessing stage, the total mass of each material subcategory not recovered was multiplied by the approximate value for which the material fraction could have been sold on the secondary materials market.

The remainder of this section contains an overview of data used in each dPFA step as defined in Figure 1. Additional detail on the treatment of the data used in each of these steps can be found in the supporting information. Finally, uncertainty has been calculated in the sales, collection, preprocessing, and material composition data, empirically where data allowed. Otherwise, a data quality indicator analysis was performed.[34]

**Sales, $S_p(t)$.** The starting point for this analysis was the use of detailed SACD sales data and projections for the years 2000 – 2014. These years were chosen due to the specificity of data available. A large portion of the sales information was gathered by ANREEE in its annual market data reports.[35-42]

SACD includes WEEE categories two through ten, as defined in the WEEE Directive: small household appliances; IT and telecommunications equipment; consumer equipment; lighting equipment; electrical and electronic tools; toys, leisure, and sports equipment; medical devices; monitoring and control instruments; and automatic dispensers.[43] The heterogeneity of these device categories complicates characterization and definitions focused on materials recovery processes. For this reason, we combined these WEEE categories within five product groups that are based on the type of product, the quality of its PCB and the materials contained within, and the projected lifespan of the device. Please refer to Table S7 in the Supporting Information for a detailed breakdown of the devices within each WEEE category into the five product groups below. The five product groups used are as follows:

1. Computing Devices
2. Telecommunications Devices
3. Printers
4. Other with 20+ year mean lifespan
5. Other with 0-19 year mean lifespan

**Generation, $G_p(t)$.** In the context of this model, a waste generation event was defined as the point in which a device enters the waste stream, after being used and/or reused for an amount of time determined by the assumed mean and standard deviation (SD) of its lifespan. The distribution was assumed to be log-normal. According to the methodology developed in this work and modelled after the work of Duan et al., the lifespan of each device included initial use, initial storage, informal reuse, and reuse storage.[6] Product lifespan data were collected from various sources, including that of Duan et al., Geyer and Blass, and Navazo et al., in conjunction with the Lifespan Database for Vehicles, Equipment, and Structures.[6, 21, 44, 45] Table S8 in the supporting information shows the mean and standard deviations used for the lifespans of the five product groups. Figure 2 shows the mass generated (i.e., that entered the waste stream) by year for an example set of computers sold in 2005 on the primary vertical axis (dashed line). The peak between 2010 and 2011 reflects the average lifespan of computing devices, as noted in Table S8. The secondary vertical axis portrays the cumulative mass generated over that time period (dotted line). The data shown in Figure 2 are for computers (product group 1) only and the shading qualitatively represents the uncertainty in the data, which is propagated throughout the analysis and shown quantitatively in Figure 4.

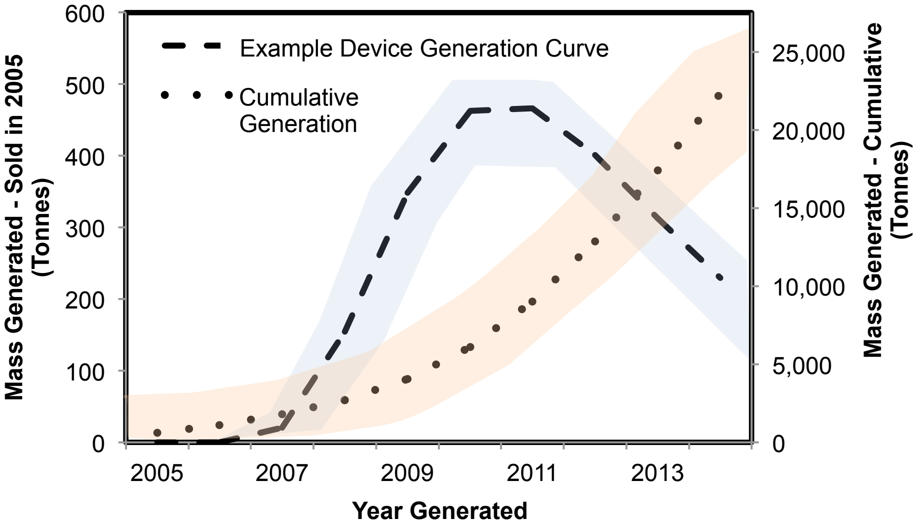

Figure 2. Mass of computers sold in 2005 that is generated until 2014 (primary axis) and the cumulative mass of computers generated over the same time period (secondary axis)

**Collection, $C_p(t)$.** The collection rate varied by the product group and over time. It was assumed that the collection rate for all devices prior to 2006 was 0% because there was a limited formal collection system established prior to when Portugal transposed the WEEE Directive. Data made available by Eurostat were used for all product groups for 2006 to 2013, and data calculated by our collaborators were used for 2014.[29, 46] For 2006 to 2013, the collection rates were calculated by dividing the mass of WEEE collected in a given year by the mass put on the market in the preceding three years. For 2014, collection rates were calculated by dividing the mass of WEEE generated in a given year by the mass of WEEE collected in that year within the Portuguese recycling infrastructure.[29] As of 2014, the average collection rate for all SACD fell between 37.0% and 40.0%.[29, 46-48] See Table S6 in the supporting information for detailed collection data by year and by product group including uncertainty.

**Preprocessing, $R_p(t)$.** To calculate material recovery and loss during preprocessing, we used data from sixteen preprocessing facilities within the recycling infrastructure of Portugal collected by one of the authors.[29] Among the 16 facilities, which comprise the outstanding majority of plants in the country, there was a wide range of material recovery percentages due to variances in their size and use of manual and mechanical separation operations. Smaller plants (twelve in total) relied mostly on manual operations to dismantle fractions for the purpose of recovering the PCB and any other valuable materials (i.e., copper). Medium sized plants (three in total) relied less on manual dismantling, and were equipped with medium sized shredders and separators for the processing, identification, and sorting of metals and plastics. For the sole large plant, a majority of WEEE processing was done in large shredders and separators (i.e., car shredders) along with other waste materials, such as end-of-life vehicles (WEEE generally represented only a small percentage of the feedstock).

As a part of the aforementioned thesis, full-scale batch tests were performed by our collaborators at the main operators in Portugal, representing more than 70% of the total installed capacity, to evaluate the industrial technologies used to preprocess the WEEE.[29] The shredded and dismantled pieces produced by these technologies were divided into the following material-level categories: ferrous, aluminium, copper, other metals, plastic, rubber, textiles, cement, glass, wood, and other. For the dPFA, the category labelled *other metals* was assumed to contain the following elements: Ag, Au, Pd, Pt, Co, Ni, Sn, Ta, W, and other nonferrous metals except aluminum. Using this dataset in conjunction with available literature, we determined the approximate material composition of all waste streams and the recovery percentages for all metals and non-metals. Material composition data for a device was broken down by product category and year manufactured. The two time periods used for mobile phones were 2001 – 2005[15, 21] and 2006 – 2014.[17-19] For the remainder of the devices, a single time period of 2001 – 2014 was used.[7, 13] See Tables S1-S5 of the supporting information for a breakdown of the material composition data used in the analysis, including uncertainty.

Preprocessing operators, facility providers, and equipment providers supplied the cost data on individual preprocessing operations within the Portuguese recycling system. The data were divided into fixed costs and variable costs by operation (manual and mechanical treatment) for each plant and varied based on the types of materials being targeted and processed.[29] The average fixed cost and variable cost to preprocess SACD (using a combination of manual and mechanical dismantling) was 10 to 80 USD/tonne and 125 to 175 USD/tonne, respectively. These cost data were compared to studies completed by WRAP[49], the WEEE Forum[47], Ramboll and Fichtner,[50] and the Department for Business, Innovation, and Skills (BIS) in the United Kingdom.[28] The purpose of this comparison was to analyze the relative costs of preprocessing throughout the EU, in order to verify the data collected from processors within the Portuguese system.

To calculate the potential profit lost during preprocessing we evaluated the economic value of the recovered and lost materials as a source of potential revenue. Values were assigned to each metal for each year based on annual data presented by the United States Geological Survey (USGS) and the United States Department of the Interior.[51, 52] All values were adjusted to 2010 USD to account for inflation. See Table S9 in the supporting information for a detailed breakdown of the material values used in the analysis.

# Results

The growth of the electronics industry, and in particular the increasing diversity of materials contained within SACD, provided a new opportunity to investigate economic potential for materials recovery at the device end-of-life. We focused on the perspective of the preprocessor, as facility infrastructure decisions at this stage of recycling hold significant impact for downstream materials recovery that results in secondary material markets. The results detailed below support the assertion that present day WEEE preprocessing is limited by inefficiencies that reduce potential revenues for operators.

Figure 3 shows the result of the product and material flow analysis by mass, depicting the quantity collected and then preprocessed over the years modelled. Here we provide an example for the mass of gold in computers spanning 2001 – 2014 where the vertical axis indicates the mass in tonnes in each year available upon generation (dashed line), after collection (dotted line) and after preprocessing (solid line). The line corresponding to the mass generated at end-of-life is a direct result of the dynamic PFA, and is derived from the assumed sales and lifetime distribution of the products. The model assumed collection began in 2006 as shown by the red arrow in Figure 3. Finally, the mass of gold recovered during preprocessing was based on the data for the 16 preprocessors in Portugal. The arrow labeled "loss during collection" reflects losses due to ineffective collection schemes and incomplete public awareness of and compliance with collection streams for end-of-life electronic goods. The arrow labeled "loss during preprocessing" represents operational inefficiencies that fail to target the high value materials locked in the devices' PCBs. These losses can occur during both manual dismantling and shredding. Based on our analysis, the largest loss of gold in 2014 was due to inefficient collection (over 3 tonnes of gold left unrecovered), however, the mass lost during preprocessing also represents significant economic potential (over 1 tonne of gold lost). The qualitative uncertainty represented by the shading in Figure 3 was calculated for the material composition, sales, collection, and preprocessing efficiency data, and carried throughout the analysis.

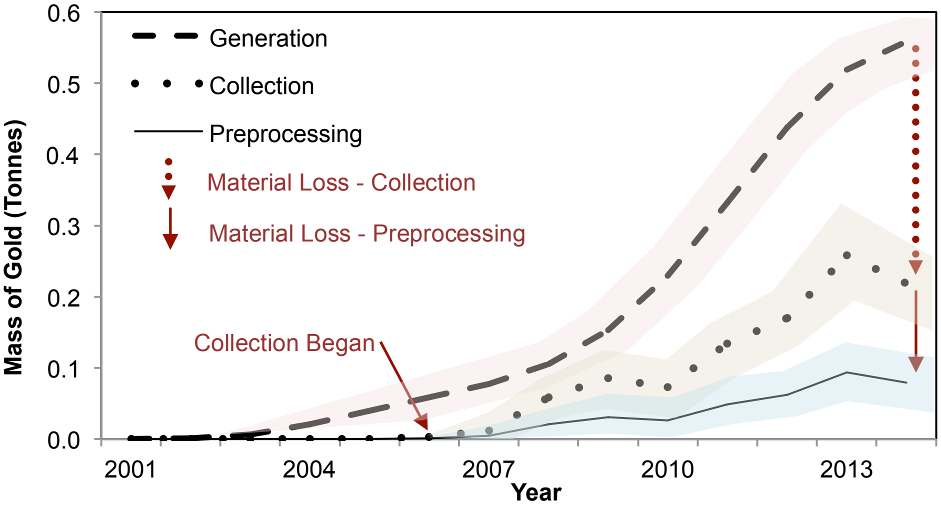

**Figure 3. Mass of gold from computers at the generation, collection, and preprocessing stages of recycling in Portugal over time. Arrows represent the materials losses incurred from inefficiencies during collection and preprocessing. All values for mass are derived from the material composition data in the PFA, and shading represents qualitative uncertainty.**

Figure 4a shows the individual market value by product group of materials recovered during preprocessing (silver, gold, palladium, copper, and tin) for each year in the first three levels: computers, mobile phones and printers. These trends over the years appear similar to those in Figure 3, but represent the total market value of each material independently in millions of USD. This figure represents the total value that is contained in the silver, gold, palladium, copper, and tin found in the end-of-life electronics that are recovered at the preprocessing facilities. Due to inefficient operational schemes, this value is lower than the potential recovery, as represented in Figure 4b, although there is significant uncertainty in these figures.

We see from Figure 4 that the recovery of mobile phones and computers is driven by the potential recovery of gold. This result is consistent with previous work that has indicated that gold is the most important metal contributing to increasing the economic value of recycling.[20, 53] The economics of printer recycling, on the other hand, is shown to be driven by the potential for recovery of copper. This is because the mass of gold in the PCBs of printers is smaller than that found in computers and mobile phones. Due to its larger size, the copper can be targeted more easily and removed from printer PCBs.[7]

Figure 4b uses the same materials price data but quantifies the value of the lost material corresponding to the arrow labeled "loss during preprocessing" found in Figure 3. For computers and mobile phones, the majority of lost value again is in the gold not recovered based primarily on incomplete separation of PCBs. Palladium is also a potentially valuable material stream to target for increased recovery within the computer and phone product groups. For printers, the losses were much less significant due to the high recovery rates of copper, but this analysis also indicates that the increased recovery of gold, palladium, and tin would have the greatest impact on reducing economic losses during preprocessing. The heterogeneity of the devices within each product group and the operations used during preprocessing introduce uncertainty into these results, with the largest contribution coming from the device composition data (For clarity, uncertainty is only shown for Figure 4b). However, even at the lower bounds of our uncertainty analysis, we found that the potential economic value not recovered in Portugal during the specified time period exceeded $70M for the materials shown.

The quantification of the value of materials recovery within SACD over time and by material demonstrates that a few key materials drive the recycling economics for electronic waste and that there are significant losses for the case of Portugal. Studies have shown that this is also the case for recycling systems in many other EU nations. Similar to the situation in Portugal, low collection rates mean that only a fraction of the potential end-of-life devices arrive at facilities able to separate and sort their contents, and that gold and other precious metals are key targets for making system wide improvements.[54, 55]

Figures 3 and 4 include data only up to 2014 for two reasons. The first is that the goal of the study was to analyze the current conditions of the recovery system, and to use that information to inform future decision making, not to make predictions. The second is that fluctuations in material prices made it difficult to project the economic implications of material losses into the future.

Figure 4 focused only on the first three categories; we next summarize this potential across all five product groups in Figure 5 and then discuss potential approaches for system improvement.

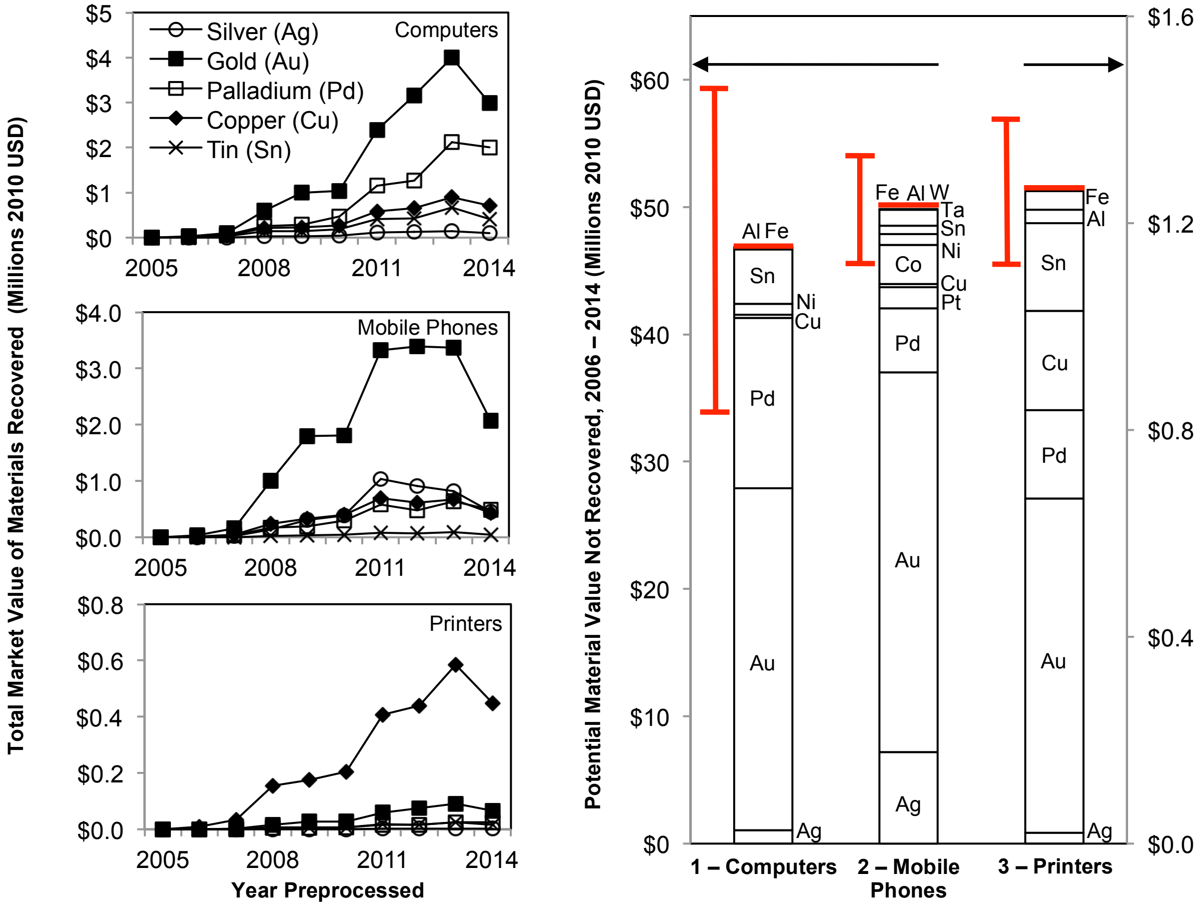

**Figure 4. (a) Total market value of materials recovered during preprocessing by product group in 2010 USD across 16 preprocessing plants within Portugal (b) Total potential market value not recovered by product group from 2006 – 2014 and the metals impacting the economic losses (Error bars represent one standard deviation). The values for computers and mobile phones are plotted on the primary y-axis, and the values for printers are plotted on the secondary y-axis.**

Figure 5a shows by product group, by mass (dotted, light grey), and by value (striped, dark grey), the percentage of material recovered from 2006 - 2014. These data were calculated using material recovery data within the PFA. Current EU legislation describes mass-based targets and Figure 5a shows that these mass targets - ranging from 65-75% according to the WEEE Directive - are met. However the value recovered is approximately 40-50% for all categories except for printers. Previous authors have highlighted this gap between the metrics of system performance as well, and noted that mass-based recycling targets do not encourage the targeting of precious metals and other valuable materials locked into complex devices.[20] Our work further supports this conclusion. Figure 5b shows that by value the lost potential per tonne for mobile phones is larger than the other categories studied because of the high value of the materials in the device PCBs and the smaller mass of the individual devices and total flow of materials. These results should be viewed as a way to compare across product categories rather than as absolute values, due to the uncertainties inherent in the assumptions used in the dPFA and the heterogeneity of preprocessing operations.

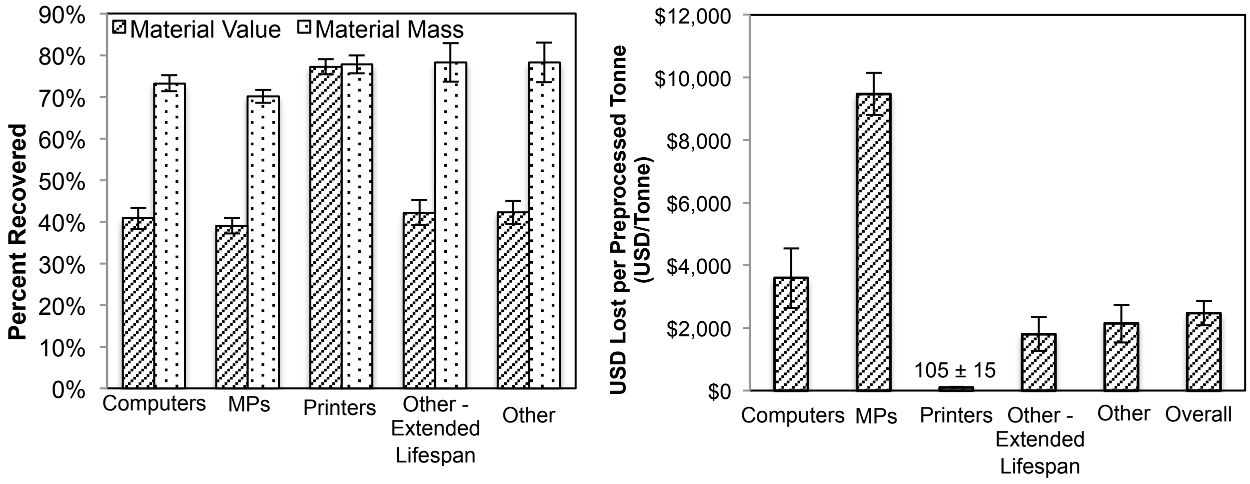

**Figure 5. (a) Comparison of material mass recovered versus material value recovered during preprocessing for all product groups as calculated in the recycling system PFA (b) Total 2010 USD lost per tonne of each product group that was preprocessed from 2006 – 2014 (Error bars represent one standard deviation).**

The results so far have shown that there is significant potential economic value not recovered from electronic waste in Portugal. The model framework developed here can be used to inform operational and investment decisions from the perspective of the preprocessor. Increased recovery of materials will come at a cost to the facility in the form of additional equipment or personnel. Our final analysis explores the impact of these potential investments.

The heterogeneity of the operations used by varying preprocessing plants presents challenges to optimizing recovery across recycling systems. However, the results presented in our analysis can provide useful insights into some of the tradeoffs between costs and recovery percentages for high value materials. Among the 16 plants studied, the major difference that we observed was the recovery of "other metals," which includes high value nonferrous metals such as gold, palladium, platinum and silver. This is due in large part to the fact that several of these plants are not equipped to remove the PCBs from devices effectively, either through manual or mechanical dismantling. For this analysis, we studied two primary operations, manual dismantling and shredding. In manual dismantling, workers remove valuable materials from larger devices such as laptops and printers and hazardous materials, such as the battery, from all devices. In mechanical dismantling, or shredding, devices that have gone through the manual dismantling step are shredded into pieces of varying sizes, and sorted using density-based, sensor, and other technologies. The degree to which these machines can identify and remove valuable materials plays a large role in the final economic output of the plant.

In order to make recommendations for future investments, we adopted several assumptions about the data. First, for Figure 6 below, we considered in detail the data from three of the 16 plants. Second, due to the low recovery rates and high values associated with so-called "other metals," we focused potential changes on fractions or processes containing other metals. In addition, based on fieldwork, we assumed that these plants had made process updates since they were analyzed fully in 2012. It is for this reason that high recovery rates are observed for several residual waste streams. Lastly, we assumed that the recovery rate of gold was the same as that for all “other metals” due to the fact that many of them are found in the PCB.

Figure 6 presents data from these three plants that could be used to inform future investments. Due to the complexity of these systems, any investments made would need to consider downstream impacts on other systems at the plants, evolving process inputs, material market prices, and many other factors. The horizontal axis indicates the material value of the entire output fraction containing other metals, divided by the tonnes of that fraction preprocessed by a given plant in a year. The vertical axis indicates the recovery percentage of other metals for a given fraction, divided by the fixed and variable costs associated with the preprocessing of that fraction. All values used in Figure 6 were calculated as a part of the dPFA in accordance with the previously described methodology. The points highest on the graph, shown in blue, represent those processes for which the largest amount of material can be recovered at the lowest cost. In this case, each of these points represents a manual dismantling process, due in large part to the low capital costs of hiring more people as compared to installing shredders and separators. Also, the further to the right that a point is located (points shown in orange), the higher the value of the materials contained in that fraction relative to the tonnes preprocessed. The orange highlighted area includes process streams from both manual and mechanical dismantling. These are significant because they represent fractions containing high value materials that have been targeted, even though the mass of that fraction is small in comparison to others, such as the ferrous metals. Therefore, the red arrow in the figure points to the desired area of the graph in terms of framing future investments, where high recovery percentages of valuable materials at the lowest costs occur. Overall, the vertical axis is concerned with the process that a given fraction undergoes during preprocessing, and the horizontal axis conveys the make-up and quantity of that fraction.

Downstream processing and refining was not included as a part of the present analysis, but it is necessary to consider the costs associated with these processes in order to make investment decisions. The costs of refining and recovery of metals from preprocessed fractions ranges from approximately \$500 to \$2,500 USD per tonne. Within this range, the cost of recovering the metals in PCBs is approximately \$1,500 USD per tonne.[29] These values are only assumptions, and may vary greatly across companies and treatment technologies used.

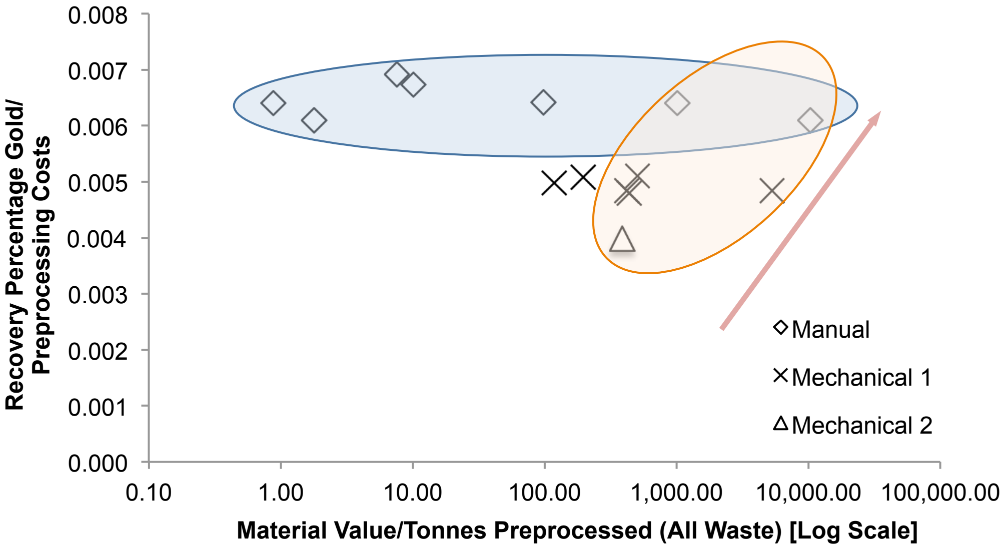

**Figure 6. Normalized process and material data showing the tradeoffs between recovery percentages, costs, material values, and tonnes preprocessed.**

Through this data-driven analysis, we identified opportunities for investment that could increase recovery and realize increased economic value of materials at the preprocessing stage of recycling. These findings are consistent with several studies completed in the past, and are strengthened by the addition of granular material market value data.[19, 21, 22, 26, 27, 56, 57] For example, incrementally adding workers to dismantle devices is the most effective way to increase the recovery percentages of "other metals" at the lowest up front cost. Additionally, making investments in mechanical dismantling that prioritize sorting operations post-shredding will have the largest impact on recovery rates, especially for those metals that are found in the PCB. This can be seen in the orange region, where most of the losses of other metals are due to PCBs that end up in waste streams. If facilities are able to minimize lost PCBs or recover other metals from material streams, then a higher economic value can be extracted. Certainly, the exact magnitude of any investments would need to be determined on a case-by-case basis depending on the location of the plant, the costs, the materials preprocessed, and several other factors. However, these findings provide a methodology and framework to identify specific operational and systems-level modifications that can drive decisions on the economic viability of materials recovery. The major implication of these findings for the preprocessing industry is the potential for an optimization of plant operations based not only on total mass recovered, but also on the economic value contained in the WEEE. We have also provided evidence for the importance of utilizing granular materials characterization data in the operational decision making process.

Overall, the key contributions of this work are twofold. First, we have quantified the economic value of materials lost due to inefficient preprocessing schemes for 16 plants in Portugal including uncertainty. The results presented as a part of this analysis can also be used to analyze preprocessing plants throughout the EU, as well as other regions and nations. Second, we have provided results that can be used to inform operational and investment decisions from the perspective of the preprocessor. Future work in this area could include an analysis of the economic implications of updating a specific process within a given plant on the final output and other processes at that plant and further downstream in the recycling system. In addition, future research on the effectiveness of specific operations to identify and remove valuable materials from complex input streams could help inform the decision-making schemes of preprocessors as to which materials to target. Such data-driven, material-specific analysis of this key recycling stage could aid a larger effort in efficient use of material resources that would have broad impact, albeit moderated strongly by regional policies and operations.

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# Supporting Information Available

Supporting information in the form of an 18-page pdf file including 9 tables is available at http://pubs.acs.org.

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