Original Equipment Manufacturer End-of-Life Equipment Collection Metrics

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Abstract— Electronics original equipment manufacturers are coming under increased scrutiny regarding their environmental performance, particularly around the issue of recycling. To address this pressure, companies need metrics that resolve the effectiveness of candidate recycling strategies. Such metrics not only provide guidance on the design and operation of recycling systems, but also serve to communicate the effectiveness of efforts to regulators and nongovernmental organizations. A methodology for a set of robust metrics is presented, designed to allow for comparison between companies. These metrics are based on both mass-based recycling rates normalized by present sales and sales based on product lifetime, along with value-weighted recycling rates that can correlate to environmental performance. These metrics provide insight on the performance of end-of-life electronics collection programs and how they might be compared to recycling of other waste streams, such as municipal solid waste.

Index Terms— end-of-life electronics, electronics waste collection programs, electronics waste, original equipment manufactures

I. Introduction

The responsibility for proper disposal of electronics waste has begun to fall, at least in part, on the original equipment manufacturers (OEMs) of these products. As policy makers and consumers demand further accountability from OEMs for proper end-of-life management, the ability for these companies to demonstrate effective recycling programs has become increasingly important. However, providing robust and diagnostic metrics to evaluate these collection and treatment programs has proven challenging for a variety reasons. There is currently no industry standard for how end-of-life electronics collection programs should be quantified [1]. Given the differences in their product lines, the various regions in which they operate, and the differences in each of their market shares, OEMs have developed a variety of strategies for encouraging and managing proper disposal of their products. Because of the differences in the availability and quality of data disparities arise in how OEMs measure and evaluate these collection programs.

There are complexities introduced by the differences in government policies regulating electronics waste on a country level as well as by the variety of state-based programs in the United States. Some of these applicable laws and regulations include the Home Appliance Recycling Law in Japan, the Waste Electrical and Electronic Equipment directive in Europe, and U.S. state-enacted recycling laws such as the Electronic Waste Recycling Act in California. These pieces of legislation provide a source of variation because OEMs operate in several different countries and therefore electronics collection programs may be established in direct response to a particular set of country-specific regulations. In the cases where policies or directives require a quantified level of participation, metrics become necessary to verify compliance. Disparities may arise if legislation in one country prescribes a different measure of compliance than in another country, requiring multiple metrics that may not translate readily from one system to another.

In order to evaluate collection efforts within a particular OEM, metrics need to inform the performance of individual programs. Internally, for a particular company, metrics provide an indication of the progress of program implementation, enable goal setting within a company, and promote auditing of downstream partners [2]. Challenges arise, even on an individual OEM level, when collection programs operate under separate business units. For example, differences arise when comparing systems that focus on residential versus commercial collection programs or efforts aimed at leased versus purchased products. This variation may confound comparison between years when determining whether goals are reached or if programs are effective. In some cases an aspect of a program that may lead to increased collection, such as a diversity of collection mechanisms (special events, donations, and business asset recovery), may also complicate data collection and comparison. Further problems arise when OEMs collect products of brands other than their own, although this may also improve overall collection rates.

Perhaps more importantly, comparisons between OEMs are a valuable part of the landscape, but without consistent reporting techniques, these comparisons are not meaningful. As fees are levied against OEMs through extended producer responsibility directives, a need arises

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for a common basis to calculate the magnitude of fees so that manufacturers are charged their "fair share". Discrepancies between brands arise if fees are apportioned based on sales of products versus number of products collected for actual recycling or reuse. For example, a study by the Florida Department of Environmental Protection demonstrated that the top brand, if fees were allocated by televisions received for recycling, would rank 10th in a system that allocated by products sold [3]. It is clear from this example that each of these allocations schemes would incentivize OEMs differently further demonstrating the need for a consistent and transparent set of metrics.

The large quantity of electronics at arriving at end-of-life each year along with the range of participants involved in the proper disposal of these electronics argues for the development of universally applied, diagnostic measures of OEM performance in end-of-life collection programs. As outlined above, several challenges arise in generating these metrics. A dialogue is emerging among companies, their stakeholders, and other interested parties. This work hopes to contribute to that conversation by developing a series of metrics that allow for comparison between OEMs and over time while considering the value of these products at end-of-life.

The remainder of this document presents examples of metrics currently in use and a methodology to generate a proposed set of metrics.

II. Examples of Current Metrics

It is informative to study the current metrics for end-of-life electronics collection by OEMs. Current metrics do not often afford the ability to compare performance between companies or even inform yearly progress within a particular company. Many metrics supplied by OEMs or state-run collection programs involve simply the mass of waste recovered. These metrics do not provide any information on how many products were available for recovery, so therefore do not convey how well the program performed. To provide this important point of relative performance, metrics can be normalized by current sales or sales some period of time prior to the reporting year. Often this prior period of time represents the lifetime of the product in question. Collection numbers normalized by "sales minus lifetime" paint a more realistic picture as those are the products that would be available for collection. However, assumptions on product lifetimes and retirement mechanisms enter into these values and may compromise their validity.

A. *Mass-based metrics*

To illustrate some current metrics for electronics waste recovery, the corporate social responsibility (CSR) reports of several major OEMs are referenced. OEMS note that challenges arise when calculating reuse and recycling rates versus the weight sold (based on the original sales year of the product) because of the variety in product lifetime influenced by product type and customer usage [4]. The 2006 and 2007 CSR reports for Dell provide the total weight in kilograms coming from various global Dell recycling programs [5], [6]. They demonstrate increased amounts between these two years, but these data are not normalized by products available for recovery in each of these years. In a separate metric they normalize the recovered products by sales 7 years ago and report this value as a percentage of sales, just over 12% for FY06 but do not include a value for FY07. These data are reproduced in Fig. 1 and Fig. 2.

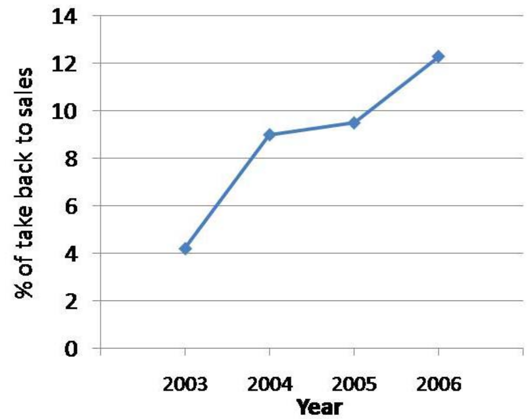

Fig 1. Comparison between units sold and returned or recovered, from Dell CSR report [5], [6].

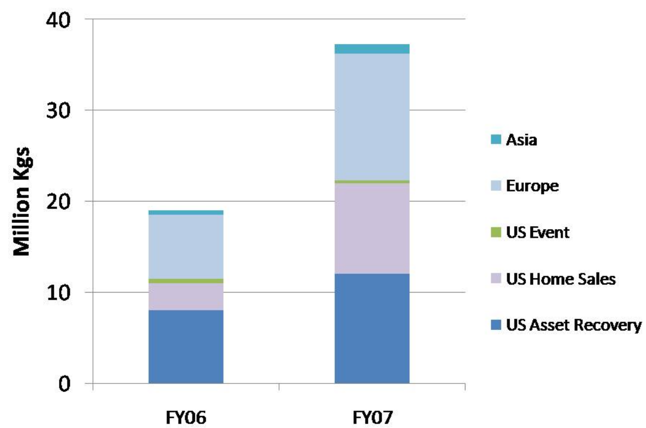

Fig 2. Reported collection by region, from Dell CSR report [6].

The variety in OEM collection programs within Dell complicates the gathering of data. They do not distinguish between recovery and recycling. Their top collection programs are asset recovery services for businesses, lease return, donation programs, and one day special events. Each of these programs may be managed differently, with programs running in several countries, resulting in a variety of data gathering approaches, quality, and resolution.

Sony reports their recycling activities by region and operates in partnership with Waste Management. In Japan they have joined a network of five other manufacturers and report results in terms of the ratio between products returned versus products sold 10 years ago for televisions and 7 years ago for personal computers. For 2006 in Japan this value was approximately 53% [2].

As another example, in its FY06 Global Citizenship Report, Hewlett-Packard describes recycling facilities in 45 countries and territories whose annual collection and recycling quantities were 165 million pounds of combined computer and hardware supplies. In addition, the report describes 2.4 million units collected for reuse, resulting in combined recycling and reused products equating to 10% of relevant sales [4]. They explain that these figures account for the time difference between when HP products are sold and when they are returned for reuse or recycling. However, they comment on the challenge of determining recycling metrics because of the variety in product lifetimes, especially when taking back products from a variety of manufacturers. They motivate the further exploration into metrics development explaining that experience with different types of metrics will determine the feasibility and usefulness of such metrics. In 2007, according to E-waste news, HP reported recycling almost 250 million lbs of its products, resulting in a 50% increase over 2006 [7].

HP's current methodology involves different normalizations depending on the product type. For example, *refurbished and reused* hardware products are estimated to be 2-4 years old; therefore, the hardware data is normalized against product sales for the yearly average of the preceding three years. Hardware products for *recycling*, however, are calculated against the yearly average of five through nine years [4]. These numbers are combined to provide an overall comparison to product sales.

There are examples of similar metrics reporting by various agencies. A report by As You Sow, a non-profit organization that advises socially responsible investing, performed such an analysis comparing Apple, Dell and HP [1]. This report compares the absolute take-back masses to previous sales numbers. The analysis made several assumptions, similar to those by OEMs in their CSR reports, including a seven-year product lifetime for all products and a constant weight of computers across the seven-year timeline. Continuing work by As You Sow highlights the challenge presented by calculating comparable metrics. For example, they explain that when comparing absolute weight of recycled computer equipment in a single year among five major companies, one company was the front runner, whereas using sales data for companies seven years prior results in a different leader among OEMs for collection [8].

The National Center for Electronics Recycling has developed an electronics recycling index that reports annual pounds collected per capita for several collection programs across the US including larger used consumer electronics in California, Maine, Delaware, Connecticut and Virginia. This is an unweighted metric that makes no differentiation between product types [9]. NCER also maintains a brand data management system that compiles OEM data when reported by a variety of state based programs. It reports a ranking based on total weight of products returned but lacks a normalizing element based on market share.

B. Value-based metrics

The previous section highlighted the variety of metrics used by OEMs and other interested parties to quantify the mass collection performance of end-of-life electronics collection strategies. This information is valuable for making comparisons between various OEMs. However, in making these comparisons, it is also important to include an understanding of the inherent value of the products to be managed. Another metric proposed here weights the materials in the product in question by value. Previous work has explored the role for comprehending *value*, signaled by economic value, in metrics for electronics waste programs [10]. This work and others [11] have asserted that the economic value of a secondary material could be a signal of its recyclability. The authors proposed a value-retained metric:

$$\frac{\sum_j Vp_j m_j}{\sum_i \sum_l Vm_{ki} m_{ki}} \tag{1}$$

where *Vp* and *Vm* describe the market value of the secondary and primary material, respectively [10]. The subscripts *i* and *j* represent values for inflows and outflows, respectively, and *k* represents the kth embedded material in a given flow. This metric provides a potential weighting factor for comprehending value in a recycling metric. Value-weighted metrics add insight into tradeoffs between recovery capabilities. Previous work comparing life cycle assessment and value-weighted metrics for several types of materials has indicated that value can be a proxy for environmental impact [12].

III. Proposed Metrics and Data Collection

This paper presents a methodology for gathering data on electronics waste collection and generating several metrics from this information. This section describes the methods used, and the next section provides an example of the metrics calculated.

Table 1 presents a summary of the proposed metrics. This includes a series of mass-based recycling rates, *MRs,* normalized by current and historical sales, alternately aggregated or separated by product category. The mass-based recycling rates take the form found in (2):

$$MR^{yc|ys} = \frac{M^{yc}_{n,C,RU|RC|T}}{M^{yc|ys}_{n,S,RU|RC|T}} \tag{2}$$

where the vertical bars indicate choices between the indicated parameters.

The following subscript definitions apply to (2):

n = individual product categories (or T for aggregated products)

C = collected amounts

S = sales amounts

$RU|RC|T$ = product fate Reuse, Recycle or Total (both reuse and recycled amounts)

The superscript *yc* indicates that the masses reported are from the year the masses were collected and the superscript *ys* indicates the masses reported were from the year the products were sold (accounts for the lifetime of the product). The superscript *ys* or *yc* on *MR* indicates which denominator value was chosen (M^{ys} or M^{yc}).

In addition, value-weighted recycling rates, *VRs*, are included that captures differences in market value between various product categories and between recycled versus reused products. The value-weighted recycling rates can also be broken down by product category or product fate (reuse vs. recycled) and were calculated according to (3):

$$VR^{yc|ys} = \frac{\sum_i \sum_n Vp_i m_{i,C,n,RU|RC|T}^{yc}}{\sum_i \sum_n Vm_i m_{i,C,n,RU|RC|T}^{ys|yc}} \quad (3)$$

where *i* represents each material present in each product *n* (monitor, TV, laptop). As mentioned previously, *Vp* and *Vm* describe the market value of the secondary and primary material, respectively. Besides *i*, the subscripts and superscripts for this metric are the same as those for *MR*. Similarly the superscripts on *VR* reflect which mass (*yc*: year collected or *ys*: year sold) is used in the denominator.

Table I. Metrics for end-of-life collection programs.

Mass-Based Recycling Rate, *MR*	
Broken Down By:	***Each Normalized By:***
Total Mass Collected	**Mass of sales in year product collected:** $M_{T,S,T}^{yc}$ **-or- Mass of sales in year(s) product sold:** $M_{T,S,T}^{ys}$
$M_{T,C,T}^{yc}$	
Reuse, Recycling	
$M_{T,C,RU\|RC}^{yc}$	
Product Category (incl. Total and Reuse, Recycling)	
$M_{n,C,RU\|RC\|T}^{yc}$	
Value-Weighted Recycling Rate, *VR*	
Mass-based metrics w/weighting based on economic value of reuse, recycling, material values (can be proxy for environmental performance)	

To generate these metrics a series of OEM specific data is required. The necessary data include sales data by electronic product category (including monitors, CPUs, laptops, and peripherals) along with the collection profile (mass collected broken down by product type and whether it was for reuse or recycling). This information will be combined with generic product data including product lifetimes and differences in value between reuse and recycling by product category. It is crucial to understand the details and context behind each number because of the differences in collection programs. The appropriate normalizations and assumptions must be understood so that comparisons between data can be made.

IV. A CASE STUDY OF METRICS CALCULATION

This example illustrates the calculation methodology for the proposed metrics based on data provided by hypothetical OEMs. These data are for a hypothetical company A and company B (B is a much smaller company) derived from actual collection data. The data include units sold by product and units collected for recycling at end-of-life. These data are based on representative trends for collection rates and sales data in the US and data published in CSR reports for various OEMs [13]. This study is meant to exemplify how the proposed metrics would be calculated and is not intended to represent the behavior of one particular firm. This example does not include reuse, which will be incorporated in future work. Reuse adds complexity based on the resale value for a product, which might be higher than the primary value of the materials going into that product.

Fig. 3 depicts two different normalizations of *MR* for company A and company B based on collection data. Plots for each company contain information on the total collection amounts followed by the breakdown of three products (monitors, TVs and laptops). The first set of metrics shown by the green bars in Fig. 3 was calculated by normalizing collection amounts by the sales data during the year of collection for that company MR^{yc}:

$$MR^{yc} = \frac{M_{n|T,C,T}^{yc}}{M_{n|T,S,T}^{yc}} \quad (4)$$

where n is either monitors, TVs or laptops. The second set was calculated by normalizing collection amounts by an estimated year the product was sold by that company (lifetimes assumed for each product in yrs: Monitor (8), Laptop (4), and TV (10)) MR^{ys}:

$$MR^{ys} = \frac{M_{n|T,C,T}^{yc}}{M_{n|T,S,T}^{ys}} \quad (5)$$

It is apparent from these data that normalizing by the year sold results in a higher calculated metric and should more accurately reflect the equipment that was available for collection in the year of interest. In addition, there are differences between calculated metrics for one product using the two normalization approaches, most clearly depicted in the case of laptops.

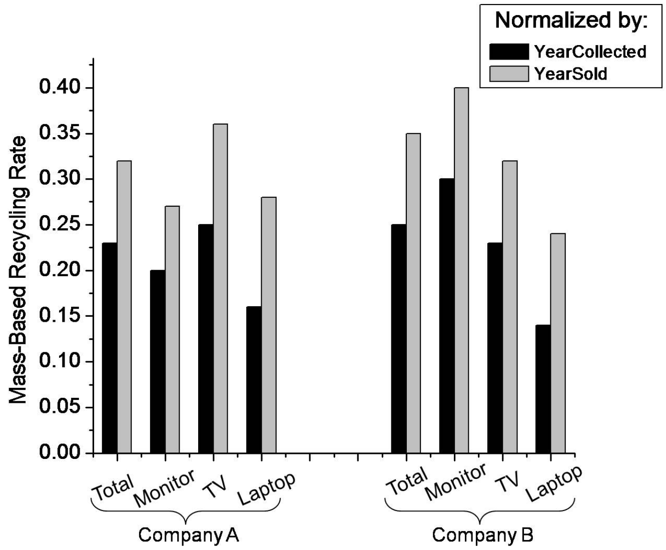

Fig. 3. Mass-based recycling rate for companies A and B, shown as a total and broken down by product. Each mass of collection is normalized by either: total mass year the product was collected (YearCollected) or the mass the year the product was sold (YearSold).

In addition, an environmental performance value, using a material's economic value as a proxy for environmental impact, was calculated based on the composition data for each product and economic values of primary and secondary materials. Each product was assigned a composition based on a product bill of materials [14] and publicly available materials scrap prices available [15]. Primary materials prices were collected from publicly-available data.

These values were scaled by the appropriate mass-based recycling rates to produce VR^{ys} as in (6):

$$VR^{ys} = \frac{\sum_i \sum_n Vp_i m^{yc}_{i,C,n,RC}}{\sum_i \sum_n Vm_i m^{ys}_{i,C,n,RC}} \quad (6)$$

where i represents each material present in each product n (monitor, TV, or laptop). The value-weighted recycling rate, VR^{ys}, for company A and B is presented in Fig. 4. The results for the full series of metrics generated from this data are also presented in Table 2.

These values were also compared to *VRs* for municipal solid waste (MSW) in the U.S., including: paper, aluminum, and two types of plastic (polyethylene, PET, and high density polyethylene, HDPE). For the MSW materials, mass-based recycling rates were found in [16]. These numbers are calculated based on materials collected in curbside recycling programs normalized by materials generated each year nationwide, from paper mills, for example. A similar environmental metric was calculated for paper, aluminum and plastic based on the primary and secondary values for each commodity and scaled to generate the comparable value-weighted recycling rate. The results of the MSW materials are added to both Fig. 4 and Table 2 for comparison with the electronics waste metrics.

These data indicate that when value is taken into account, electronics recycling programs perform on the same level, or perhaps outperform, some MSW commodities such as paper and plastic, despite their somewhat lower mass-based recycling rates. For example, the *MR* for paper equals 0.52 compared to the 0.28 *MR* for laptops from company A. Once the value of the laptop is added to the metric, the value-weighted rate comparison for paper versus laptops collected by company A becomes 0.06 and 0.16, respectively. The range of *VRs* for electronics from 0.13 to 0.19 is slightly higher than those of the plastics commodities described at 0.9-0.11. Aluminum still outperforms electronics recycling due to the high value of aluminum scrap along with the high recycling rates for this commodity.

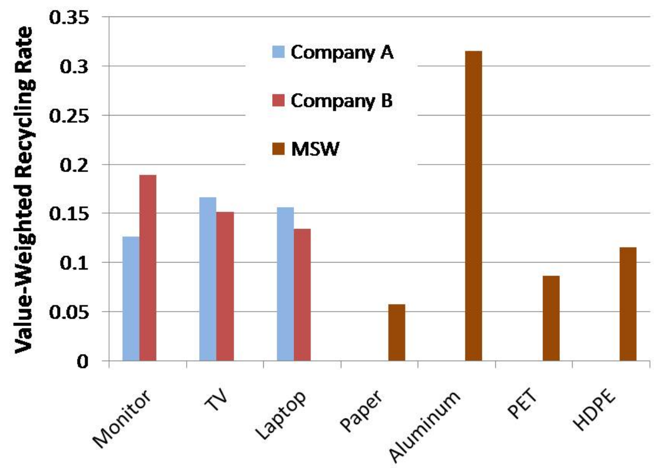

Fig. 4. Value-Weighted Recycling Rates for companies A and B compared to paper, aluminum and plastic.

Table II. Results of example metrics calculations including both *MR* and *VR* for electronics waste collection and MSW materials.

	MR		***VR***
	MR^{yc}	MR^{ys}	-
Company A	**0.23**	**0.32**	**-**
monitor	**0.20**	**0.27**	**0.13**
TV	**0.25**	**0.36**	**0.17**
laptop	**0.16**	**0.28**	**0.16**
Company B	**0.25**	**0.35**	**-**
monitor	**0.30**	**0.40**	**0.19**
TV	**0.23**	**0.32**	**0.15**
laptop	**0.14**	**0.24**	**0.13**
Paper	**0.52**		**0.06**
Aluminum	**0.45**		**0.32**
HDPE	**0.30**		**0.11**
PET	**0.30**		**0.09**

V. CONCLUSIONS

This study contributes to the development of diagnostic metrics of electronics waste equipment collection by OEMs by providing a methodology for generating these metrics

and proposing additional value-based metrics. If properly formulated, such metrics will enable comparisons and evaluations across programs and over time as well as provide a concise mode of communicating accomplishments by OEMs. As OEMs invest resources to improve their electronics collection programs, these metrics provide a benchmarking of that progress. In addition, these metrics can be used to drive design for recycling within companies as the amount of recyclable material per product increases.

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