Operational Sustainability Metrics: A Case of Electronics Recycling

by

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B.S. in Environmental Science
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Submitted to the Engineering Systems Division and the
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in Partial Fulfillment of the Requirements for the Degrees of

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Abstract

In the past 15 years corporations and governments have developed a growing appreciation of the need for "sustainability" and have worked the term into their goals, strategy and mission statements. Despite extensive efforts to define the term, there is still little clarity on how to move toward sustainability or measure improvements. Further advances toward sustainability will require system specific metrics to assess both current performance and the impact of operational, technological or regulatory changes on that performance.

Not only are there currently few operational metrics by which to practically assess progress toward sustainability, there is also very little understanding of how to judge the effectiveness of such metrics. Electronics recycling is used in this thesis as a case problem in developing and evaluating system specific performance metrics for sustainability.

Electronics recycling is a growing national and international concern due to the increasing volume of waste, the potential toxicity of the scrap, and reports of improper handling and disposal. Despite this concern, there is limited understanding about the electronics recycling system. There is a need for systematic ways to describe system functioning and quantitative methods to assess system performance. Existing evaluations of eco-efficiency or sustainability are either too aggregated to guide operational decisions or too complex and data intensive to be performed in the context of a low-margin system.

A range of performance metrics were developed and assessed for several electronics recycling operators. These included measures of resource recovery and environmental performance. These metrics were assessed for their ability to provide insights on resource efficiency comparable to more complex indicators, with minimal data required beyond that collected for normal business operations. The informative value of these metrics, their ability to capture system behavior, and the similarity between evaluations using different metrics were compared.

Recovery effectiveness results for three US Electronic recycling operators are presented based on several quantitative indicators. Results show that current simple measures such as "mass percent to landfill" are not sufficient to fully assess system performance. Composite indicators of systems performance can provide valuable insights even using currently available data collected by operators for business purposes.

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List of Acronyms

APC	American Plastics Council
BAN	Basel Action Network
CRT	Cathode Ray Tube
EIA	Electronics Industry Alliance
EPA	Environmental Protection Agency (US Government)
EoL	End of Life
EU	European Union
IAER	International Association of Electronics Recyclers
ISO	International Standards Organization
LCA	Life Cycle Analysis
MFF	Materials for the Future Foundation
MSW	Municipal Solid Waste
PC	Personal Computer
PWB	Printed Wire Board
RCRA	Resource Conservation and Recovery Act (US)
ROHS	Restriction of the use of certain Hazardous Substances
TCLP	Toxicity Characteristic Leaching Procedure
WEEE	Waste Electrical and Electronics Equipment

1. Introduction

This thesis uses the problem of electronics recycling to provide insights into measuring progress toward a sustainability objective. The issue of how best to deal with end-of-life electronics is a real, current, and messy problem based around a low value, high toxicity, complex waste stream about which there is little existing data and no comprehensive understanding. In contrast, discussions of sustainability have to date existed at a mostly theoretical level with many proclamations about aspects important to improving society, but very little practical help available to industries and societies making operational level decisions with regard to sustainability. This thesis uses electronics recycling as a case study to ground the discussion of sustainability in order to develop operational sustainability measures. These measures can help to better understand and evaluate the electronics recycling system while the process of developing, assessing, and applying these measures is applicable to the development of operational sustainability measures for other systems.

1.1 Sustainability - Why it Matters

The industrial revolution began in a world with abundant natural resource and relatively scarce human labor. The industrial revolution creatively addressed the limitations imposed on production by the need for human labor and its associated costs by finding ways to use natural resources, machines, and innovative manufacturing systems to increase the amount of work that one person could do. This dramatically increased productive output, but also greatly increased consumption of natural resources. After 250 years of technological advance, human labor is much more plentiful whereas there are many indications that both natural resources and the sinks for non-cyclical emissions may be approaching limits.

While years of directed effort have led to a very high labor productivity, resource productivity in the US in terms of GDP per unit of materials consumption has only moderately increased (Ayres, Ayres et al. 2003). Also since 1900 both the amount of material used per capita and total material consumption levels have steadily increased, with the great depression and WWII causing the only decrease (Wernick, Herman et al. 1996; Ayres, Ayres et al. 2003). Recognition that current trends cannot ultimately be sustained, and that the impacts of approaching limits are beginning to be felt, has led to growing interest from businesses, government, and individuals in sustainability.

While many see current trends as un-sustainable, there has been no clear consensus on what sustainability is. In general, sustainability as a concept is recognized as addressing the environmental, economic, and human components of taking care of society for the long term, in order to "Meet the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Employment and Development 1987). While this mantra provides general guidance, it does not and cannot provide sorely needed direction to guide specific improvements in industry or social systems. Thus efforts must be directed toward finding concrete ways to evaluate and guide progress toward "sustainability", with the understanding that increased focus and effort based on such measures should be able to move society closer to this ill-defined but critical objective.

1.2 Metrics for Sustainability

Many of the metrics used to measure progress in the industrial revolution are embedded in our society to the point that they are only infrequently questioned. However, as society's goals have shifted, these metrics may no longer be sufficient, and may direct society toward obsolete or incomplete objectives. It is commonly recognized in management that what is measured strongly influences outcomes; thus, society must have some quantitative measures of progress to guide decision making, despite the fundamental difficulties in doing so.

The effort to develop new measures of sustainability is the subject of much current study. However, this effort is complicated by the presence of two fundamentally different paradigms for sustainable development: in one, resource stocks are finite; while in the other, substitutability (between resources and human-made capital, or between different resources) and technological progress work to offset resource depletion in such a way that makes resource scarcity irrelevant (Tilton 1996). Over the last 25 years a significant body of literature has developed on both sides of the divide which is reviewed in (Pezzey and Toman 2002). These paradigms mark the extreme bounds of viewpoints in the discussion. Additional factors in the argument include differing values regarding intergenerational equity, the rights of other species, and "quality of life". These differing viewpoints make it so no measure is incontrovertible, and much effort is expended on the controversy.

The fundamental challenge is that sustainability cannot be measured directly. A system is not "sustainable" at any one point in time, and whether or not a current trend will be sustainable in the future requires un-available foresight on a multitude of social, technical and environmental factors. The sustainability of material use and recovery patterns is emblematic of this issue. Resource scarcity and the effectiveness of recovery at any point in time is a function of resource substitution, available technology and supply/demand economics at both local and global levels, and how these factors work to ameliorate the effects of resource use by (1) increasing regeneration rates, (2) making depletion of a particular resource less likely or less economically significant, or (3) increasing the capacity to minimize or buffer the effects of resource consumption (such as pollution from emissions, attendant impacts to climate change, eutrophication, etc.). Sustainability ultimately depends on interactions between these factors over a long time period.

While one cannot measure sustainability directly, it may be possible to observe the current state and evaluate the extent to which alternatives encourage or discourage progress toward a more sustainable system, in light of current knowledge of trends and possible system limits. As such, even in the absence of an absolute measure of sustainability, in many instances it should be possible to measure relatively whether activity A or activity B results in trends that bring the system closer or further from possible environmental limits (of resources or sinks) or specific social goals, all else being equal. Ultimately, the metrics and tools used must be able to evaluate the sustainability trends of a system and provide insight into the effect of changes (in operations, technology, etc).

Once we have moved beyond definitions, practical issues with measurement become the overriding concern. Like sustainability itself, many of the factors which could indicate whether or not a system is trending toward greater sustainability are also problematic to measure and forecast. Even with apparently simple measures, such as the mass of material flowing through a system, data collection is not assured. While sustainability remains a secondary priority to economic competitiveness the cost of additional data collection may not be considered justified. Also, those actors able to conduct the measurement may not be the same as those who want the information.

Not only are there currently few operational metrics by which to practically assess progress toward sustainability, there is also very little understanding of how to judge the effectiveness of such metrics. The process of developing more appropriate measures requires both a more critical assessment of new and existing metrics, and a period of trial and error. Few efforts to develop measures of sustainability have tested those measures on actual systems with real data.

This thesis will place those efforts into a framework and then apply a subset of sustainability metrics to a particular system to begin to evaluate the appropriateness of those measures. Electronics recycling is used as a case to examine the ability of simple or synthetic measures to provide an operational indication of progress toward sustainability. Realistically, there will never be sufficient data to truly measure sustainability in any system. Thus one critical question is how to move toward sustainability with less than optimal information – often far less. The electronics recycling industry is in need of better ways to assess all aspects of industry performance, with sustainability as the ultimate objective.

1.3 Electronics Recycling - Metrics to Evaluate an Industry

Disposal and recycling of electronics is a growing national and international concern. The generation of electronic waste is increasing at a more rapid rate than any other waste stream and the concentration of hazardous materials is higher in waste electronics than most other waste streams. In addition, both disposal and recycling practices can be environmentally damaging and contribute to poor worker health and safety. Public attention to the issue has been raised by a number of public reports critical of the industry, and both the industry and regulatory bodies are struggling with ways to assess best practices, characterize the system, and address the issues raised.

Public concerns have driven legislation and pilot projects on electronics recycling worldwide. New regulations on end-of-life (EoL) electronics in the EU, Japan, and many other countries address issues of Extended Producer Responsibility and EoL material handling and transport, with many new laws under development.

At the same time that electronics recycling is becoming a greater political imperative, the material value of electronics is steadily decreasing, making electronics more difficult and expensive to recycle. The consumer-driven progression toward smaller lighter electronics, increasing complexity, greater variety of products, and specialized materials within products all combine to make electronics harder to disassemble and recycle. The cost-cutting measure of reducing precious metal content also reduces the value of waste electronics to the recycler while the constantly changing end-of-life material stream makes it harder to optimize recycling efforts. Unlike automotive recycling, the value recovered from electronics materials does not cover the cost of recycling. Substantial discussions are underway about how to finance these recycling systems and what are the most preferable means of recycling to meet multiple objectives.

In general, recyclers need a better understanding of the environmental and social impacts of their processing choices or how these choices affect the demand for the materials they recover. Regulators need further insight into how constraints, which they might impose on a system, affect the performance of that system. Product designers need a better understanding of how product changes influence recovery.

While the overall objectives of electronics recycling are economic, environmental, and social (thus implicitly encompassing all aspects of sustainability), stakeholders have vastly different individual concerns. All industries have differing objectives among stakeholders; however in electronics recycling these differences create additional difficulty. The recycling industry has neither the interest nor funds available to report on an extensive set of metrics and those with the greatest ability to collect information have the least incentive to do so. The industry as it exists currently prefers asymmetrical information; recyclers are service providers that, for a fee, assure clients that the waste is diverted from landfill and should no longer concern them. After that the recycler is essentially free to do away with the material as they see fit so long as it does not return to haunt the client. The service provider's economically preferred methods are not always in line with the original environmental goals that drove recycling.

1.4 Central Questions (thesis roadmap)

A more complete understanding of the system and better means to evaluate progress would facilitate the move toward more effective recycling policies and Design for Environment (DfE) efforts. The objectives of this research are to characterize what makes effective metrics (for sustainability), to assess operational metrics for electronics recycling, and to provide a balanced characterization of the existing electronics recycling system.

The thesis will first identify characteristics of effective metrics for sustainability. Next it will characterize electronics recycling in the USA, and then it will provide an overview of metrics for sustainability to provide a basis from which to discuss the effectiveness of existing and alternative metrics for the case study. Rather than working with an exemplary industry with a sustainability focus and extra funds for data collection and training, the arguments about sustainability are grounded in the practical realities of trying to assess and make improvements in a low margin industry fraught with inconsistencies and poor data. The results from applying these metrics will be explored to see what can be learned in terms of (1) developing effective metrics for sustainability, (2) what metrics might be appropriate for the electronics industry, and (3) what value could be added by collecting additional data for alternative metrics. Ultimately, implications for product design and appropriate legislation will be discussed.

The overall issue of developing metrics for sustainability within the context of the electronics recycling industry is addressed through the four central questions outlined below.

1. What are the characteristics of effective metrics for sustainability? (Chapter 2)
2. How does the electronics recycling system work today? (Chapter 3)
3. Are existing recycling industry metrics effective in indicating whether the industry is moving toward sustainability, and are the alternative metrics evaluated "better" indicators for evaluating electronics recycling efforts? (Chapter 4,5)
4. What are implications of this research for appropriate metrology, legislation, and product design? (Chapter 6)

What are the characteristics of effective metrics for sustainability?

As discussed above, there is a substantial gap between announcing sustainability as a goal, and the ability of organizations, governments, and individuals to actualize that goal. Among the barriers to sustainability improvements is a lack of effective metrics to focus efforts and indicate progress. Chapter 2 of the thesis will provide an overview of current work toward defining and quantifying sustainability. Dimensions of merit will be identified and these criteria will be used to discuss the quality of existing and proposed metrics.

While metrics for social and economic aspects of sustainability will not be applied, the principles discussed for developing effective metrics should be illustrative and serve as a basis for future efforts to include those factors. For the purpose of completeness, social and economic aspects of the case system will be discussed, if not measured.

How does the electronics recycling system work today?

There is surprisingly poor characterization of the electronics recycling system in the USA. This thesis will pull together the existing literature, stories and statistics from recyclers, and data on material flows to provide a comprehensive snapshot of current practice and assess whether industry claims reflect actual operations. More particularly, Chapter 3 will explore the system in terms of the economics and practical operation of the system, material flows, legislative developments, and environmental implications.

Are existing recycling industry metrics effective in indicating whether the industry is moving toward sustainability, and are the alternative metrics evaluated "better" indicators for evaluating electronics recycling efforts?

The ways in which metrics are used by the sectors involved with end-of-life electronics can help or hinder general efforts toward sustainability of the industry. This section looks at operational metrics for sustainability from within the electronics recycling system. Because of their particular relevance to a material recovery focused industry, this thesis will focus primarily on measures to assess the environmental aspect of system sustainability performance. The characteristics of current metrics for sustainability and the strengths and weaknesses of these approaches will be discussed in Chapter 4.

In Chapter 5 a comparative analysis is made of metrics to evaluate recovery from individual recycling facilities. The efficacy of specific metrics in evaluating a material recovery system is compared using three primary criteria: the usefulness, robustness, and feasibility of the metric. Specifically, what metrics could give higher resolution for making current decisions at a reasonable cost?

The hypothesis is that current metrics and summaries provide neither a good characterization of system operation, nor a useful means to evaluate whether changes in system operation result in environmental (or sustainability) improvements. Rather, despite an underlying environmental goal, the current metrics in use in electronics recycling do not necessarily map toward sustainability, and obscure differences between facility operations.

What are implications of this research for appropriate metrology, legislation, and product design?

The final section will dispel commonly held myths about electronics recycling and discuss what lessons can be learned from the system characterization and the application of different metrics. Ultimately, these lessons must be transferred into improved design of products and more effective recycling regulations. Recommendations for actualizing these improvements based on an increased understanding of system operations are presented. These recommendations focus first on improving measurement and reporting from within the industry, then on policy regulation that take into account operational realities of the industry, and finally on improving design-for-end-of-life, which does not always mean design-for-recycling.

1.5 Research Methods and Data Collection

The methods used in this research involved a combination of surveys, interviews and literature reviews, as well as the development, testing and analysis of different measurement schemes for electronics recycling facilities.

To address the first of the four primary questions outlined above, an extensive literature review of sustainability indicators for business, industry, and material systems was performed. The literature search encompassed the the environmental economics literature and sustainability literature that specifically addressed industry. The literature search addressing question 2 focused on literature of the electronics industry and literature on electronics and the environment specifically. Table 1 provides a subset of the databases, journals, and search terms used for all literature searches. These lists are illustrative, not comprehensive, of the literature surveyed. Search terms were typically combinations of the words listed below and others.

Table 1: Literature search components (illustrative, not comprehensive)

Databases	• The Institute of Electrical and Electronics Engineers' IEEE Xplore • Science Direct • ProQuest • LexisNexis • scholar.google.com
Journals	• IEEE International Symposium on Electronics and the Environment • IEEE Transactions on Electronic Packaging Manufacture • Resources, Conservation and Recycling • Journal of Industrial Ecology • Journal of Cleaner Production • Resources Policy • Ecological Economics • Environment and Resource Economics • Environmental Science and Technology • Corporate Environmental Strategy
Search Terms	• Sustainability Metrics: metrics, measure, indicator, performance, operational, comparator; sustainability, environmental, social, energy, exergy • Electronics Recycling: recycling, recyclability, recovery, waste, export, reuse; material specific search terms

With the papers on sustainability metrics for industry, any criteria listed for developing effective metrics were tabulated, with selected criteria described in greater detail in Chapter 2. Indicators relevant specifically for material recovery systems are described in greater detail in Chapter 4.

1.6 Relevance of This Work

This research will test various metrics in order to find measures that can improve a recycling facility's understanding of their own material flows as well as allow for benchmarking amongst firms and among material recovery pathways. Improved measurement benefits both those directly involved in the recycling and those who make use of the measurements for evaluating and improving recycling pathways: recycling operators directly affect the performance of the system by improving operations; OEMs and municipalities are better able to evaluate available recycling alternatives and guide waste to more effective operators; DfR efforts are facilitated by an increased understanding of product design aspects problematic to recyclers; and regulators can use the results of these measures to construct system conditions/constraints which favor effective operations. A balanced description of the electronics recycling system and its economics, along with a methodology for assessing recycling system effectiveness, should facilitate reasoned discussions on recycling alternatives among all stakeholders.

In the long term it is hoped that this research into quantitative measures of system and operation performance for electronics recycling will lead to a model of recycling system behavior which will help reveal the impact of technological changes and provide feedback to designers / process operators. The primary aim of this thesis however, is to present an example of a useful approach toward developing effective operational sustainability indicators for a specific industry.

In addition to recycling, the approach described in this thesis for developing and evaluating operational metrics for sustainability could be applied to most other industries and systems. As discussed above, there is a great need for effective operational sustainability metrics in many different systems. A more rigorous development process for metrics and a means to evaluate their potential and actual effectiveness in practice would be of substantial benefit.

2. Sustainability Metrics

What are the characteristics of effective metrics for sustainability?

2.1 Defining Sustainability

Since early attempts to define sustainability over 15 years ago (World Commission on Employment and Development 1987), there has been extensive work toward reaching consensus on the definition of sustainability. Ultimately, many of these efforts have coined definitions of their own. Although these definitions (see Table 2) have many differences, overall they have a set of common foci. Sustainability is generally considered to encompass economic, environmental, *and* social factors and take into account the needs of the present while preserving the capacity to meet the needs of the future. Following this framework, sustainability thus includes both intergenerational issues such as environmental conservation & economic potential as well as intra-generational issues such as social equity & worker health and safety.

While the lack of a consistent definition can make analysis difficult, Herman Daly cited in (Definitions 2004) argued that:

> "Lack of a precise definition of the term 'sustainable development' is not all bad. It has allowed a considerable consensus to evolve in support of the idea that it is both morally and economically wrong to treat the world as a business in liquidation."

Most aspects of sustainability are difficult to define and measure. Nevertheless, real decisions are continuously being made with regard to the use, purchase, production, and design of products and processes that have real impact on that selfsame sustainability. Influencing those decisions cannot wait for unanimity. As such, the process of defining and developing measurable indicators for sustainability represents the next critical step and must begin if we are to move beyond words to more sustainable industries and societies.

Table 2: Definitions of Sustainability

Source	Definitions of Sustainability
Brundtland Report (World Commission on Employment and Development 1987)	"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."
(Thayer 1993)	"a characteristic of a process or state that can be maintained indefinitely."
(McCloskey 2005)	"Actions are sustainable if: • There is a balance between resources used and resources regenerated. • Resources are as clean or cleaner at end use as at beginning. • The viability, integrity, and diversity of natural systems are restored and maintained. • They lead to enhanced local and regional self-reliance. • They help create and maintain community and a culture of place. • Each generation preserves the legacies of future generations."
(The Global Development Research Center 2005)	"Sustainable development is maintaining a delicate balance between the human need to improve lifestyles and feeling of well-being on one hand, and preserving natural resources and ecosystems, on which we and future generations depend."

Source	Definitions of Sustainability
(Sustainable Measures 2005)	"There may be as many definitions of sustainability and sustainable development as there are groups trying to define it. All the definitions have to do with: • Living within the limits • Understanding the interconnections among economy, society, and environment • Equitable distribution of resources and opportunities However, different ways of defining sustainability are useful for different situations and different purposes."
(Veleva and Ellenbecker 2001)	"Sustainable Production is the creation of goods and services using processes and systems that are: non-polluting; conserving of energy and natural resources; economically efficient; safe and healthful for workers, communities, and consumers; and, socially and creatively rewarding for all working people."
(The Natural Step 2005)	"In a sustainable society, nature is not subject to systematically increasing: • concentrations of substances extracted from the earth's crust; • concentrations of substances produced by society; • degradation by physical means and, in that society. . . • human needs are met worldwide."

2.2 Measuring Sustainability

Metrics are universally critical to accomplishing any goal insofar as they implicitly or explicitly define: 1) system boundaries, 2) traits which are emphasized (or not), and 3) the definition of improvement. Hence, metrics significantly influence actions of individuals and firms. If metrics are inappropriate, goals and actions may be inconsistent, due to a skewed system understanding and over- or under-attention to issues. Examples of this within the recycling industry are given in Chapter 4. Sustainability will not be successfully incorporated into firm actions until there are effective ways to measure progress toward it (Handfield 2001).

While this section will include a discussion of metric frameworks that also applies to social and economic aspects of sustainability, the focus of this thesis will be on the environmental aspect. From an abstract perspective, environmental impact (EI) can be modeled as depending on relative rates of consumption and the impact per unit of consumption, as indicated by the I=PAT equation (Impact = Population x Affluence x Technology) developed by Ehrlich in the 1970s and modified by many (Chertow 2001). One adaptation helpful for this discussion is the industrial ecology "master equation", Eq. 1, (Graedel and Allenby 1995).

$$\mathrm{EI} = Population \times \frac{GDP}{Person} \times \frac{ResourceUse}{UnitGDP} \qquad \textbf{(Eq. 1)}$$

In terms of Eq. 1, total consumption is composed of population and per capita consumption (*GDP/person*), while all impacts per unit of consumption are described by the term *ResourceUse/UnitGDP*.

A comparable measure for the environmental aspects of sustainability would have to include not only impact, but the capacity of the system to absorb that impact without reducing the ability of future generations to meet their own needs as per most definitions of sustainability. Eq. 2, which provides a measure for the sustaining of x, does this so long as x can apply to any of the following:

1. a resource extracted and the regeneration rate for that resource

2. an emission and the sink for that emission
3. utility provided by consumption and the total capacity to provide that utility

Thus $UseRate_x$ is the rate at which x is (1) depleted, (2) emitted, or (3) provided, while $CarryingCapacity_x$ is the rate at which x is (1) regenerated, (2) benignly re-absorbed, (3) made possible through new alternative means.

$$\%Sustainability_x = \frac{\int_{t=0}^{t=\infty} UseRate_x}{\int_{t=0}^{t=\infty} CarryingCapacity_x} \qquad \textbf{(Eq. 2)}$$

At its simplest, Eq. 2 establishes that a system is sustainable over a long time period, so long as the net use of x over that time period does not exceed the carrying capacity of x over the same time period (Figure 1). Some degree of fluctuation is perfectly acceptable however.

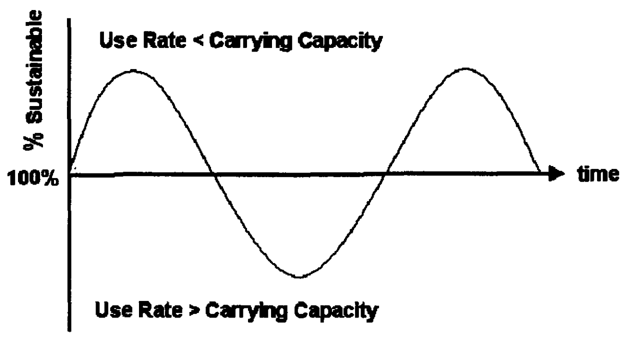

Figure 1: "Percent sustainable" measured over time

The two paradigms for sustainable development described in Chapter 1 present a complication to this picture. In what is generally the point of view of environmental science, resource stocks are finite. In this view, termed "strong sustainability" sustainability requires that "different types of capital (economic, ecological, and social) should be independently maintained" (Ayres, Bergh et al. 1998) indefinitely for future generations. In this view natural capital is seen as the foundation on which all economic activity is based; that "the economy is a wholly owned subsidiary of the environment, not the other way around" (Nelson 2002). The extreme of this view is that there is no substitutability between species, physical stocks, or ecosystem processes.

Ultimately, this viewpoint of strong sustainability is true; if all stocks were maintained there would be no loss of capacity for future generations. However, achieving this is unlikely to be optimal, or even possible. First, natural systems (without humans) do change, and there is some degree of substitutability across elements of the biosphere through adaptation and redundancy (e.g., multiple species occupying the same or similar niches). Secondly, this would require the cessation of use of non-renewables such as metals, oil, coal, and gas, on which so much of our society depends.

In a working definition of sustainability, therefore, there must be some allowance for the substitutability of different resources. Once again, at the extreme, the weak sustainability argument also becomes absurd. In this view substitutability (between resources and human-made capital, or between different resources) and technological progress work to offset resource depletion in such a way that makes resource scarcity irrelevant (Tilton 1996). The failure of Biosphere II ((CNN 2005) and other examples clearly illustrate that humanity has not yet come close to being able to replicate and replace fundamental ecosystem services. However, declining resource prices and numerous other examples show how technological progress and substitutability work to remove potential environmental constraints.

A framework that allows for some flexibility between the two paradigms (or at least allows them to coexist) is as follows.

In Eq. 2 above, and illustrated in Figure 2 below,

UseRate is a function of:

- population
- consumption (GDP/person)
- resource efficiency (resource/GDP or /service)
- substitution (extent to which resource B is utilized instead of resource A to meet a need),

and *Carryingcapacity* (rate) is a function of:

- the natural regeneration rate
    - Resource: the natural renewal of the resource
    - Sink: the capacity to absorb emissions without relevant impact
    - Utility: the aggregate renewal rate of all materials that provide the specified function
- the amelioration rate
    - Resource: the anthropogenic regeneration rate (recycling, etc)
    - Sink: the capacity to render emissions harmless
    - Utility: the aggregate anthropogenic regeneration rate for all materials that provide the specified function, and the rate at which technology develops new means of providing the specified function (substitution).

Using Eq. 2 to discuss utility is the most comprehensive approach and allows both paradigms to coexist. Using utility x as the quantity of concern, one might examine the societal need for lightweight and strong electrical conductivity. This function has a utility for society and aluminum is well suited to that function. However, it is inappropriate to simply look at sustainability of aluminum (resource), but rather the ability of society to provide that function over a long time period. Thus, the carrying capacity is an aggregate capacity for all materials that can provide that function. Thus, substitutability affects carrying capacity rather than use rate.

For resources which are not part of most biological systems, and, as far as we can tell, are only actively utilized in human systems, evaluating carrying capacity for utility x is a useful approach. For resources such as light metals the carrying capacity is defined, appropriately, in anthropogenic terms. However, for resources such as trees (and forests) this approach becomes much more problematic. One could look at the carrying capacity for all materials that provide the function of heating; wood, oil, gas, and coal would all be substitutes for each other with the carrying capacity an aggregate of these. However, trees also provide numerous other functions including carbon sequestration, air purification, humus building, and habitat. An approach that attempts to evaluate the sustainability of each and all of these functions and all of the tree substitutes that can provide these functions would be difficult, if not impossible. For trees, then, a simpler and more appropriate response is to measure sustainability in terms of the individual resource, not the many functions the resource provides.

An increasingly sustainable society, therefore, would be one in which the use of biologically relevant resources and pollutant sinks would be monitored in terms of a "stronger" sustainability paradigm, whereas primarily anthropogenically relevant resources would be monitored in terms of a "weaker" sustainability paradigm, with the extent to which substitutability is considered dependent on the number and kind of uses for which a resource is of some utility.

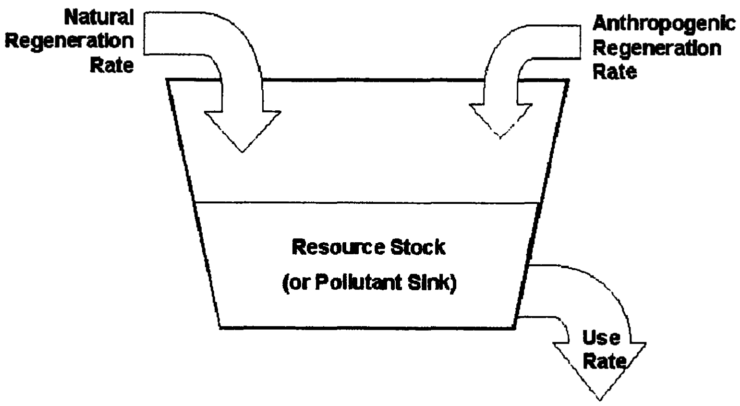

Figure 2: Stocks and flow view of Eq. 2

While this framework will not be used explicitly in the measures described and assessed in this thesis, the framework is one which should allow efforts to measure sustainability to integrate the two sustainability paradigm extremes in a useful way. Even with this framework however, the challenge is that sustainability cannot be measured directly and therefore both paradigm extremes remain strong. A system is not "sustainable" at any one point in time, and whether or not a current trend will be sustainable in the future requires un-available foresight on a multitude of social, technical and environmental factors.

The impact of technological development comes in many forms:

- Impact and Efficiency: the direct impact per unit of new technology or per unit of consumption affected by that technology (material selection for products, recycling, efficiency measures, development of a of a less emissive energy source, etc)
- Amelioration: the ability to reverse or remedy environmental impacts per unit of technology (through remediation, carbon sequestration technologies etc)
- Capacity: the size of the resource stock or sink (for example by increasing the economically feasible reserves through mining technology
- Substitution: expanding the resource base that can provide a function.

The significance of the impact is altered by the rate and form of technological development, which is difficult to predict. It is just as difficult to forecast potential constraints – such as technological potentials for improvement, availability of new sources and sinks for materials and also rates of regeneration/recovery – on which rides the relative importance of resource recovery.

Thus, there are both theoretical and practical difficulties to measuring sustainability. At the theoretical level, it can be posited that sustainability is not directly measurable. This is because it is not an end state. Rather, it depends upon relative rates of consumption and technology development of different forms. In addition, predicting the influence of technology may be impossible – those who do so often simply follow their natural tendencies toward pessimism or optimism without providing much illumination to the situation as a whole.

However, even without predicting technological development and its impacts, using this framework as a guide it should be possible to identify certain characteristics of a sustainable system and to measure whether a system is improving or declining – moving closer to or further from sustainability, all else being equal. This ability to recognize and measure trends is critical, for if our efforts are to move us closer to sustainability, it is critical to have metrics that enable people to begin to evaluate the impacts of changing practices, processes, design conditions, and technology. This thesis is based on the premise that imperfect practical measures *in use* are more valuable than idealized indicators that cannot be measured in practice. This premise agrees that "it is better to measure the right things approximately than the wrong ones with great accuracy and precision" (Veleva and Ellenbecker 2001) and (Vollmann 1996).

Along those lines, if proxy measures can be found which can provide insights into sustainability but are simple enough for continuous use, they would be a critical addition to the analytical toolbox. These proxies would complement more data intensive measures that would still be used to provide strategic insights and as a check to ensure that use of the proxy remains appropriate over time.

2.3 Proposed Sustainability Metrics and Frameworks

For sustainability, as with all new measurement frameworks, there is both a development process and an adjustment period. Some analysis on changes to product design methods suggests that, because Design-for-Environment (DfE) is a relatively new concept, it must pass through a number of difficult phases before it becomes de rigueur as part of the design process (Sandborn and Murphy 1997). This observation would reasonably extend to the consideration of a complex concept such as sustainability.

One development framework (Sandborn and Murphy 1997) suggests that the maturity of "Design for X" activities progresses through three phases:

1. Problem articulation with few metrics.
2. Formation of a concise metrology for measuring the magnitude of the problem on an application specific basis.
3. Linking the metrology to the product design cycle and mapping the metrology to economic impact.

In 1997, this author suggested that environmental considerations for product design were beginning to move from step 1 to step 2. In 2005 it appears that overall movement toward measuring sustainability has passed the first phase, with general agreement over the problem and definition, but has not yet achieved the second phase. A number of indicator frameworks have been developed for reporting by companies and nations, and some industries have begun to define operational metrics, but with little consistency or uniformity. The current use of environmental and sustainability indicators "shows little standardization and...[the field] is highly diversified with approaches based on LCA, economics, management accounting, ecology and a physical gate-to-gate analysis...little comparability exists currently" (Olsthoorn, Tyteca et al. 2001).

Several papers on sustainability metrics differentiate between core (applicable in all cases) and supplemental (applicable to specific cases) indicators (WBCSD 2000; Veleva and Ellenbecker 2001; Global Reporting Initiative 2002), while many papers simply provide a broad scope of possible metrics (Wernick and Ausubel 1995; Wernick 1995; Kuhre 1998; National Academy of Engineering 1999; Olsthoorn, Tyteca et al. 2001; Wall and Gong 2001; Azapagic 2003; Sikdar 2003) While most authors recognize that no company could complete all of these metrics, there is little insight for how a company would pick and implement these metrics, and only a few case studies describing this implementation (O'Rourke, Sunér et al. 2000; Veleva, Bailey et al. 2001). There have been few comparative critiques of metric alternatives (Emblemsvag and Bras 2001; Luo, Wirojanagud et al. 2001) and no systematic studies comparing the relative efficacy of measures or whether these metrics provide consistent indications of system behavior. Given this state of the research, it would be reasonable to characterize sustainability-motivated decision frameworks as migrating from Sandborn's Stage 1 to Stage 2.

Broad reviews of existing sustainability metrics and metric frameworks exist (GEMI 1998; Emblemsvag and Bras 2001). Rather than replicating those efforts here, this chapter will focus on clarifying approaches toward developing a useful set of metrics for a particular area of application out of the plethora of general metric options presented in the literature. What follows is a discussion of 1) the criteria for effective metrics, 2) an approach to developing a useful set of metrics, and 3) in Chapter 4, a focused literature review of metrics that could address material resource use at the facility level. Chapter 5 will take this general discussion and put it into practice, applying and evaluating a simple set of metrics for use in electronics recycling facilities.

Selecting appropriate metrics requires first articulating the decision and/or goal that the metric will inform, and then finding the appropriate measure for that purpose. In order to clarify this discussion, the metrics and metric sets described will be placed in the framework shown in Figure 3. This framework illustrates the scope, assessment level, and sustainability area considered by the metric. The scope category is intended to determine the boundaries for the metric, whereas the assessment level and sustainability area provide the realm of application.

The substance section within the scope category refers to a specific mass type or a collection of mass that is of interest and is not necessarily constrained by geographic or economic boundaries. The product classification typically encompasses life cycle metrics. A natural system could be an ecosystem. A material system consists of the flows of a material through various economic, industrial, and geographic paths. With regard to electronics recycling and the operational methods used by firms to recovery materials, it is material systems as well as the firm, facility, and process classifications that are most relevant. The other classifications are included in the framework for completeness.

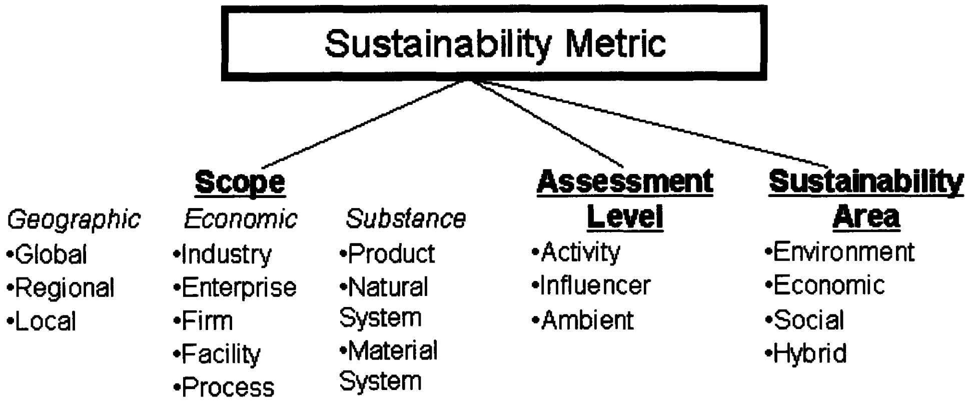

Figure 3: Framework for Sustainability Metrics

The assessment level category specifies the application area of the metric. First, the activity classification is broadly defined so that it includes items such as operations within a facility or the use phase of a product. Second, the influencer assessment level is geared towards metrics that are used by managers or policy-makers to assist in decision-making processes. Third, the ambient classification is used for metrics that are related to the state of the "external" environment (external to anthropogenic structures), such as the toxicity of a lake or the acidification of air.

Finally, the sustainability area category defines the metric's topic of concern as it relates to sustainability. Metrics typically fall into the traditional areas of environmental, economic, or social sustainability, but there are often cases where a metric is actually a hybrid of two classifications, as is the case for an eco-efficiency metric, which is an environment/economic hybrid. Normalization of metrics often results in hybrid metrics.

While ideally metrics would be able to be used at all scopes and assessment levels, this is rarely if ever possible. The same general indicator may be used in multiple contexts, but often these measures will differ in the specifics in order to meet the needs and data of a particular application. The metrics in this study, outlined in Chapter 4 and applied in Chapter 5, were evaluated for use at the facility level scope to evaluate the environmental sustainability area (at times with a hybrid approach). The measures are at the activity assessment level; designed to assess facility operations and best practices for material processing and recovery pathways.

For a metric to be effective in application, it must meet several qualitative criteria. These criteria are the topic of the next section. In addition, the quantitative structure of the measure must be carefully selected.

2.4 Criteria for Metrics

As discussed above, metrics are universally critical to accomplishing any goal. However, in order for metrics to help in accomplishing goals they must be of reasonable quality and actually used. Unfortunately, identifying quality and effectiveness can be difficult. There have been a number of attempts to begin to define the dimensions of merit for sustainability metrics, and ultimately determine what makes a "good" metric. Criteria mentioned in the literature on sustainability metrics are catalogued in Table 3. Ultimately, a successful metric must be (1) useful, (2) feasible, and (3) robust. The criteria listed in the literature fit within these three categories. In addition to these three fundamental characteristics, a number of criteria have been proposed to address the development of an appropriate *set* of metrics. These criteria also could be described as contributing to the measurement systems usefulness, feasibility, and robustness; however, they are listed separately for clarity.

Table 3: Criteria for metrics mentioned in literature

Criteria	Discussed in
USEFUL	
1. Simple, Easy to apply (user friendly)	A, E, F, H
2. Understandable, easy to interpret, evaluate	A,C,E, F, H
3. Useful (appropriate to task and goals/objectives, relevant)	A, E,C, H
4. Diagnostic	F, H, I
5. Facilitate the use of econometric and statistical tools	I
6. Responsive to change, contribute to prediction, analyze trends, ("able to measure progress over time")	H, K
7. Have associated reference value, benchmarkable	F, K
8. Private/protective of data	A
9. Allows for cross-company, other meaningful comparisons (geographic units, facility, industry, process)	E, C, F, H
10. Consistent with other relevant indicator sets	E, F
11. Can be integrated with other information (economic, forecasting, information systems)	F
12. Represent environmental conditions & impacts & responses	F
FEASIBLE	
13. Cost Effective, based on available, accurate data	A,E, C, F, H,K
14. Based on data regularly updated of known (good) quality	F, G?, I
ROBUST	
15. Reproducible, verifiable	A, E, K
16. Robust and Nonperverse	A
17. Modular/Stackable (can be aggregated to different scopes, scales)	A
18. Based on international standards, with consensus on validity	F
19. Clear system boundaries	B
20. Clear uniform definition of indicator & uniform data collection	G
21. Objective	C
22. Subjective elements explicit	B
23. Stakeholder involvement in indicator development, and/or responsive to stakeholder expectations	E, C, K
Criteria for metric frameworks/sets	
24. Manageable number, but a set – not a single indicator	E
25. Compromised of core and supplemental indicators	E (others?)
26. Addresses all key issues and aspects, representative	E,C, K, H, I
27. Metrics independent	C,D
28. Uses both qualitative and quantitative indicators	E

References used in Table 3:
A: (Schwartz, Beloff et al. 2002)
B: (Newell 1998)
C: (Olsthoorn, Tyteca et al. 2001)
D: (Sikdar 2003)
E: (Veleva and Ellenbecker 2001)
F: (Persson) referencing OECD
G: (Verschoor and Reijnders 2001)
H: (Warhurst 2002)
I: (Hardi and DeSouza-Huletey 2000)
J: (von Bahr, Hanssen et al. 2003)
K: (Keeble, Topiol et al. 2003)
L: (Handfield 2001)

A short list of criteria (Table 4) was distilled from the list catalogued above. The short list is generic, and intended to cover the basic elements needed in any indicator. Criteria that were not uniformly relevant or that were redundant were excluded. Together, these criteria should allow for reasonable and reproducible comparison or ranking of candidate indicators. Many of these criteria however, do not have a quantitative measure. Whether such objective criteria for indicators could or should be developed is an open question. These criteria are used as a qualitative guide to discuss the metrics explored in Chapter 4 and those applied to the electronics recycling case in Chapter 5.

Table 4: Shortlist of indicators

USEFUL
1. Addresses clear goal
2. Simple/Specific
3. Diagnostic
4. Comparable (consistent & compatible with other relevant indicator sets and data)

ROBUST
5. Subjective elements explicit
6. Reproducible (clear boundary definitions, calculation & data collection methods)
7. Nonperverse
8. Quality data available (accurate and updated)

FEASIBLE
9. Cost effectively Measurable

While some of these criteria may appear obviously necessary, there are nonetheless many suggested indicators that do not meet these standards. Those designing and selecting indicators would do well to keep this or another set of standards on hand for reference. A brief explanation of each criterion follows.

2.4.1 Useful

1. Addresses Clear Goal

Stating a goal for an indicator ensures that there is a clear understanding of the desired change in the indicator (increase or decrease) that will lead to sustainability (Kuhre 1998; WBCSD 2000; Veleva and Ellenbecker 2001). Additionally, measuring without a clear associated goal can result in diversion of limited data collection resources for extraneous measurement, and a focus on the metric rather than the underlying improvement objective.

2. Simple/Specific

Too frequently, those designing metrics appear to prefer the ideal and comprehensive measure, to the simple measure that would suffice. As with so many things, the "80/20 rule" is a useful heuristic for metric development. Often the purpose for which a measure is developed is served by taking 20% of the work to capture 80% of the phenomena. Too often, however, the effort to capture 100% of the phenomena through use of a more complex measure that requires doing another 80% of the work results in the abandonment of the effort so that none of the phenomena is ultimately captured. Simple measures are more likely to be adopted, and rapidly implemented. It is easier to track down spurious results or identify any perverse issues and there is less computational expense from their use.

The same rule applies to developing a set of measures. Some authors attempt to develop an all-inclusive set of indicators, whereas other researchers attempt to find a single indicator which will encompass all issues. It is likely that an intermediate approach will be most effective where industries, companies, etc, choose a short set of integrative and proxy metrics to account for as much of the issues as possible without overwhelming their data collection capacity and budget, or ability to assess and make changes. For this reason, there needs to be a framework for evaluating metrology and adjusting it as needed.

3& 4. Diagnostic and Comparable

The purpose of measurement is to enable comparison and problem solving. Good metrics are capable of facilitating both activities. However, a significant fraction of proposed sustainability indicators seem unable to assist with either.

To be diagnostic, a metric must facilitate the identification of patterns in metric results, development of hypotheses, and the determination of causation that underlies differences in metric values.

To be comparable, a metric must be consistent (reproducible: see criteria #6) and compatible, or useful in conjunction with other relevant indicator sets and data. Consistency allows benchmarking (across or within a facility), whereas metrics that can be used in conjunction with other measures facilitate a broader level of analysis and thus are of greatly increased value. Achieving comparability often involves some form of standardization, as discussed below.

> "...metrics are not meant simply to compile information. Their purpose is to embed the data in a context that recognizes the larger system and is relevant to how it works...To adequately respond to complex questions of environmental performance requires both context and an array of metrics." (Wernick and Ausubel 1995)

2.4.2 Robust

5. Subjective Elements Explicit

In a broad assessment like sustainability, there are inevitably multiple contributing factors which must somehow be evaluated together. Ultimately there must be some way to deal with the inherent tradeoffs among these factors. The way in which different contributing factors are made commensurate can impact measure results.

For example, with measures of environmental impact there is often a need to convert physical data (such as weight of chemicals) into impact data through a potency factor. This weighting allows impacts to be compared, but also introduces subjective or normative elements into the evaluation.

Unless these elements are made explicit, it can be difficult to assess why different measures give different results. Because the final score in many Life Cycle Assessments (LCAs) is dependent on the weighting system for the metric, the priorities of the tool's creator, rather than an agreed standard or the priorities of the tool user, can determine the measure's results and thus alter the decision made. There have been some attempts to correct for this directly (Newell 1998), while other LCA tools simply allow the user to choose multiple weighting systems for comparison or allow the user to alter the weighting scheme to check sensitivity of the results. These adjustments increase the utility of the indicator by clarifying the subjective elements of the process.

For social indicators, there are even more substantial subjective and normative elements, increasing the need to be explicit, and also to consider how embedded priorities are chosen (discussed in the section below on stakeholder involvement).

6. Reproducible

Achieving consistency requires a sufficiently simple measurement process, with less room for re-interpretation of metric factors such as system boundaries and modeling approach. Reproducibility requires clear boundary definitions, calculation, and data collection methods.

As a more general test of robustness, it is also informative to assess the level of cross-metric consistency. Do metrics that are purported to measure the same phenomena actually give consistent results, at least to the level required for consistent decision-making? If not, why not? Are there hidden values assumptions which cause the differences – how much do those have to change to create consistency? Are slightly different phenomena assessed?

Differences between measures' results may be workable if the context for their divergence is understood, otherwise it will lead to confusion. However, ones confidence in a measurement result should increase if a number of metrics give similar results.

7. Non-perverse

There are three primary ways in which a metric may ultimately be 'perverse'.

(1) If a metric measures a conflicted goal where either an increase or a decrease could be considered positive. For instance, the number of jobs per value added. In this case, management's traditional economic goal would be to lower this number, whereas the sustainability objective would be to increase job creation.

(2) If a metric encourages actions that have unintended negative consequences. For instance, 1) if a primary metric is mass of toxic solid waste, with the goal of toxic waste reduction, there is a natural tendency to shift the problem to toxic air emissions, or 2) if automotive recycling is measured by % mass recycled, automobile companies are incentivized to build heavier cars, thereby reducing fuel economy.

(3) If a metric encourages actions that oppose the original goal. Some might say the MCAS tests for high school students do this. The original intent is monitoring how well students are doing in school in order to address the goal of improving education. The result in cash

strapped environment is teaching for the test, at the expense of comprehension learning. A more directly applicable example is the use of abatement expenditures as a measure of environmental performance. Increasing expenditures on abatement could indicate either a worsening of environmental performance (requiring more effort to fix), or simply that impacts already created were being addressed.

8. Quality Data Available (Accurate and Updated)

There have been a number of indicators suggested for which there is no data to conduct the measurement, or for which the available data is inaccurate, or rarely if ever updated. This could be because the topic was not previously a concern for which data collection was considered important, because data collection was deemed not cost effective, or because collection of the necessary data is simply not feasible. A measure should not be rejected simply because quality data is not currently available if it can be shown that the required data is feasible and cost effective to collect.

2.4.3 Feasible

9. Cost Effectively Measurable

While this seems the most self-evident, there are number of aspects of sustainability for which measurement is costly or otherwise potentially infeasible, including:

- Resource availability
- Ambient exposure
- Impact on biodiversity
- Social welfare.

For a surprising number of suggested indicators measurement is cost prohibitive. For example, while it would be great information to have, no electronics recycler is going to pay to analyze and record the material composition, by weight, of every incoming electronic item.

Otherwise "good" indicators may go unused because those who could benefit from applying the measure do not believe that the informative value outweighs the expense and effort of data collection and analysis. In some instances, this may be due to a cultural preference for heuristics over data analysis, while for others it may be truly that the incremental benefit from improved decision making is outweighed by the cost.

While ultimately the "cost effectiveness" of a measure depends on an individual firm's needs, one can still compare measures by assessing the data intensity and informative value of a metric. The data intensity (data requirements) of a metric (a factor one would hope to reduce as much as possible) could be assessed by counting the number of data sets required beyond standard data collection.

2.4.4 Additional Criteria of Significance

Most criteria excluded from the consolidated list will not be described in detail. However, there are a few additional criteria which deserve some discussion.

Modular/Stackable

The informative value and usability of a metric is increased by the extent to which it can be "stacked", or aggregated - so that the same metrology can be used at different levels. One benefit to using money as a measure is that it naturally lends itself to this kind of aggregation. However, this has to be balanced by making sure metrics meet the needs of those at the level using them. Some metrics will only be appropriate at specific levels, while other measures involve wide scopes that prevent aggregation.

Independent

Currently many indicator systems have redundant (non-independent) variables (Olsthoorn, Tyteca et al. 2001). Means of assessing impact that rely on redundant variables may skew the importance of particular results(Neufville 1990).

Stakeholder Involvement in Indicator Development

The approach to developing business indicators described in Keebel et al. (Keeble, Topiol et al. 2003) involves three steps: 1) establish a pool of candidate indicators, 2) apply a 'screening" criteria developed and refined by the participants to generate a workable short list, and 3) use a set of ranking criteria to choose between related or duplicative indicators. The authors note that making this a participatory process is critical to ensuring that the indicators actually meet the needs of the organization and instilling a sense of ownership (increasing the likelihood that the indicators will actually be used).

Attention to process is especially important for the social aspect of sustainability, as there is a great deal more subjectivity in the development of these metrics. According to Keebel et al, metrics to which the stakeholders feel a sense of familiarity and ownership are more likely to be used, and are generally more appropriate to the situation – however odd they may seem to others (Keeble, Topiol et al. 2003). Community sustainability indicators are perhaps a more immediately apparent example than business indicators. A group called Sustainable Seattle worked to refine an indicator list that ended up being 99 indicators long. This seems absurd to some, however, at the community level there are a number of different concerns, many of which are not commensurable. It is perfectly appropriate for one community to track robustness of salmon runs and daycare centers per mile, even though another community would gain no value from tracking these same things. At the business level as well, different factors will be of greater concern to different companies. Taking this into account when developing the indicator set should greatly increase its ultimate utility in assessment and decision making.

Addresses all Key Issues and Aspects

No indicator or set of metrics perfectly represents underlying phenomena. Furthermore, new factors may emerge or become increasingly important and/or goals may change. Keeble (Keeble, Topiol et al. 2003) emphasizes the need to put into place a means for evaluating and updating the indicator set over time.

The issue of drift between goal and measure is particularly important with respect to the use of proxy measures. Proxy statistics are often selected when there is no data available to create the precise indicator of relevance. As such, by definition, proxy measures create measurement error, biasing the results. It is important to look for good proxies to approximate the actual or true observations and indicators; otherwise the use of a proxy may lead to a systematic distortion of the statistical and analytical results (Hardi and DeSouza-Huletey 2000). It is also critical to re-evaluate these proxy measures and see that they continue to approximate phenomena in an informative way. This is especially important for systems where measurement is of limited scope and goals are likely to change.

2.5 Summary

Sustainability will always be difficult to define and measure, because, ultimately, characterizing sustainability requires foresight as to the balance and form of technological development, population growth, human preferences, and natural systems over a long time period. The framework described above should aid this effort by presenting a way to integrate the two paradigms for sustainability which involve opposing perspectives on the ability of technology and the market to remove potential environmental limits. Finding ways to measure, to the best of our ability, whether systems are trending toward or away from sustainability is a critical step in assuring our continued well being.

Ultimately, sustainability measures must be selected to inform a particular decision or issue. However, to be efficacious, any metric must be useful, robust, and feasible, and there are a number of criteria which can be used to determine whether a given metric has these features. In addition, having a metric structure appropriate for the purpose is ultimately likely to be an important criterion; however, as discussed above, there is no clear understanding of metric structure or its effects currently.

In Chapter 4, sustainability metrics with particular relevance to material systems will be discussed, and a subset of these metrics will be applied to the electronics recycling case in Chapter 5. In both chapters the potential efficacy of these measures will be discussed using the framework and criteria outlined above.

3. Electronics Recycling

How does the electronics recycling system work today?

Disposal and recycling of electronics is a growing national and international concern for a number of reasons. The generation of electronic waste is increasing at a more rapid rate than other waste and a presumed significant (but unverified) fraction of the toxic content of landfills is due to electronics. Recycling practices are also a concern as they too can be environmentally damaging and contribute to poor worker health and safety. Public attention to the issue has been raised by key reports critical of the industry (Puckett 2002), with the role of export and prison labor in recycling among the inflammatory issues. Both the industry and regulatory bodies are struggling with ways to assess best practices, characterize the system, and address the issues raised.

This chapter will first attempt to put the issue of end-of-life electronics into perspective, and will then provide an overview of the existing understanding on the recycling system, economics, environmental concerns, technologies, and legislative developments. This chapter also briefly summarizes the available information on WEEE material flows and issues throughout the full recycling chain. A more thorough accounting of material flows is presented in Appendix B.

In addition to an extensive literature search, the information presented in this chapter was collected from direct interviews with recycling operators and others involved in the recycling process. A list of dismantling operations was acquired from an industry association web site (IAER), and operators active in the eastern US were approached for interviews. The operator set was limited to those in the east to limit expenses from follow up data collection. 20 dismantling operations were approached, 8 were interviewed over the phone using a standard questionnaire as a guide, and 5 agreed to be partners in the project. Partnering meant allowing for a site visit, additional data collection, and allowing their partner firms to be contacted. The 30 subsequent recycling operations (second and third tier recyclers) were also contacted and interviewed when possible. Some facilities were unreachable or unwilling to provide information, and some language difficulties were encountered with facilities based overseas or involved primarily in transport of material overseas. The questionnaire used for dismantlers and further processors is included in the appendix. The questionnaire addressed questions such as:

- What is being recycled
- By what processes are different products refurbished or recycled
- What are the intermediate processing steps and market transactions
- Who are the agents involved at each step in recycling (3rd party orgs, smelters, etc)
- What are the markets for secondary materials from waste electronics
- How vulnerable the material markets are if more materials are introduced

Upon execution of the questionnaire, as well as follow up site visits and data collection (described below), it became clear that the available data was insufficient to provide a thorough quantitative description of material flows from initial dismantlers through subsequent processors. Reasons for this include:

1. Low value of commodity stream: not a sufficient driver to engage in data collection.

2. For subsequent processors the commodity stream becomes indistinguishable from other flows.
3. Secrecy concerns by dismantlers, disinclination to share information on subsequent processors or processing.

This thesis was not able to provide a quantitative evaluation of electronics recycling material pathways; however a comprehensive qualitative picture was achieved through the interviews and literature search. Current industry reports focus primarily on initial disassembly operations, thus this qualitative analysis still provides a better understanding of material flows and recycling pathways down the recycling chain. The results of this are detailed below.

3.1 How Much of a Problem? EoL in Perspective

Concern over end of life electronics is growing; however the problem itself is rarely put into context. This section explores the problem of EoL electronics in four major contexts:

- **A life cycle view:** How significant is the EoL stage relative to other life stages?
- **A material systems view:** How significant is the mass of material in electronics relative to the total material flows?
- **A waste reduction view**: How significant are EoL electronics relative to other waste sources in terms of the volume and hazard?
- **An improvement potential view:** How much recognizable potential for improvement is there?

3.1.1 Life Cycle Impact

Life Cycle Analyses (LCAs) typically look at the environmental impact associated with all stages of a product's life cycle: material acquisition (or premanufacture), manufacture, use, and end-of-life. Existing research on the life cycle impacts of electronics suggest that the use phase is typically the most significant for PCs with the production stage coming in second overall but first for some impact categories (Tekwawa, Miyamoto et al. 1997; Anonymous 1998). The end-of-life has been attributed to the least impact in these studies, as well as in a study comparing LCDs and CRTs (Socolof, Overly et al. 2001).

However, these studies may overlook indirect benefits of materials recovery at end-of-life. Notably, effective material recovery can reduce the intensity and impact of raw material extraction and processing both of which contribute to the production stage impacts. Furthermore, conventional LCA studies may not fully represent the impacts of the end of life stage, as there is still little consensus on how to account for either resource depletion (and therefore resource recovery) issues or localized EoL impacts (e.g., potential environmental justice issues of overseas processing). Similarly, if LCAs underestimate the significance of either toxic material in landfills and incinerators, or the value of landfill space as a limited resource, than the current focus on diverting material from landfills would have greater justification.

In any case it makes sense to focus efforts - regulatory and operational – on areas where the greatest benefit can be made. Thus, if the end-of-life stage is significant only when recycling results in the displacement of environmentally-intensive primary materials, then it makes sense to focus on the recycling of these materials with high production impacts. Additionally, if use phase impacts are typically dominant (with production of secondary importance, and end-of-life less significant), then it makes sense to ensure that any efforts toward increased recyclability and recycling do not compromise the ability to maximize improvements in the use and production phases. Such hindrances could occur in the form of constrained design, inefficient materials choice, or by slowing the replacement of existing products with new more energy efficient models.

Ultimately it is important to review the impact of any proposed change (legislative and operational) on other aspects of a system (such as other life cycle stages) to prevent having efforts in one area result in bigger problems elsewhere.

3.1.2 Material System

For many materials contained in EoL electronics, the mass consumed in these products is a minimal or insignificant proportion of the total material flows. For example, out of the US consumption of lead in 1993, leaded glass accounts for 3% of the total, whereas lead acid batteries (not typically associated with consumer electronics) accounts for 84% of that total, with the majority used in automobiles. However, for select precious materials there is a different story. Capacitors for electronics accounted for 65% of the total US consumption of Tantalum in 1998 (Cunningham 2003) . Because of the lack of a concerted effort at recycling electronics, the recycling efficiency for tantalum is only 35%. The majority of recycled tantalum is from manufacturing scrap, superalloy scrap, and tantalum-bearing cemented carbide scrap (Cunningham 2003). An increase in electronics recycling, done in such a way that Tantalum is recovered, could have a significant impact on the tantalum material system.

The relative significance of electronics flows in total material flows for select materials is summarized in Table 5. An additional point to take notice of is the amount of "old" scrap used. The USGS defines pre-consumer, or industrial scrap as "new scrap", and post consumer scrap as "old scrap". For many materials and specific applications (including electronics), the amount of new scrap dominates the total cycled flows. This may occur where material flows of manufacturing waste dwarf material flows in the final product or because new scrap is generally relatively pure, known material in large quantities, and is thus easier to recycle. Efforts to improve material systems efficiencies must consider pre-consumer losses and material cycling as well as the post-consumer flows that have become the target of much recent legislation.

From a pure tonnage perspective it is hard to argue that electronics recycling is particularly critical to materials reuse. However, for specific materials – materials which happen to be high value, energy intensive to produce, scarce, toxic, or possibly all of the above –end-of-life electronics may represent the critical element to materials system efficiency. In some cases manufacturing losses have already been significantly reduced to the point where losses from waste electronics and electrical equipment (WEEE) become a major fraction of material lost. Whatever the reason it makes sense to focus recycling efforts on these materials.

Table 5: Significance of Electronics in Material Flows[1].

Material	**US Apparent Consumption 2002**		**Material Scrap Profile**			**Material Substitutes**
	Total (MT)	% used for Electronic Products	% of AC[2]	% Old[3]	Scrap Source	Substitutes
Ga	18.6	42%Optoelectronics 49%Integrated		0	New scrap: GaAs (low process yield)	

		circuits				
Ge	28	25%infrared optics; 20%fiber-optic systems; 12% electronics/solar	30W[4]	~0	New scrap: 50% of Ge used.	
Au	163	7%(2004 MCS)	50	13-25		Gold clad base metals, Pd, Pt, Ag,
Be	180	75% in Be-Cu [2%Be] alloys for electrical and electronic components.	10	>0		Graphite composites, phosphor, bronze, steel, Ti
Y	334 (as Y2O3)	79% lamp and CRT phosphors	~			No substitute, but large resource base
Ta	500	Capacitors >60%	20	>0	Ta cemented carbides and superalloys, not capacitors.	Al, Zr, Re, Ti, W, ceramics; poor substitutes
Cd	560	78% Nicad batteries	10W		11%of portable NiCd 53%of industrial NiCd	
Hg		Switches, lighting, instruments	5		Amalgam	
Pb	1.51mil	Leaded Glass - 3%	77	>90	Old scrap: 91% batteries New scrap: smelter operations, solder	Sn, plastic, Al, Fe
Cu	2.61mil	23%	31	29		Al, Optical fiber
Al	6.31mil	insignificant	42	40	53% beverage cans	
Steel	107mil	insignificant	64	49	Auto	

1. Data from (USGS 2002; USGS 2004).
2. % of US AC = the % OF US Apparent Consumption that is from scrap consumption
3. % Old = the % of the scrap consumed which is "old" scrap (scrap from EoL material) rather than "new" scrap (manufacturing scrap). Old + new scrap = 100%
4. W = % of World-Wide Apparent Consumption that is from scrap consumption (US data was not available for these materials)

3.1.3 Waste System

It is surprisingly difficult to get reliable numbers on the amount of e-waste, the percent of waste that is WEEE, the relative growth rate of WEEE as compared to waste in general, or the percent of toxic content in the waste stream that is due to WEEE. Nonetheless, allegations in the literature are that WEEE has a lower recycling rate, a higher growth rate, and represent the majority of toxics as compared to the general waste stream. These allegations are a concern internationally. The exponential growth rate of new electronic sales and also end-of-life equipment is shown in Figure 4, which is a graphical representation of the results from a model of the end of life fate of computers that was developed in 1991 and updated to reflect new data in 1997 (Matthews, McMichael et al. 1997). Figure 4 also shows the limited extent of material recovery and product reuse.

Supporting data found that addresses the issues of the magnitude and growth rate of WEEE are as follows: (1) in the USA, electronics represent 1% of MSW with a recycling rate of only 9%

as compared to 28% for MSW as a whole (EPA 2002) (2) in the EU, electronics represent 4% of MSW with a projected growth rate three times that of MSW in general, at 16-28 % every five years (Crowe, Elser et al. 2003). With regard to toxic content, no primary sources were found, however allegations in the literature are that WEEE contribute an estimated 40-70% of the lead and other heavy metals in landfills (Lin 2002) and 78% of the heavy metal in incineration plant sludge (Danish EPA study cited in (Tojo 1999)). As discussed further in section 3.5 below, electronics can contain any of eight regulated hazardous materials, and both printed circuit boards (PCBs) and cathode ray tubes (CRTs) exceed the regulatory threshold for lead in the federal government's Toxicity Characteristic Leaching Procedure Leachate test (TCLP). PCBs and CRTs thus qualify as hazardous waste, although industry associations contest that, for CRTs at least, the lead is not mobile(Evans 2001). Unfortunately, as with many claims regarding e-waste, there is little if any robust research available to support or refute these numbers.

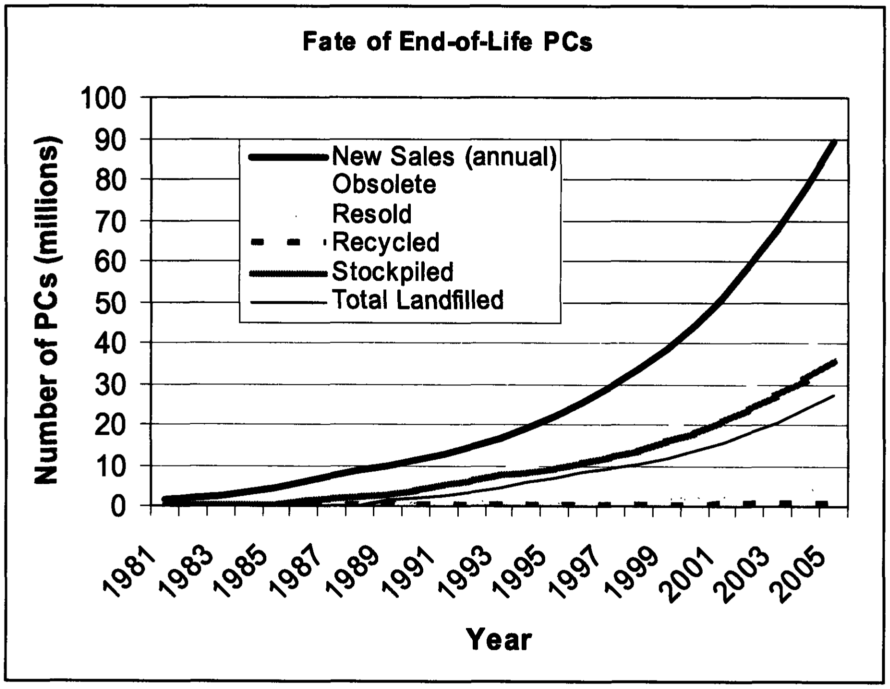

Figure 4: Growth and fate of EoL electronics (Matthews, McMichael et al. 1997)

The extent to which the *volume* of waste is a concern depends on the apparent scarcity of landfill space as well as local tipping fees and regulations. The concern over waste toxicity depends on opinions of the efficacy of landfill liners, and differences of opinion about the availability (or stability) of the heavy metals in electronics components. This is discussed further in the section on CRTs. Nonetheless, it is fair to say the WEEE represents a new problem for solid waste handling. The pervasive use of electrical and electronic products emerged in the latter part of the twentieth century; the pervasive disposal of WEEE is emerging at the advent of the current century. Judicious examination on any novel waste is warranted given its scale and particular characteristics.

3.1.4 Improvement Potential:

Both the automotive and electronics industries have been working with Design for Environment (DfE) and Design for Recycling (DfR) for a number of years now. These efforts have influenced, and been influenced by some highly innovative designs and numerous design tools such as Life Cycle Analysis (LCA) and design-for-disassembly tools. There have been extensive tool development and numerous case studies presented in the academic literature, however it is unclear the extent to which these initiatives have actually had any overall result toward lowering environmental impact and increasing recycling. One significant difficulty is that DfR efforts and attention to improving recycling technology can be counter to technological trends toward smaller more complex electronic products.

Nonetheless, as compared to the automotive industry, the electronics industry appears to have a strong potential for successfully utilizing these tools and frameworks in general for the following reasons:

- **Short product life and design time:** This allows for much quicker incorporation of environmental features, less risk to experimentation, faster feedback, and greater ability to respond appropriately to changes in regulation and demand for eco-features.
- **Modular components and processes:** There is a high degree of modularity in electronics design (Matzke, Chew et al. 1998).
- **Use of Analytical design tools:** As compared to the automotive industry, the electronics industry may make greater use of CAD and /other analytical tools. For a new car there often is NOT an existing dataset/CAD model from which data for an LCA can be extracted. The automotive design process is largely normative; new designs are based on small modifications to existing cars, and much of design time is spent optimizing assembly. Analytical (dynamic CAD) modeling is only standardized for crash testing (where the cost of the alternative is substantially higher). However, the environmental tools in use by Apple & IBM primarily involve product profiles & goal setting, not data embedded in current analytical tools, so whether this is a good indication of potential is unclear.
- **Clear advantages to the firm from reducing environmental impact in the form of reduced cost and reduced risk of liability:** In the automotive sector safety issues dominate liability, whereas for electronics the destination of toxic waste is an increasing concern.
- **Some indication of consumer preference for 'eco-features'**: In the automobile industry there appears to be a consumer dislike for eco-features (or desire for features that inevitably reduce environmental performance), as indicated by the sales of SUVs. Consumer preference is still unclear for electronics, however requests for environmental information are common (Matzke, Chew et al. 1998).
- **Non-conflicting regulatory requirements:** In electronics as with the automotive sector, there is a dual emphasis on energy efficiency and waste reduction, however in the automotive sector there is a trade off between these (lightweighting vs ease of disassembly & recycling) which is not apparent in electronics.

In terms of Design for Recycling (DfR) in particular, the effort expended currently is primarily driven by the EU's new electronics recycling regulations, although there may be some push from the industry's desire to retain the characterization as a "green" industry.

Unfortunately, efforts toward DfR are often insulated from the concerns and realities of electronics recyclers. There is currently no direct flow of information or standard mechanism to assess whether DfE efforts are having their intended effect. The time lag before products reach end of life may prevent serious consideration of EoL results by product designers “15 years is such a long and irrelevant time frame to product designers…it has to effect the bottom line”.

There is room for improvement at the end of the product life cycle as well. There are research efforts focused on developing better methods for material segregation, cleaning, and recycling. At present many recyclers view these as costly and impractical given a low value material stream. However it is not inconceivable that a new technology will ultimately break through that cost barrier and transform what is currently a manual disassembly dominated industry. In addition the lack of understanding of system functioning as a whole leads to inefficiencies which a better systems understanding could help to correct.

In short, it is important to keep these alternative perspectives in mind when designing metrics, policies, and products for recycling. It is not helpful to design regulations which increase the mass of electronics material recycled but stilt design efforts, result in lower level re-application of materials than would otherwise be achievable, or negatively impact the energy efficiency of electronics in use or material efficiency of industrial processes.

The following section provides a brief overview of the electronics recycling industry as a whole and its basic operations followed by sections focusing on the economics, environment, and policy issues surrounding WEEE.

3.2 Recycling System

The recycling industry for WEEE is undergoing rapid transition due to changing regulations and economics, and also new technologies (including product design, which affects recycling inflows and development of new recycling processing alternatives, which affects outflows). Certain end-of-life electronics have been recycled over the last 20 years, however the industry has changed dramatically from recycling only high-precious-metal content materials, to service-providers that sell a recycling service for low value material and also extract value by harvesting reusable components and materials from the waste stream. This transition likely occurred because the push to recycle for environmental reasons has increased while the revenue/cost ratio for e-waste recycled has been steadily declining.

Unlike some other recycling industries (such as automotive), the value recovered from materials does not cover the cost of recycling, and so, if materials recovery is to occur, the difference must be subsidized in some way. Substantial discussions are underway about how to finance these recycling systems, and what are the most preferable means of recycling to meet multiple objectives (Staff 2004).

At present, the majority of electronics are still disposed of rather than recycled. The International Association of Electronics Recyclers (IAER) estimates that 10% of electronics (by units) are recovered for recycling, which corroborates the EPA estimate for 1999 that about 9% of the electronics destined for MSW are recovered (by mass). There is a wide range of electronics products (Table 6), however information products, which have a recovery rate of 21%, account for 99% of recovered electronics (EPA 2002). This is a poor recovery rate relative to the total 1999 MSW stream, of which 14.7% is combusted. 57.2% landfilled, and 28.1% is recovered by recycling (Table 29,(EPA 2002).

Table 6: Selected consumer electronics (EPA 2001)

Video Products	**Audio Products**	**Information Products**
Televisions Projection TV HDTV LCD TV TV/VCR Combinations Videocassette Players VCR Decks Camcorders Laserdiscs players Digital Versatile Disc Players TV/PC Combinations	Rack Audio Systems Compact Audio Systems Portable CD Portable Headset Audio Total CD Players Home Radios	Cordless/Corded Telephones Wireless Telephones Telephone Answering Machines Fax Machines Personal Word Processors Personal Computers Computer Printers Computer Monitors Modems/Fax Modems

Currently the source of recycled materials for domestic recyclers is primarily from businesses and manufacturers (Table 7). Large users are required to dispose of electronics as hazardous waste meeting Resource Conservation and Recovery Act (RCRA) requirements or recycle it. For companies required to dispose of this material to RCRA standards, recycling presents a cost competitive "greener" alternative.

Table 7 Source of electronics collected for recycling (IAER 2003)

Source	**%**
Manufacturer	30%
Industry Users	30%
Consumers	10%
Govt agencies	10%
Schools	10%
Other	10%

For consumers there is little or no incentive to recycle electronics, and there is often little knowledge about how to do so. However, the recent push for recycling of consumer electronics will likely an increase in the percentage of recovered electronics from consumers, so long as there is a mechanism to provide sufficient funding for the recycling.

Dismantlers typically claim to recycle (or divert from landfill) over 90% of the material entering their doors. However there is little monitoring of what happens beyond the first tier of recycling. Material that is landfilled by later recyclers in the chain is typically not accounted for, and because of the negative economics of the system there is no economic driver that automatically guarantees the material is really getting recovered.

3.3 Recycling Process

Electronics collected for recycling typically go through some combination of (1) assessment for reuse, (2) disassembly, (3) size reduction, material sorting and pre-processing, (4) smelting or other final processing of secondary material for reuse (Figure 5).

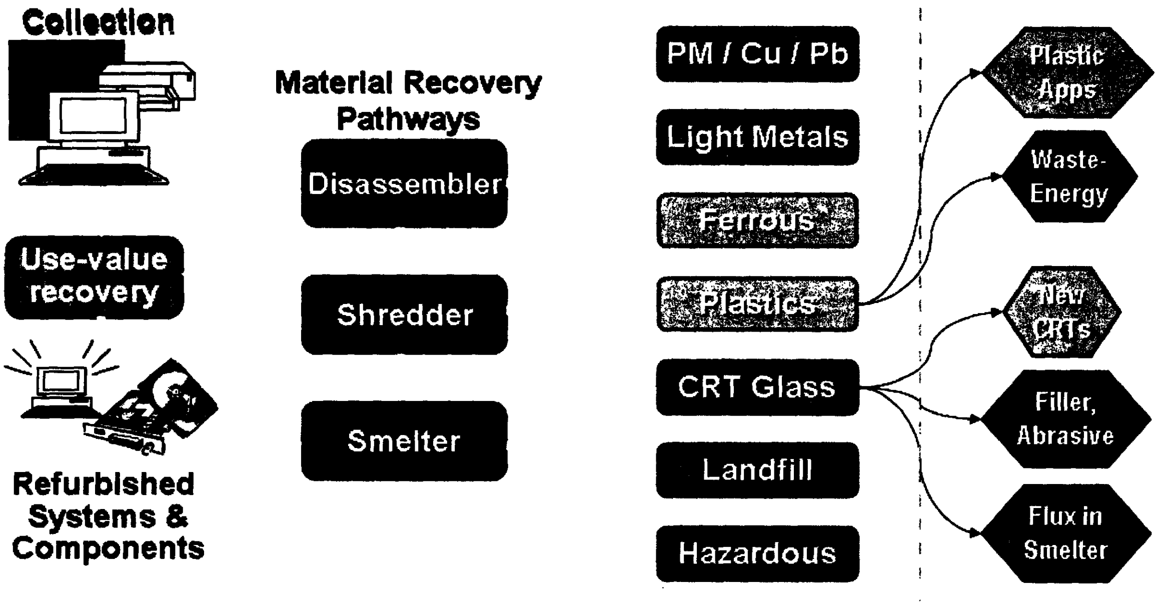

Figure 5: WEEE Recovery Pathways Schematic

To date, studies of the WEEE industry (Council 1999; IAER 2003) give a thorough characterization of dismantlers, but provide little coverage of the subsequent processors. This may simply be a reflection of the fact that the majority of businesses involved in WEEE -focused industry associations are dismantlers. The IAER breaks down e-waste recycling into seven industry segments; Asset Management, Product Reuse, Demanufacturing, Parts Recovery, Materials Recovery, Broker, and Materials Processing. Only about 25% of respondents to the IAER survey of recyclers responded that they do material processing, whereas at least 50% of respondents operated in each of the other segments, and 80% did some demanufacturing. The prevalence of dismantlers over material processors is due to (1) the fact that material processing operations tend to require large capital investments and large material throughputs, thus there are fewer of them in general, and (2) for many material processing operations e-waste is a minor and low-value contributor to their total flows, and thus not of great concern. Some smelters and other material processors are beginning to realize that by offering more complete recycling services they could potentially capture a significant share of the e-waste processing cycle and associated profits from recycling service fees.

Most dismantlers in the USA use manual disassembly as their primary dismantling process. Many will do some subsequent mechanical shredding and baling in order to reduce volume for shipment, meet size requirements of downstream processors, or meet certified-destruction requirements of their e-waste customers (recall that for many recyclers, the producer of e-waste provides the major source of income via recycling service fees, and thus is considered their primary customer). Dismantlers with additional specialties, such as precious metals, may process a particular material to a further level before passing it on to a subsequent processor. Brokers may simply transfer material with little to no disassembly, and smelters may take in electronics with limited to no pre-processing.

The exact sequence that a particular product will go through depends on the needs of the originator of the waste, the technologies of the chosen processor, the value of the material, and the current economic situation. More specifically, the level of disassembly and processing pathway will depend on:

- **Objectives** of both the originator of the waste and recycler (e.g., maximize profit, reduce landfill, liability, intellectual property protection, other)
- **Economics** (labor cost, capacity of secondary markets, material prices, transport costs, other)
- **Technology** available for sorting, sophistication of method, changes in incoming WEEE mix
- **Product Characteristics** (condition and age of the product, product composition, etc)

The recycling process for end of life electronics, including the different fractions recovered from manual disassembly compared to a shredder dominated process, is illustrated in Figure 6. As is illustrated by the shading key, the highest value is obtained from reuse of equipment and parts.

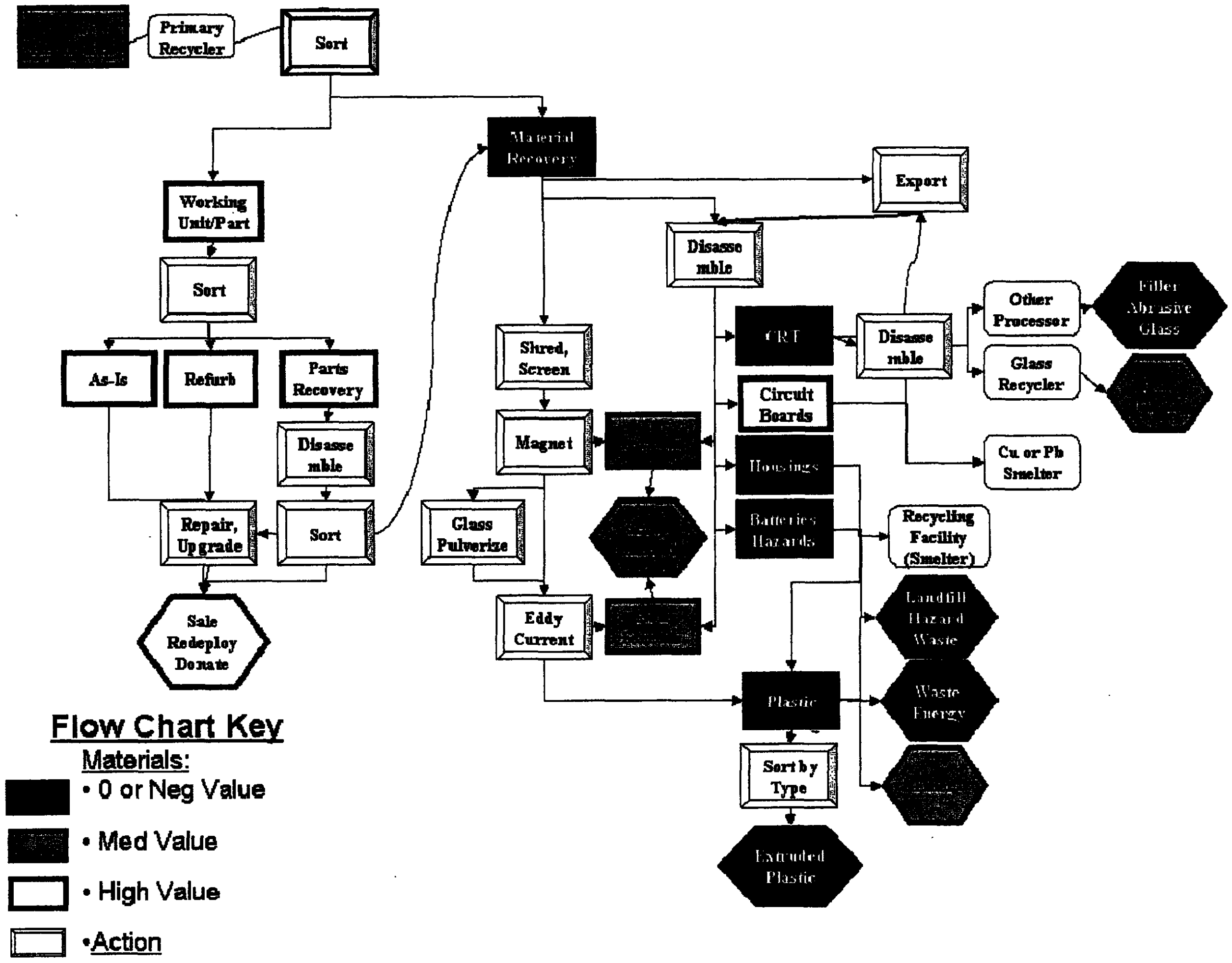

Figure 6: Electronics recycling process

Currently, two alternatives exist to the labor intensive manual disassembly process. One is use of a shredder to separate materials, followed by a magnetic separator to isolate ferrous metals, and then an eddy current separator to isolate non-ferrous metals (Cui and Forssberg 2003). The remaining material (i.e., plastics, etc.) is generally disposed. This method greatly reduces manual labor requirements, but also results in lower purity commodity streams. Furthermore, this method is capital intensive, thus requiring a large and constant material stream to be cost effective. The ability to adjust labor costs to meet variability of supply is another reason recyclers prefer manual disassembly. A third alternative recovery method, especially attractive for precious metal dominated products such as cell phones, is to use the products directly as feedstock in a smelting operation (Huisman, Stevels et al. 2002). This process reduces precious material losses and preprocessing costs; the metals are recovered and the plastics provide energy in combustion.

Modern electronics contain a wide variety of materials including metals, plastics, and ceramics as shown in Table 8.

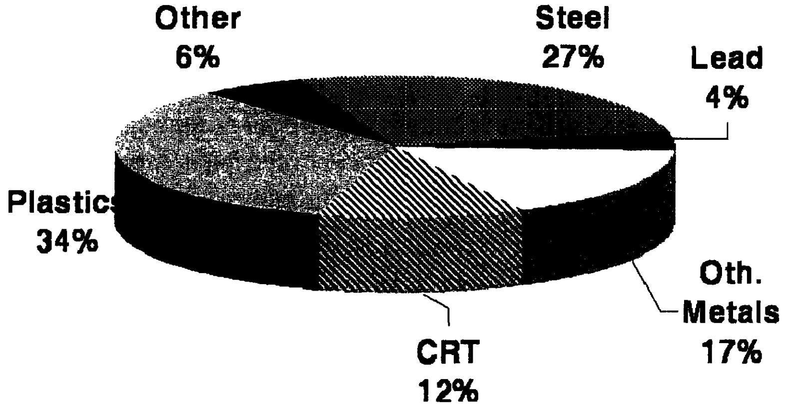

Figure 7: Material composition of EoL electronics

Not surprisingly, the eventual recovery pathways for these materials can be substantially different. The typical destinations for these materials are listed in Table 8. A more complete summary of the common processing routes and associated issues for major categories of EoL materials is presented in Appendix B.

Table 8: EoL Electronics material pathways

Material/Parts	**End Uses, processing**
Reuse, refurbish Reuse, parts	Reuse markets, overseas, donation Repair, refurbish, manufacture of lower-end product
CRT Glass	New CRT glass, fill material, flux for smelters, other shielding applications
Non-Ferrous metals	Remelt, or primary or secondary smelters
Ferrous metals	Steel recovery
Precious metals	PM recovery in smelter
Toxics (batteries)	Specialized recovery (lead, cadmium) or hazardous waste disposal
Plastics	New polymer, non-polymer product applications, road grade, waste-to-energy, disposal

In addition, scrap varies significantly by source. Many WEEE recyclers also process manufacturing, or prompt, scrap in addition to EoL electronics. Prompt scrap is typically better identified, less commingled, higher value material which requires lower processing. Industry scrap also tends to have a higher collection and recovery rate than consumer electronics, not simply because of RCRA requirements, but also because the material is likely to be of higher quality (and value) both because industry EoL material is likely to consist of more uniform products, and because material from businesses and leasing programs is typically newer and thus is more likely to be reusable. Military and very old electronic scrap is also typically of higher value because of lower complexity and greater precious metal content. Over the years electronics products have steadily trended toward smaller, more complex products which are more expensive to disassemble, and the content of non-ferrous and precious metals, which accounts for the majority of material value from e-waste, has been steadily declining. The increasing speed of technological obsolescence has also reduced the percent of material acceptable for resale. The incoming end-of-life material changes rapidly, reflecting the quick product cycle for electronics. This, and changing markets, requires recyclers to constantly adjust their recycling processes to meet the current material streams and economics.

3.4 Economics: Recycling System Market Dynamics

While a few recycling systems, such as the system for end-of-life automobiles (Chen 1995), are inherently cost effective, the economics of electronics recycling more closely resembles hazardous waste processing and liability reduction. What recyclers understand too well, but the public sometimes has difficulty realizing, is that the value of a computer after it has reached the end of its technological life is less than zero: unless the computer is only a few years old, the computer becomes a liability with a disposal cost that exceeds any harvested materials value. The electronics recycling business does not currently make a profit from the recovery value of end-of-life electronics. Rather, it requires a subsidy in the form of a fee. The material value of a $2000 computer at end of life is approximately $1.50 to $2.00 (IAER 2003), whereas it costs approximately $10 - $29 (Dell 2005; IBM 2005) for a consumer to send a PC for recovery. It is worth analyzing whether the environmental externalities from materials extraction and depletion justify subsidizing material recovery by spending $5-$15 to get $1 return. However, worthwhile alternative comparisons include viewing this cost relative to the environmental cost of disposal alternatives and with consideration of the industry's developmental stage. The recycling industry is still very much in flux. Thus, the impact on costs of future changes in product design, processing technologies, demand for commodities, and development of more streamlined collection networks is unclear.

To recycle electronics, highly diverse and widely dispersed EOL products must be retrieved from the end-user, transported to recycling facilities, processed by multiple operators, and hopefully transformed into useable secondary materials to be sold and transported to a buyer. The International Association of Electronics Recyclers (IAER) reviewed costs reported by residential electronics collection programs and found that collection and transport, as opposed to the actual material recycling process, typically accounted for 80% of program costs. The cost of collection and the fees for the actual recycling each average $300/ton (Table 9). This cost is a significant hindrance to the recycling of consumer electronics.

Table 9: Cost Comparisons for collection and recycling of residential e-waste

	Cost Range $/ton	Source
Collection	$100-500/ton (average $300) [$1,000-20,000/site]	Summary of 7 residential collection program studies(IAER 2003)
Recycling	$200-500/ton (average $300)	
MSW disposal	$14-73/ton (CA low, MA high)	(Kaufman, Goldstein et al. 2004)
MSW incineration	$45-81/ton (GA-NH)	

Before recycling became both mandated and an issue of popular concern, the industry recycled only what was profitable to recover. The fee-for-recycling service model has now come to dominate domestic recycling operations(Council 1999). Recyclers vary in their business model and the percent mass of the incoming material that is recoverable as reusable products; however for many recyclers the recycling fee and sales for product and part reuse dominates revenues. Reuse may subsidize the disassembly process because the value of reusable products and parts is often significantly higher than the value for even high value materials (Table 10).

Table 10: Value of secondary material from EoL electronics (IAER)

Product or Material	Value: $ or cents/lb	Comments
Computers	Resale:<$1000 Parts: ~ $100 Materials:~$1	Resale: approaches $0 with technology over 2 generations Laptop value is two times desktop value Parts value: $100/machine between 3-10 yrs old hard drives 2/3 of total recovery value Commodity recovery: $1-2/machine
Cu (including foil)	11-69	
Al	19-49	
Steel (incl. Stainless)	5-23	
PC Boards	65-125	
Plastics	3-4	Possible value $1/lb (APC 2003)
Cables & wire	18	
Connectors	94	
Cardboard	(5)	
Batteries	(23)	
Trash	(5)	
CRTs	1-12	Negative value with cost of transport, packaging, processing.

Some non-CRT waste can be net positive. In general, Costs >= Value; thus profit made by fee-for-service

Some recyclers focus on manufacturing scrap as a major source of income, or do recycling merely as a service for customers that provide other more profitable business. Downstream processors typically focus on high volumes of a particular material for revenues, but some are beginning to consider capitalizing on the fee-for-recycling-service model by taking in end of life products directly.

The high volatility of materials markets, especially secondary materials, creates an additional hindrance to recycling. A glut in supply of recycled materials or a shift in the usage of a particular material can dramatically influence the commodity price received by recyclers. Recyclers may adjust to these changing prices by altering their dismantling processes, such as switching between separating plastics or not.

The industry is growing rapidly to capitalize on increased demand for recycling services, and is also consolidating to take advantage of economies of scale (IAER 2003). As the industry develops, there are increasing efforts toward developing standards such as scrap specifications (EETP 2001; Anonymous 2003) and best practice processing guidelines(EPA 2004).

The revenue/cost comparison is often more favorable in developing countries for a number of reasons. The up-front cost of material recovery is more comparable to the value of those materials, partly because of reduced labor costs[1] and better markets for secondary materials, but also because of lower environmental health and safety requirements. This value difference, whatever the source, is a substantial driver for sending material overseas. This export occurs both legally and illicitly, and has brought up international concerns around environmental justice issues and also domestic debates around fair market behavior.

The lack of a domestic market for recycled commodities alone may make export inevitable. Many materials enter the USA already embodied in products. A simple mass balance would show that if the majority of manufacturing is done overseas and products are imported, then this material would have to return overseas if it were to re-enter the manufacturing stream2. Existing international regulations (discussed later), meant to stem the tide of waste electronics from developed nations in the Organization for Economic Cooperation and Development (OECD) to non OECD nations, do not alter the favorable economics of this transfer of waste, thus the flow continues. At the same time *both* the transfer of manufacturing and waste processing to locations with cheap labor and lax environmental regulations presents potential equity and environmental justice issues that cannot be solved through a focus on pure economic efficiency.

3.5 Environment

Some economically-motivated recycling of precious metals from electronics has always occurred, but the primary impetus for expanding electronics recycling has been concern over the environmental impact of disposed EoL products. The issues of concern with regard to the handling of EoL electronics are appropriate handling of hazardous material, air and water emissions, loss of landfill space, use of resources and associated impacts, and the impact of processing options on environmental justice and worker health and safety. However, recycling also has associated environmental impacts. Because of the complexity of the involved stream and processes, the most environmentally friendly strategy for dealing with EOL electronics is not always readily apparent.

End-of-life electronics can be dealt with through a number of different pathways. Listed roughly in order of least to most preferable in terms of environmental impact, these are: uncontrolled dumping, landfilling (uncontrolled or controlled), incineration (without or with energy recovery), materials recycling (down-cycling to lower level application, or recycling to same-level application), parts recovery, remanufacturing, and reuse. While this ranking is appropriate in general, for specific materials or circumstances different pathways may be more preferable.

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[1] The issue of labor costs also comes up when discussing UNICOR, the prison industry's recycling operations. Other recyclers are concerned about the possible labor distortions, and also are eager for government (especially military) scrap as the value of this material is typically substantially higher.

[2] This issue is discussed further in the section on CRTs.

Also of environmental significance is that the majority of e-waste is currently not recycled, and recycling this waste will require significant financing, thus a balance may need to be found between economic feasibility and maximum environmental returns – ultimately allowing for greater recycling benefit.

3.5.1 Hazardous Materials

Electronics can contain a number of potentially hazardous materials that are outlined in Table 11. As indicated, eight of these materials are currently regulated under the Resource Conservation and Recovery Act (RCRA) in the USA and five are regulated under the Restriction of Hazardous Substances in the EU, while other materials in the list are of concern, but have not to date been regulated or banned.

Complicating the issue of hazardous material handling are debates over the availability of the hazardous fraction of specific products in landfills. The reasoning is that if a heavy metal or other problematic material is bound up in a solid matrix or otherwise inaccessible to leaching or other chemical processes then it does not actually represent an environmental hazard. The question of the bioavailability of hazardous materials in products deserves further attention, and is of particular importance in the debate over leaded glass from CRTs. The electronics industry association (EIA) states that the lead in CRTs is "bound in a glass matrix, is stable and immobile, and likely remains in the product even when landfilled"(Evans 2001). While this seems a reasonable supposition, no study was found confirming it. One study comparing lead leaching from PWBs and CRTs for a variety of leachates found the lead concentration to be consistently higher for CRTs (Jang and Townsend 2003). The main thrust of the research however, was to address whether actual landfill leachate showed similar lead leachability as the Toxicity Characteristic Leaching Procedure (TCLP) used for determining RCRA hazardous waste qualifications. The study found leaching in landfills to be significantly less than indicated by the TCLP test. However the study acknowledged that the landfills go through an acid phase and the RCRA test is meant to be a worst case scenario using an acid leachate, whereas the landfill leachates tested were all close to neutral (pH 6-8).

Also, while CRTs may be receiving the most focus in terms of end-of-life regulations, product design regulations such as RoHS, which mandates the reduction and elimination of a number of hazardous materials, affects other electronic components just as significantly. For example, the move toward lead free solder, which has its own environmental issues, is driven by these environmental regulations.

While the problem of toxic materials is a major concern, many recycling systems originated to deal with an apparent scarcity of landfill space. The location of dumps and the transport of waste across states, countries, and even continents, has been the focus of much acrimony. As mentioned above in the section on waste systems, the volume of electronics waste, representing only 1-4% of total MSW, should not be in itself a concern, however when the high rate of growth and the potentially high toxicity are also taken into account, it is easy to see why electronics have become a focus of attention. It is relevant to note, however, that packaging waste, which accounts for a larger percent of the total, received EU regulatory attention in 1994 (European Parliament and Council 1994), many years before electronics.

Table 11: Potentially hazardous material contained in electronics (Five Winds International 2001)

Hazardous Material	**Where found**	**Uses, issues**
Mercury [RoHS, RCRA]	LCD display bulbs	Back light
	Batteries	
	CRT	Transforming UV to visible light
	Mobile phone	
Lead [RoHS, RCRA]	Tin-lead solder	Interconnection materials, good conductivity; used in printed circuit boards, motherboards, printers, capacitors
	CRT (monitors & TVs)	Radiation shield, leaded glass (lowers melting temp), Molding agent in plastics manufacture, packaging inks
	Cabling	Stabilizer in PVC cable, surface treatment for Cu alloy
	Batteries (early laptops)	
Cadmium [RoHS, RCRA]	battery	NiCd
	CRT	Phosphorescent coating on screen
	Cabling, plastic housing	Plasticizer, stabilizer, flame retardant, pigment
	PWB	Surface finish, chip resistors, semiconductors
Beryllium	Motherboards, Relays, switches	Be-Cu alloy (2% Be), contact springs, improves elasticity of alloy
	Finger clips	Maintain conductivity in metal housings
	Laser printer	Rotating mirror; lightweight rigidity
Hexavalent Chromium (Cr VI) [RoHS, RCRA]	PCs, Monitors	Colorant, hardner, housing, PWB, anti-corrosion treatment,
	Cabling	Stabilizer, with PVC
	Motherboard	components
	Hard discs	Hard disc plate, hardner
Brominated Flame Retardants [RoHS: PBB, PBDE]	Printed circuit boards,motherboards	PBBs, TBBPAs, PBDEs
	Plastic housings, keyboard buttons	PBDOs, PBDEs, PBBs
	Connectors, cabling	
Antimony [RCRA]	PCs, plastic housing	Flame Retardant
	Monitors	Melting agent in CRT glass
	Cabling	Stabilizer, flame retardant, solder alloy (antimony-tin)
arsenic, cobalt, selenium		Also listed under RCRA
PVC	Monitors, keyboards, cabling, plastic housing, cellular phone window	
PCBs [Banned in US]	Capacitors, cabling	Some sources say PCBs have never been used in PCs, however others cite possible uses.
Beryllium is a new material of concern, and PVC has been the target of concern by environmental groups…		

Unfortunately, increasing recycling does not necessarily remove environmental justice concerns. As will be discussed further in the regulatory section, there remain serious concerns regarding the transport of material for recycling in the same way that these concerns exist for transport of waste for landfills. This concern is not unfounded given the current lack of controls on such recycling systems, and the fact that the material is sometimes of no greater value than the rest of MSW. In addition, environmental health and safety (EH&S) for recycling workers has not always been safeguarded, as documented by the watchdog organization Silicon Valley Toxic Organization (Puckett 2002). Recycling in less developed nations can include both open burning of plastic waste (e.g., burning of copper wire to remove plastic coating or burning of printed circuit boards after solder and valuable chips are removed); and uncontrolled dumping of hazardous materials (such as dumping of acid washes used to remove precious metals (See Figure 8, Table 12).

Laborer heating aqua regia acid mixture along riverside chemical stripping operation to extract gold from imported computer chips. All waste acids and sludges are dumped into the river. The only protective equipment used are rubber boots and gloves. © BAN

Open burning of wires and other parts are common to recover metals such as steel and copper. Dioxins and furans can be expected due to the use of PVC and brominated flame retardants. © BAN

Figure 8: Images of e-waste processing in China (Puckett 2002)

Research that assumes appropriate handling of end-of-life material may understate the significance of end-of-life electronics within global waste systems, material systems, and life cycle impacts. This is especially true if indeed 50-80% of e-waste collected for recycling in western US is exported (Puckett 2002), as it is not clear how much of this e-waste is handled inappropriately. All life cycle analyses done to-date have been executed against a model for end of life operations that does not include the "worst-practice" activities that can exist in Asia. Similarly, assessments of waste systems are considering the relevance of e-waste with respect to other municipal solid waste, not the impacts of unmonitored bad recycling processes in other places.

There remains, however, the possibility that, if done with reasonable controls, electronics recycling can be an environmental benefit, both by preventing unsafe disposal of hazardous material and by reducing the need for raw materials and their associated impacts (as discussed in the section on material systems). A summary of existing legislation is presented in the next section.

Table 12: Environmental and Occupational Impacts in Asia. Copied from (Puckett 2002)

Computer/ E-waste component	**Process witnessed in Guiya China**	**Potential Occupational Hazard**	**Potential Environmental Hazard**
Cathode ray tubes (CRTs)	Breaking, removal of copper yoke, and dumping	Silicosis, Cuts from CRT glass in case of implosion, Inhalation or contact with phosphor containing cadmium or other metals	Lead, barium and other heavy metals leaching into groundwater, release of toxic phosphor
Printed circuit boards	De-soldering and removing computer chips	Tin and lead inhalation, Possible brominated dioxin, beryllium, cadmium, mercury inhalation	Air emission of same substances
Dismantled printed circuit board processing	Open burning of waste boards that have had chips removed to remove final metals	Toxicity to workers and nearby residents from tin, lead, brominated dioxin, beryllium, cadmium and mercury inhalation, Respiratory irritation	Tin and lead contamination of immediate environment including surface and groundwaters. Brominated dioxins, , beryllium, cadmium and mercury emissions
Chips and other gold plated components	Chemical stripping using nitric and hydrochloric asic along riverbanks	Acid contact with eyes, skin, may result in permanent injury, Inhalation of mists and fumes of acids, chlorine and sulpher dioxide gases can cause respiratory irritation to severe effects including pulmonary edema, circulatory failure and death.	Hydrocarbons, heavy metals, brominated substances, etc. discharged directly into river and banks. Acidifies the river destroying fish and flora
Plastics from computer and peripherals, e.g. printers keyboards, etc.	Shredding and low temperature melting to be reutilized in poor grade plastics	Probable hydrocarbon, brominated dioxin, and heavy metal exposures	Emissions of brominated dioxins and heavy metals and hydrocarbons
Computer wires	Open burning to recover copper	Brominated and chlorinated dioxin, polycyclic aromatic hydrocarbons (PAH) (carcinogenic) exposure to workers living in the burning works area.	Hydrocarbon ashes including PAH's discharged to air, water, and soil
Miscellaneous computer parts encased in rubber or plastic, e.g. steel rollers	Open burning to recover steel and other metals	Hydrocarbon including PAHs and potential dioxin exposure	Hydrocarbon ashes including PAH's discharged to air water and soil
Toner cartridges	Use of paintbrushes to recover toner without any protection	Respiratory tract irritation, Carbon black possible human carcinogen, Cyan, yellow, and magenta toners unknown toxicity	Cyan, yellow, and magenta toners unknown toxicity
Secondary steel or copper and precious metal smelting	Furnace recovers steel or copper from waste including organics	Exposure to dioxins and heavy metals	Emissions of dioxins and heavy metals

3.6 Regulatory Frameworks

The last 10 years have seen extensive legislative activity on electronics waste. There are new regulations on end-of-life electronics around the world and many more laws under development. In addition, there are a number of voluntary industry led initiatives and public-private partnerships addressing or studying the e-waste problem. The disparate concerns of different stakeholder groups are reflected in the variety of legislation as well as in system assessments. Existing regulations exhibit potentially conflicting objectives including saving landfill space, protecting industries, increasing material recovery, proper disposal of hazardous waste, encouraging DfE, or simply taking the cost burden of disposal off of municipalities. Inconsistencies in the existing regulatory framework are a known problem for their potential to create market distortions and loopholes through which improper practices can continue. Existing domestic and international regulations are briefly summarized below and are summarized in Table 13. The majority of these policies include one or more of: landfill bans, toxic use bans, collection mandates, recycling targets, extended producer responsibility and product takeback requirements, or advanced recovery fees as shown in Table 13. Information on existing electronics recycling regulations described in the following sections was collected primarily from the EIA (Evans 2000) and Raymond Communications Inc.(Raymond Communications Inc. 2005)

Table 13: Policy frameworks for electronics

Policy	**Description**	**Who**
Landfill Bans	Bans the landfilling of toxic-containing products such as CRTs, mercury switches, etc.	MA, CA,
Financing mechanisms	Advanced Recovery Fee (fee at purchase), Producer Pays, Disposal Fee (fee at disposal)	Most regulations include some financing mechanism
Hazardous material bans, restrictions	Restricts or bans hazardous materials from products	EU(RoHS), Taiwan
Import/Export bans, restrictions	Restricts transport of specified substances	International (Basel Ban), China
Extended producer responsibility, takeback	Holds the producer responsible for EoL materials in order to encourage consideration for EoL during design phase	EU(WEEE), South Korea, Brazil
Recovery, collection targets	Mandates targets for collection and/or recycling of material	EU(WEEE), Japan, Taiwan, China

3.6.1 USA Framework

There are currently no national regulations in the USA mandating recycling of electronics waste. However, waste electronics (WEEE) are regulated as hazardous materials under the Resource Conservation and Recovery Act (RCRA). Concerns that RCRA hinders material recovery have led to application of the Universal Waste Rule (UWR) to electronics in some states, and specific RCRA exclusions for certain materials destined for recycling. The UWR is designed to reduce handling and reporting requirements for specified materials to facilitate their recycling. The down side of the UWR, and other streamlining efforts is the potential to exacerbate problems overseas. In 1997 the EPA qualified used PCBs destined for recycling as "scrap metal" not subject to RCRA. This "scrap metal" may be exported legally, and imported into China against Chinese law (Gaba 2001). Additionally, as RCRA provides no penalties for labeling waste as "for recycling" when it is eventually disposed of after export, a commentator has characterized the United States' hazardous waste regulations as imposing only "cradle to border" liability (Lin 2002).

While there is no national regulation mandating recovery, 26 US states[3] have some level of legislative effort on the minimization, recovery and recycling of EOL electronics waste. Some of these efforts were driven by states intent on reducing landfill costs. However, most are recent grass-root efforts driven by concentrated efforts of environmental organizations such as the Silicon Valley Toxics Coalition to expose problems domestically and overseas. In this, as in many environmental issues, non-governmental organizations (NGOs) provide a remedy for the Olsonian problem of collective action by concentrating interests and catalyzing concern so that action is made around a diffuse public benefit. However NGOs may also lock in to less optimal but easily explained solutions, such as "no export" or other technically impossible absolutes.

3.6.2 Overseas Activities

In the early 1990s, the problem of waste electronics began to receive the attention of regulators worldwide. Since then a plethora of regulations have been suggested or adopted. Most prominently, the EU has adopted a Directive on Waste Electrical and Electronic Equipment, or "WEEE Directive" (European Commission 2003) which creates a uniform framework for the extensive regulations on e-waste adopted by EU member nations. These national activities, and the directive itself, can be traced back to the 1993 Fifth Environmental Action Program when a list of waste streams was identified as important for focused treatment and management.

The WEEE Directive is based on the principle of Extended Producer Responsibility (EPR), originally laid down in Article 174 of the European Community Treaty. EPR posits that holding producers responsible (financially and otherwise) for the final treatment of end-of-life products ensures feedback and creates incentives for producers to incorporate end-of-life considerations such as recyclability and toxic content into product design. Producer responsibility for e-waste starts at designated collection points and is limited to the actual treatment, recovery and disposal of collected waste. Treatment of e-waste must comply with the Basel Ban Amendment and other cross-border hazardous waste transport regulations. Member states will have to demonstrate progress or compliance towards specific recovery targets (Table 14) as early as December 2004, and no later than December 2006. Detailed rules for monitoring compliance are to be established by December 2005.

Table 14: EU WEEE Requirements

Recovery Targets (Valid until 2008) By Product	Recovery % Mass	Recycling % Mass
Large Household appliances	80%	75%
Small household appliances, consumer electronics, electrical and electronic tools and toys	60%	50%
IT & telecommunications equipment	75%	65%
Gas discharge lamps	80%	80%
All electronic and electrical appliances containing CRTs	75%	70%

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[3] Arkansas, California, Colorado, Florida, Georgia, Hawaii, Idaho, Illinois, Iowa, Massachusetts, Maine, Michigan, Minnesota, Nebraska, New Hampshire, New Jersey, New York, North Carolina, Oklahoma, Oregon, Pennsylvania, South Carolina, Texas, Utah, Virginia and Washington

The EU also adopted a Directive on the Restriction of the use of certain Hazardous Substances (European Commission 2003) which requires the reduction and elimination of specific hazards (lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE)) from electronics and other products by July 2006. Certain applications are exempt.

Over the same time period, advanced disposal fees or take-back regulations have been implemented in Argentina, Brazil, China, Columbia, Japan, Mexico, South Korea, and Taiwan with other countries debating similar actions. Legislation is developing so rapidly that the Electronic Industries Alliance (EIA) and Raymond Communications Inc. have created subscription service updates of legislative actions worldwide.

3.6.3 International Agreements

International concern about improper disposal of waste in developing countries initiated the Basel Convention in 1987. The convention was followed by an amendment in 1995 to immediately ban the export of waste intended for disposal from OECD to non-OECD countries with a provision to extend that ban in 1997 to export of wastes intended for recovery and recycling. On the import side, China's Solid Waste Environmental Pollution Prevention Act of April 2000 banned imports of 10 categories of waste electronics. The USA has agreed to respect this rule despite not ratifying the Basil Convention[4].

The Basel Action Network claims that despite these regulations on export and import "around 80% of what come[s] through the [US-based recycler's] doors will be exported to Asia, and 90% of that will end up in China" (Puckett 2002). However a study by the Northeast Recycling Council (NERC) found that only 38% of US electronics scrap was exported to Asia, with 9% of the total going to China. The NERC study found that WEEE was exported throughout the world to Africa, South America, Australia, and Europe as well as Asia. The drive for export is easily comprehended if recycling a computer costs $0.38/lb in the US but only $0.15-$0.30/lb overseas (all costs included), or even as low as $0.05/lb (Lin 2002). Simply put, it makes economic sense to export the material. In the EU, the decision to abide by the Basel Ban was not as momentous as it would be for the USA. In the EU, low wage environments within Eastern Europe can serve as a sink for material, components, and old electronics (Rubinstein 2003), reducing demand for Asian processing.

While some WEEE creates severe environmental harm, some of this trade is neither illicit nor environmentally damaging. The export of benign pre-processed scrap to secondary material markets in Asia is difficult to argue against on environmental, EH&S or equity grounds (except for the difficulty in monitoring the content of shipments).

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4 Currently only three countries of the 156 parties have not ratified the Convention; Afghanistan, Haiti, and the United States. This is consistent with the USA's general approach to international environmental issues and international law in general; the USA has also not ratified the Kyoto Protocol, and is long overdue on UN dues. The Basel Ban Amendment (as apposed to the Convention) does not enter into legal force until a ¾ majority, or 62 countries have ratified it. However, the prohibition of all exports of hazardous wastes have been observed by all EU member states, Norway, Liechtenstein, Monaco, and Iceland even though only 36 ratifications have been received thus far.

E-waste is an easily transportable effluent; thus, ultimately, local and national regulations intended to promote recycling and proper disposal of hazardous waste can shift the problem overseas where exported WEEE may be processed incorrectly in developing nations. International regulations were put into place to help solve this problem. However, without effective monitoring and enforcement neither national nor international laws will have the desired effect.

3.7 Summary

The problem of e-waste is complex, with a number of critical factors that must be remembered when designing metrics, policies, and products:

- Consider the significance of e-waste from the perspectives of the product life cycle, the waste system, the material system, and the improvement potential to ensure that real problems are addressed, and solutions do not create bigger problems elsewhere.
- Material recovery from electronics recycling today does not cover costs, and thus recycling is a net-negative operation which is made viable through a fee-for-service business model
- Currently only 10% of e-waste is recovered for recycling, and of the e-waste destined for recycling 50-80% of it is shipped overseas.
- Different end-of-life materials have different optimal recovery pathways.

There are a number of existing recycling regulations, including such mechanisms as hazardous material bans and restrictions, import/export bans and restrictions, landfill bans and restrictions, extended producer responsibility and takeback requirements, recovery and collection targets, and recycling financing mechanisms. Existing policies differ in the extent to which they take into account the factors outlined above.

A more complete understanding and balanced characterization of recycling operations, alternative recovery pathways and market dynamics is critical if regulatory structures and incentives are to succeed in creating an effective electronics recycling system. This means understanding processing requirements for different materials, existing and potential markets for secondary materials, effects of market fluctuations, and ultimately, drivers for DfR. While much work is being done to better understand existing e-waste recycling systems and develop improvements, these efforts are hampered by the difficulty in defining improvement. The ability to converse using recognized metrics for benchmarking and assessing best practices would facilitate major system improvement. The remainder of this thesis is focused on the development and assessment of metrics that could address this need for the electronics recycling system. The next chapter provides an overview of existing metrics in the industry and alternatives that could improve system understanding. In chapter 5 a subset of these measures are applied to three case recycling facilities. Lessons regarding both metric development and electronics recycling learned from the application of these metrics are presented in the concluding chapter.

4. Sustainability Metrics for Electronics Recycling

Are existing recycling industry metrics effective in moving toward sustainability, and are the alternative metrics evaluated "better" indicators for evaluating electronics recycling efforts?

The selection of metrics has a strong effect on the behavior of decision makers and the systems within which they work. Poorly selected metrics can cause performance to deviate from intended goals. The ways in which metrics are used by the sectors involved with end-of-life electronics can help or hinder general efforts toward sustainability of the industry. This chapter outlines existing metrics used in the electronics industry and then reviews a number of metrics that could complement or enhance existing measures of recycling performance.

The existing recycling system is based on the predication that it is "good" to recycle material. However, there are few metrics currently in use that indicate whether a benefit is actually obtained, the magnitude of the benefits, or what results constitute a benefit. It is important to make sure that metrics for the system do indeed identify trends toward improvement. The current metrics in use may be too simplistic to do that. This thesis investigates the hypothesis that current metrics provide neither a good characterization of system operation, nor sufficient means to evaluate whether changes in system operation result in environmental (or sustainability) improvements. Rather, despite an underlying environmental goal, the current metrics in use for electronics recycling do not necessarily map toward sustainability and obscure differences between facility operations.

In particular, many domestic operators focus on reducing the percent of total material mass going to landfill. On the surface, this sounds like an objective that would trend toward sustainability. However, some prior research has given an indication that this may not always be the case (Huisman 2003). There could be a number of reasons for this:

- If the weight of material is not a good indication of the impact (for instance, toxicity or other factors may make some materials of much more concern than others)
- If the material is diverted from landfill by the first recycler, only to be sent to landfill by the subsequent processor
- If the cost of recycling material increases as a greater percent is recycled and this cost premium hinders increased collection of material
- If the effort (expense, energy, environmental impact) put into recycling the material is greater than that of both the raw material processing it is replacing and the consequences of disposal.

If any of these are the case, then continuous reduction of material going to landfill may not actually trend in the same direction as sustainability, and thus the focus on this measure may skew decision making away from underlying goals. This issue is indicative of the problem of using an overly simple measure. However, high resolution measures may be disregarded because the expense of data collection appears to exceed the potential decision making benefit of the improved metric. The optimal approach is then to evaluate (and re-assess) potential metrics in order to choose the simplest possible set of metrics for the given need, while retaining an awareness of the gaps in vision that that these metrics present.

What follows is an overview of existing metrics in the electronics industry and descriptions of a number of measures that could improve decision making. In Chapter 5, the efficacy of specific metrics in evaluating a material recovery system is compared with attention to the three primary criteria from Chapter 2: the usefulness, robustness, and feasibility of the metric. Specifically, what metrics could give higher resolution for making current decisions at a reasonable cost?

4.1 Existing Metrics in the Industry

What measures are of most use depends on which stakeholders are using the metric. The major stakeholders with regard to electronics recycling are (1) OEMs, who are responsible for product design and sales and more recently, for the take-back of their equipment at end of life, (2) recycling operators who are responsible for providing a recycling service to their customers and dealing appropriately with end-of-life materials, and (3) regulators, who are responsible for developing regulations that improve environment, health and safety Retailers, large generators of e-waste, and consumers are also stakeholders, however, they have a smaller stake in electronics recycling developments and to date they have played a less active role.

The generally cited goal for electronics recycling is to reduce environmental impact and to lessen demands on landfill space. However, each stakeholder group has a different set of priorities (Table 15). For the OEM and the large generator of e-waste, the primary purpose of recycling electronics is to achieve liability reductions in a cost effective manner. For the recycler, business viability is critical and meeting the customer's needs for recycling services in a cost-effective manner is the primary means for achieving that. The degree to which customers demand accountability differs. Thus, some recyclers are much more attentive than others to their environment, health and safety (EH&S) performance and the traceability of materials. For Government the goals are generally to improve environment, health & safety and maintain international relations. System-wide, the goal of reducing environmental impact can be broken down into (1) reducing indirect impacts, by using primary instead of secondary materials, (2) reducing emissions and waste from EoL material, and (3) conserving landfill space.

Table 15: Stakeholder goals regarding electronics recycling

Government	OEM	Recycler
Environment, health, and safety International relations No undue burdens on industry	Liability risk reduction Cost reduction Reputation protection Environment, health, and safety	Business viability Customer value; liability, asset management, traceability Cost reduction Environment, health, and safety

Differences in goals, economics, and data availability for different stakeholders affect the metrics they use currently, and should continue to guide selection of metrics.

For recycling facilities, as well as other recycling stakeholders, the primary measure of performance remains the percent of material diverted from landfill. However, there are also a number of metrics used by specific actors in the industry (Table 16). These measures may be economic, environmental, or mass based in nature, qualitative or quantitative, and address the product, process, or system scope. Each of these measures has its own set of best applications and limitations, making different metrics preferable for different contexts. While the ideal metrics would be useful at all levels, could be aggregated, and be valuable for cross-comparisons, as well as real-time decision making, this is rarely achieved in practice.

Table 16: Metrics in use regarding electronics recycling

Actor (right) Performance Metric (below)	**Government [product or system]**	**OEM [product, process, or system]**	**Recycler [process, or system]**	**Systemwide [system]**
ECONOMIC [quantitative]	$/lb recycled (collection, recycling)	Recycling fees paid, system costs, disassembly time/product	Throughput: lbs/month Costs: processing $/lb processed, Pounds processed /person hour Productivity: Lbs processed /FTE/day Value: recovered $/lb processed	none
MASS BASED [quantitative]	% EoL mat'l collected % "recycled"/ product [WEEE regs]	% recycled material /product % "recyclable" mat'l /product Mat'l use efficiency: output /throughflow	% recycled, % diverted from landfill	Material Recycling Rate (USGS) MFA
Env. Impact, "Green-ness" Compliance, Liability, [quantitative or qualitative]	[RoHS], Requirement checklists.	LCA, "Recyclability", Facility Audit, EH&S Audit, ISO14000	Facility Energy Use, EH&S Audit, ISO14000, Ethics; "No Export", "No prison labor",	Material LCA

An approach to evaluating the recycling industry from the manufacturing perspective is through indicators that attempt to quantify the recyclability of an electronics product (Middendorf, Nissen et al. 2000; Hesselbach and Herrmann 2001; Hiroshige, Nishi et al. 2001; Mathieux, Froelich et al. 2001; Oyasato, Kobayashi et al. 2001; Ardente, Beccali et al. 2003; Huisman 2003; Kim, Hwang et al. 2004). Some of these indicators evaluate disassembly time for a product, but many include information on end-of-life recycling costs, product composition, recyclable material mass, environmental impacts of product use and disposal, material toxicity, and material energy content. However, these "recyclability" assessments are often developed in isolation from the market realities of the recycling industry.

A corresponding metric used by recyclers is time-to-recycle or pounds of EoL material processed per person-time. For facilities, metrics such as pounds processed per person-time can be non-diagnostic, unless data is controlled for different incoming streams. If time to recycle is increasing, it may be due to inherent changes in incoming material (such as product complexity, age and composition), rather than operational efficiency.

Whereas 'recyclability' measures typically assess the effort involved in recycling, the basic mass recovery metric measures the result of recycling efforts, or, what percent of EoL material is actually recycled. This measure provides a general understanding of results, but is significantly flawed as a sole indicator for two reasons. First, the mass recovery measure fails to assess indirect impacts of the recovery of secondary materials. Recycling creates a secondary material stream, which, if used in place of primary materials, creates the same use-value, or utility, but typically with a lower energy and environmental cost. This is because the recycled materials are generally more homogenous than the corresponding primary ore. These homogenous streams lead to less impact in the way of extraction, purifying and processing. Second, the mass recovery measure fails to address differences in downstream impacts. Recycling electronics doesn't simply divert mass from landfills; it can prevent the emissions of hazardous materials into groundwater and air. Considering these issues, all materials and all end-uses are *not* created equal.

Existing measures of environmental impact with regard to electronics recycling tend to be qualitative in nature. Recyclers typically indicate responsible behavior through facility audits and the adherence to guidelines and standards. Likewise, OEMs and large generators demand these same qualitative reviews from recyclers. More quantitative environmental measures have been developed for products, and similarly, the most prominent government quantitative measure are the RoHS requirements limiting or eliminating hazardous materials from electronics products. Qualitative measures may be useful for customer assurance, or even to inform strategic decision making, however alone they are insufficient for making tactical decisions regarding business operations. There is a need for quantitative environmental measures with regard to the environmental impact of recycling operations.

While manufacturers and government actors are often concerned with product based measures, for the recycler (as well as from the material systems perspective), product based measures are of little significance. Instead, process based measures and metrics related to the total through-flow of materials are more relevant. Additionally, it is important to note that product based measures are generally based on some perspective of how the system works, but do not measure how that system changes over time or how it changes independent of changes in the product.

There is a need for metrics that can better assess the effectiveness of the system as a whole. This is relevant for OEMs and government as well as for recyclers. For instance, while OEMs can develop measures of recyclability based on disassembly time per product, they have no way to assess the effectiveness of recycling pathways to which they send EoL material other than recycler's claims of the percent material diverted from landfill and any ISO or other certification. There is a need for quantitative measures beyond mass based measures to assess recycler performance, and the performance of the recycling system as a whole.

The previous paragraphs describe the benefits and limitations with the current set of measures. Some measures are more useful for strategic decision making, while others are useful for tactical decisions. There are few quantitative measures of recycler environmental performance or system wide performance. Possible methods for addressing this need are addressed in the next section.

4.2 Metrics for Material Recovery Systems

This section presents greater detail on specific metrics and approaches that can be used to evaluate material systems and facilities for their environmental sustainability. First, metrics developed to assess material flow and recovery-efficiency will be discussed because of their particular relevance to a material recovery focused industry. Then, life cycle assessment (LCA) and a variety of other measures that could be used to provide a relevance-based rather than mass-based understanding of performance will be discussed. Virtually any measure of environmental impact outlined below can be used in some form as an environmentally based assessment of recovery effectiveness.

Along these lines at least three frameworks have been proposed in the literature. QWERTY (Huisman 2003) uses an LCA based approach to provide "environmentally weighted recycling scores rather than weight-based recycling scores" for end of life relative to best and worst case scenarios. Currently, QWERTY is effective for material recovery, not reuse, and is made for product level analysis, not facility level analysis. Exergy has also been suggested as a way to evaluate resource recovery (Connelly and Koshland 1997; Ayres, Ayres et al. 1998; Sciubba 2003), and energy analyses have been done comparing end-of-life strategies for plastics, and for electronic equipment (Patel, von Thienen et al. 2000; Williams and Sasaki 2003). None of these measures have yet been applied to analysis at the level of the recycling facility. QWERTY and exergy will be discussed along with a number of other possible approaches, and later, a measure will be developed and applied for energy performance at the facility level along with environmental-impact and value performance measures.

As discussed above, there are numerous indicators to evaluate environmental impact of products. In general, the focus here is on metrics for use at the level of the recycling facility or material system and product specific measures will not be discussed further. A subset of the metrics examined will be applied in Ch 6 to the problem of assessing the sustainability performance of the electronics recycling industry.

4.2.1 Material Flow and Mass-based Measures

Material flow and cycling metrics are of particular relevance to the sustainability of materials use. Bailey and coworkers (Bailey, Bras et al. 2001; Bailey, Allen et al. 2004; Bailey, Bras et al. 2004) have developed indices for material cycling in industrial systems using input-output modeling originally derived for economic systems. They claim that current recycling metrics are ad-hoc because they don't take into account the entire system. Hashimoto and Moriguchi (2004) propose six indicators of societal material cycles using material flow analysis. Both of these modeling frameworks are appealing in that they are a more accurate representation of material flows, but they require explicit definitions of the material systems in question and input data that may be difficult to obtain on the system level.

In contrast, Wernick and Ausubel (1995) have developed metrics for the environmental performance of national material flows that are based on publicly available data that is assembled by the US government. Wernick's framework considers three primary components: "inputs to the economy (including imports), outputs (including exports), and extractive wastes". The indicator categories are meant to be comprehensive and allow for a national mass balance. The authors acknowledge that many environmental impacts are not reflected by weight metrics (e.g. volume, land disturbance, toxicity), and they also note the need for smaller-scale metrics to provide information on local impacts and distribution. However, the authors see weight based national indicators as providing the same level of insights as the GDP metric provides. (What they do not comment on is that using GDP as a denominator would create very useful normalized metrics.) They suggest eight classes of metrics: Absolute National and Per Capita Inputs, Input Composition, Input Intensities, Recycling Indices, Output Intensities, Leak indices, Environmental Trade index (the net mass of waste & emissions generated from foreign trade), and Mining Efficiency (mining wastes, by-product recovery). With simple systems, Wernick's metric for recycling rate result in the same values as Bailey et al's more complex measure (Bailey, Bras et al. 2001).

It should be noted that the field of material flow analysis (MFA) is also relevant as it tracks the inputs and outputs of materials within a system. However, there is not a standardized set of metrics that are associated with MFA. Rather, MFA is a tool that is used to provide information to calculate any number of metrics that may be chosen to suit a particular case or preference, including metrics related to exergy, material consumption, or material cycling.

Materials-based life cycle metrics have also been proposed, such as the material intensity per service unit (MIPS) (Schmidt-Bleek 1993), which accounts for the total amount of material consumed in manufacturing a material or product and the degree to which that material or product is used. Hanssen et al. (2003) also use a "material intensity" measure, which is the quantity of material used per unit of economic output, to analyze the Norwegian packaging industry. This concept is a useful one for material systems and recycling operations, for which the denominator would be a commodity output or single material.

It is critical to note that quality data on material flows form the basis of any of the other measures discussed. Life cycle measures, including energy and exergy, all require data on mass inflows and outflows but each has additional data requirements. Emissions data is merely one form of outflow data. LCA and the other measures presented in Table 17, and discussed below could all be used as relevance-based mechanisms for a massflow-based assessment.

Table 17: Environmental measures (discussed further below)

Measure	**Advantages**	**Disadvantages**	**Data requirements**	**Issues**
LCA	**1, 3, 7***, Some software compares different weighting methods, links developed with cost and performance measures, comprehensive	**2, 4,5,6,8,9***, Data intensive, inconsistent methods to address resource depletion, not useful for operational decisions, static	Mass in & out by commodity, detailed inventory data from process, environmental impact data, weighting scheme	Strategic: useful to determine most significant environmental impacts.
Exergy	**1,3,5, 6, 7**, Accounts for downcycling, facilitates comparison between resources,	**2,4, 8,9**, Does not address environmental issues such as toxicity	Mass in & out by commodity, exergy quantified from process and throughflow data	Sometimes maps with economic value
STM	**1, 2, 3, 4, 6,** Understandable, closest to a comprehensive (environmental) sustainability measure	**5, 7, 8, 9** Approach breaks down with non-renewable resources	Mass in & out by commodity, detailed inventory data from process, carrying capacity estimates	Assumes impacts map with distance from carrying capacity
Waste Index	**1, 4, 5, 6,** Comparable, use of a control volume allows for "unambiguous scaling"	**2, 3, 7, 8,** Environmental issues addressed is limited, assumes impacts map with concentration of substance in earths crust	Mass released, degradation times for materials	Assumes impacts map with concentration, and only indirectly assesses resource scarcity or loss of value
Value	**1,2,3, 4, 5, 7,8,9** Combines economic and mass efficiency, gives market driven view on efficacy of material systems, uses generally available data	**3,7,** For subsidized systems like electronics, results may be better indicator of cost than recovery (eg favoring export to disposal)	Mass in & out by commodity, cash flow (fee) in, transfer price by commodity	Sensitive to primary value and material stream compositions
Energy or EI	**1, 2,3,7, 9** Addresses differences in recovery value for different material applications	**4,5,6,8** must calculate value for primary as well as secondary materials	Mass in & out by commodity, product mix composition, energy (or environmental) savings for each alternative use	Could use most LCA, impact, or output measures

***Numbers in the Advantages column indicates metrics' ability to meet criteria shortlist from Chapter 2, whereas numbers in the Disadvantages column indicate criteria that are not met.**

4.2.2 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is an analytical process, not a metric. LCAs are often used to determine the environmental impacts of a product from cradle (extraction of raw materials) to grave (disposal of the eventual product). This approach is also useful for a material system. However, it is less relevant at the facility level, which is one cog in a material or product system. LCA essentially allocates all impacts of material and energy use over a product's creation, use, and disposal to that product. For product design decisions, where all impacts can be affected, this is a very useful framing. For a facility scope however, assigning all upstream and downstream impacts of the flows through that facility would be of dubious value. However, an LCA consists of both the life cycle approach (less applicable to facilities) and a means to measure environmental impact (applicable to all scopes). These are discussed separately below.

Using the life cycle approach

Because of the time and cost of analysis, full LCAs are more appropriate for strategic decision making and one-off studies than for ongoing operational decisions. However, life cycle approaches may form the basis for simpler environmental measures that augment mass-based assessments and would serve as proxy metrics for a full LCA. In fact, there are many instances where the life cycle approach that looks at impacts of a product from "cradle-to-grave" has been adopted, but rather than the full life cycle assessment methodology, simpler measures are used, such as the qualitative "simplified LCA" (Graedel and Allenby 1995). Input-Output LCA (I/O-LCA) simplifies the LCA process by developing industry level impact assessments based on the inputs and outputs to each industrial sector (Cobas, Hendrickson et al. 1995). A product LCA is thus simply the aggregate of the materials from each sector, weighted by the impact allocated to that sector. As discussed below, there is a wide variety of options for measuring environmental impact.

Measuring environmental impact

Many LCA methods, such as Eco-indicator (Spriensma 2000) and EPS (Steen 1999), calculate one aggregated metric based on analyses of traditional environmental impacts such as global warming and eco-toxicity. The data required to compute such scores include a Life Cycle Inventory for the system, a means to convert that inventory into environmental impacts, and a weighting system to put the impacts on the same scale and allow for development of a single score. Because the final LCA score is dependent on the weighting system for the metric, newer LCA tools may allow the user to choose multiple weighting systems for comparison, or allow the user to alter the weighting scheme to check sensitivity of the results. These adjustments increase the utility of LCA by clarifying the subjective elements of the process. Other LCA measures, such as TRACI (Bare, Norris et al. 2003), conduct a similar analysis, but without the weighting necessary for a single metric result. These measures present results as a series of impact potentials such as "toxicity", "eutrophication", and "global warming".

Measuring environmental impacts for a facility can be determined and an environmental score calculated using an LCA scoring system such as that used in EPS or TRACI, a single impact such as global warming, an input such as energy use, or another composite indicator. Indicators such as energy (Williams and Sasaki 2003), exergy (Connelly and Koshland 1997; Ayres, Ayres et al. 1998; Connelly and Koshland 2001; Gong and Wall 2001; Wall and Gong 2001; Brown and Buranakarn 2003; Sciubba 2003), emergy (Brown and Buranakarn 2003), the Sustainable

Target Method (Dickinson, Mosovsky et al. 2003), or the Waste Index (Emblemsvag and Bras 2001) described below, can also be used with either the LCA process or at the discrete scope of a facility level analysis.

The energy metric is a measure of the energy consumption in the manufacturing, use, and disposal of a product, whereas exergy and emergy use thermodynamic entropy definitions to account for environmental and economic life cycle factors.

4.2.3 EXERGY

An exergy analysis answers the issues raised by use of the I/O LCA framework. Whereas in the I/O framework, environmental impact is directly tied to economic output as a shorthand evaluation method, exergy uses thermodynamic principles to explore resource use, providing insight into both energy use and material degradation.

Connelly and Koshland (2001) propose that consumption be evaluated as the sum of two parameters – "throughput" measured by total mass flows, and "degradation", or loss of quality, measured by exergy. Degradation is an effort to measure the "extent to which a consumptive process removes resource quality". From an industrial ecology perspective, this provides a mechanism to accurately account for cyclical material use and "downcycling", the recovery of end-of-life materials for lower quality applications. A mechanism to account for this is critical in determining the effectiveness of any recovery system because considering downcycled material as equivalent to materials returned to a similar quality application seriously mischaracterizes the system.

The exergy measure also enforces a degree of physical realism on the industrial ecology goal of cyclical resource use by accounting for the fact that recycling and recovery which increases the exergy of a particular material mass causes greater exergy losses to the larger system. This cost of resource recovery *must* be considered in analysis of recovery efforts, but may be neglected in policy decisions that take "recycling" as unquestionably good.

At the same time, while exergy captures an important concept of entropy, there is significant controversy over the direct translation of exergy to impact. Also, exergy cannot quantify degradation from macro-level mixing (such as materials in a landfill), "loss of information content", or structural changes (Connelly and Koshland 1997) .

4.2.4 Sustainability Target Method (STM):

There have also been some efforts to develop indicators of sustainability that do not simply provide an environmental impact score, but are "true" sustainability metrics for commercial activities. These measures are based on concepts of "carrying capacities" (Dickinson, Mosovsky et al. 2002; Yossapoll, Caudill et al. 2002) and "environmental space" (Ragas, Knapen et al. 1995). Yossapol (2002), Dickinson (2002), and colleagues differentiate between environmental performance metrics, which "express environmental impact on a relative basis to allow comparison of businesses, products, and services", and sustainability metrics, which "establish a relationship between carrying capacity and both the environmental impact and economic value of products" (Dickinson, Mosovsky et al. 2002).

The absolute indicator within the STM, Eco-efficiency (EE), is "a ratio of the economic contribution (% of GDP) of the business or operation to its environmental burden (% of carrying capacity)"(Dickinson, Mosovsky et al. 2002). Thus, if all businesses achieved exactly 100% EE, all GDP activity would occur exactly within the estimated carrying capacity for a given impact category.

The calculations are broken up into nine impact categories for which carrying capacities and reference levels have been estimated. These are expressed in terms of rates, which is most appropriate for the majority of environmental impacts. Environmental phenomena involve rates of purification, cycling, and regeneration; operation that does not exceed these natural rates could reasonably be considered sustainable.

These concepts are based in the "strong sustainability" paradigm discussed in Chapter 2, which allows for limited to no resource substitution and assumes that the carrying capacity of a particular environmental effect or resource consumption can be accurately determined.

Depending on how carrying capacity is assessed, there is certainly the potential problem of embedding valuation implicitly in these definitions. However, there is a significant body of scientific research on carrying capacities for biologically relevant resources and on the carrying capacity to absorb burdens such as greenhouse gasses, thus a relatively value-neutral definition should be achievable. With most of the aspects for which Yossapoll, Caudill et al. (2002) develop a carrying capacity (greenhouse gasses, ozone depletion, acidification loads, etc.), the approach seems effective. However, when developing a carrying capacity for resource depletion, Dickenson et al did reflect that defining a true "carrying capacity" would be impossible, and that a more anthropocentric view would be appropriate in this case – along the lines of the "weak sustainability" paradigm discussed in Chapter 2. In addition, there is no differentiation between resources used aside from the difference between use and carrying capacity for each resource. This essentially means all resources are considered equal.

4.2.5 Waste Index

The Waste Index (WI) developed by Emblemsvag and Bras(2001), in conjunction with an Energy Index, is intended to supplement Activity Based Costing, providing an effective set of easily understood and applied metrics across industries and products. The metric is relatively simple, but allows for significant extra understanding of impacts, and is coupled with cost accounting data. The metric is an improvement over simple mass measures for assessing the relevance of emissions, however it does not account for the energy and performance value lost by disposal of materials (ie, the added benefit of resource recovery).

WI is based on the premise that "Any substance in a sufficient amount beyond the natural amount of the substance in a control volume (environment) can be considered waste (pollution)". Interestingly, like value, WI could provide some account of scarcity of a material, in that emitted materials which are not common in the control volume (such as gold) will have a higher waste index. However, a metal, if it does not leach material, will not have a degradation function, so the waste will be measured only as a function of the volume relative to the control volume.

The publication introducing WI is one of very few to provide an analysis of the cross comparability of results with other metrics. Specifically the authors evaluated WI against two LCA metrics: Eco-Indicator and EPS. The authors found that WI correlated with most atmospheric releases (over 85%), but only about 44% with Eco-Indicator and very little with EPS. The authors' conclusion was that WI was better able to handle atmospheric emissions than either of the other indicators. An additional analysis for a list of materials found that while WI results varied by material, EPS and Eco-indicator showed many materials to be very similar. Out of this the authors concluded that WI had a better resolution. However, they used a specific critique of EPS: "the EPS-Indicator… assesses the production of cotton to be 11,516 times more environmentally damaging than the production of plain concrete. This cannot be true unless very persistent pesticides are used and taken into account" (Emblemsvag and Bras 2001). In fact, very persistent pesticides are used, and so it is a credit to EPS if it did manage to account for that.

4.2.6 QWERTY

QWERTY (Huisman 2003) uses an LCA-based approach to provide "environmentally weighted recycling scores" for end-of-life products. The score is relative to the best and worst case scenarios for the end-of-life of that particular product. This metric includes the "environmental value" of secondary materials and the "environmental burden" of EoL treatment. The QWERTY tool is combined with an assessment of costs to evaluate the eco-efficiency of end-of-life strategies.

QWERTY can be evaluated using any environment score, be it a full LCA indicator (Eco-indicator or EPS) or a single environmental effect score such as global warming potential. Regardless, a best and worst case scenario must be developed to calculate the indicator. To date, QWERTY is applicable for product level material recovery and not reuse, and hasn't been used at a facility level. To use this measure at the facility level would require development of best and worst case scenarios for all commodity streams, with the QWERTY score a mass-weighted aggregate of these material flows. The benefit of this approach is its ability to provide an easily communicated benchmarking picture of how well product or facility X is doing relative to the best and worse case alternatives. This measure is, however, sensitive to the choice of best and worst case brackets.

4.2.7 Eco-Efficiency

Of the measures discussed above, only STM includes an economic measure (GDP) in the basic measure. However, the eco-efficiency approach of combining environmental and economic impacts is a popular approach first used by the World Business Council for Sustainable Development (WBCSD 2000) for incorporating economic factors into decision-making. The differentiation amongst various methods is typically in the definition of environmental impacts and economic costs. The QWERTY method is designed for use in conjunction with recycling costs/profits in order to assess the eco-efficiency of recycling products as a vector. Hesselbach and Herrmann (2001) also analyze the recycling industry by developing a cost-reduced recycling ratio that combines a product's recycling ratio (recycled weight/total weight) with the recycling costs. Finally, Vogtlander et al. (2002) are somewhat unique in that they use economics to describe environmental impacts *and* the value of a product in their eco-costs/value ratio; the environmental "costs" are based on pollution "prevention costs".

The ability to measure eco-efficiency in some form is of significant value; however both numerator and denominator must be carefully defined. The Hesselbach paper uses the standard mass-based recycling measure, and the QWERTY method can be applied to virtually any environmental-impact measure. The effort here is to assess options for measuring recycling performance which could then be used as the numerator in an eco-efficiency calculation. Each of the metrics presented above provides insights into material recovery and could be used for eco-efficiency calculations.

4.3 Metric Development

As discussed above, there are numerous performance indicators that could be applied to augment a mass-based recovery measure. These include measures to account for environmental impact (through an LCA scoring system), retention of material performance or quality, or retention of exergy or embodied energy. Because each represents key elements of a system's eco-efficiency, it is likely that a set of simple relevance-weighted performance metrics would be needed. The three metrics developed and evaluated within this thesis are value, energy, and environmental impact-weighted mass recovery indexes.

4.3.1 Value Based Recyclability

The following section examines the use of value as a recycling performance measure. At its most basic level, value-weighted mass recovery assessments, when compared against simple mass recovered, provide a better estimate of both environmental impact (Cobas, Hendrickson et al. 1995) and retained quality (Villalba, Segarra et al. 2002). For materials, value (i.e., price) reflects 1) quality, 2) the cost of production or use (including energy consumption) and 3) scarcity rents for current use of that resource (Hotelling 1931). As such, even with the omission of significant externalities, value does provide significant information about the effectiveness with which resources are reclaimed and returned to productive use.

Like exergy, value provides a measure of the level of application, or degree of downcycling, of materials. Proponents of the exergy measure suggest that this is "an insufficient measure since value depends both on the physical properties of a substance and on the temporal variances of supply and demand" (Connelly and Koshland 2001). They argue that only the physical properties, through the exergy property, should be used in defining this parameter. However, exergy too has significant flaws with this regard - there is significant controversy over the direct translation of exergy to impact. Ultimately, the determination must be whether the results of these measures provide appropriate directional guidance while being cost-effective to calculate.

Value Retention

The "recyclability" index developed by (Villalba, Segarra et al. 2002) uses the concept of value as a proxy to examine resource recovery. The basic assumption of (Villalba, Segarra et al. 2002) is that "the recyclability of materials will be reflected by their monetary value". This leads directly to the Recyclability Index, *Vp / Vm*, where *Vp* ($/kg) and *Vm* ($/kg) represent the market value of secondary and primary material, respectively (Figure 1).

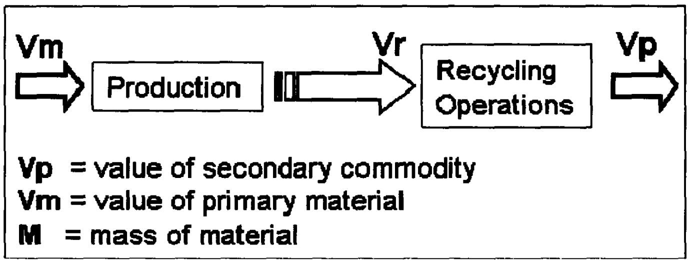

Figure 9: Value based recyclability (Vr is used only in the Value Added measure)

Although originally applied to examine aggregate material flows, this metric can also be used to analyze the recovery effectiveness of a recycling operation or industry. Specifically, this leads to the *value-retention weighted mass recovery index:*

$$ValueRetentionIndex = \frac{\sum_{j} Vp_j m_j}{\sum_{i}\sum_{k} Vm_{ki} m_{ki}} \qquad \textbf{(Eq. 3)}$$

Where subscripts *i* and *j* represent values for inflows and outflows respectively and *k* represents the *k*th embedded material in a given flow. m_x represents mass of a given flow. This measure is essentially the recovered material value over the primary material value for a given system.

This measure would indicate those industries that are able to reclaim not only mass, but also significant EoL value (*Vp*) relative to the value of materials which were originally consumed (*Vm*). Although this measure is conceptually simple (and potentially diagnostic), computing it for complex products or systems can be difficult. For a complex product, there are many materials embedded within the product that flow into and out of various elements of the system. Knowledge of the composition of these flows would be required to compute a recycling index weighting vector for each flow.

The value retention measure gives insight into recovery effectiveness and also provides a quantitative accounting of aggregate downcycling. However, as the only indication of incoming material quality is primary material value (*Vm*), this metric provides only weak indication of the effectiveness of individual operators. Nevertheless, the value-retention recyclability measure should provide useful insight of aggregate system performance to electronic manufacturers and interested regulatory agencies.

Note that if the recovery effectiveness is defined as material recovery effectiveness, any application for reuse is likely to bring the value up above 100%, because the value of electronics sold for reuse is typically far greater than the materials making up the product. If the aim is to understand material recovery effectiveness, it may be necessary to exclude materials destined for re-use. However, in order to evaluate both material recovery effectiveness and utility recovery effectiveness it would be appropriate to set up a separate index to account for the application value or reuse value retention, in which case the appropriate *Vm* value would be the highest potential reuse value, or the value of the piece of equipment when new. For part reuse, Vm would be the value of the new part which the used component would replace.

Value Added

A metric useful in assessing the performance of electronics recyclers must resolve the effect of varying incoming material quality. In a value context, this can be accomplished by integrating the residual value (*Vr*) of incoming materials at EoL (ie., the price paid by the recycler, Figure 9). Given *Vp* and *Vm* as defined above, the impact of recycling processes is characterized by the quantity *Vp – Vr*, which is the value added by recycler activities. To compare various material streams, this quantity needs to be normalized. Conceptually, a useful normalization option is the quantity *Vm – Vr*, which is the maximum possible value-added that a facility could achieve. This leads to the *value added efficiency* measure:

$$ValueAddedEfficiency = \frac{(Vp - Vr)}{(Vm - Vr)} \qquad \textbf{(Eq. 4)}$$

Combining this with mass recovery information yields the *value-added weighted mass recovery index*:

$$ValueAddedIndex = \frac{\sum_j Vp_j m_j - \sum_i Vr_i m_i}{\sum_i \sum_k Vm_{ki} m_{ki} - \sum_i Vr_i m_i} \qquad \textbf{(Eq. 5)}$$

This measure works well except for cases with significant device/component reuse, as described above. This measure is essentially the value generated in the process over the maximum value that could be generated. In cases with significant reuse, Vr may easily exceed Vm leading to a negative value for the measure as a whole, unless a separate reuse index is set up for which Vm is the highest potential reuse value, or the original value of the electronic equipment. Alternatively, if it were desirable that a combined measure clearly indicate the added value from reuse over that of material recovery, the normalization may best be achieved by simply using Vm as a measure of embedded value in the stream, yielding the *value added potential* measure:

$$ValueAddedPotential = \frac{(Vp - Vr)}{Vm} \qquad \textbf{(Eq. 6)}$$

In practice, where this segregation of data for reuse and recovery is possible, the relative value added metric is the preferred metric.

4.3.2 Energy and Environmental Impact Measures

While value-weighted indicators give indirect insight into environmental issues (e.g., energy use, resource degradation), some externalities are not embedded in market derived values (e.g., emissions). To ensure unequivocal progress toward eco-efficiency, measures are needed to address these discrepancies. As noted previously, some life cycle assessment studies have addressed EoL impacts (Anonymous 1998; Socolof, Overly et al. 2001). While these are not useful for ongoing operational decisions, life cycle approaches may form the basis for simpler performance measures which could be used to augment mass-based assessments.

For many life cycle assessments, energy use and its associated environmental impacts is the dominant contributor to total environmental impact. This, along with lesser data requirements than the environmental impact (EI) measure, makes energy a desirable proxy indicator. Because the impacts of energy use do not always dominate impacts, measures of both energy-weighted recovery and EI-weighted recovery were developed and assessed for the three recycling facilities. An EI-weighted mass index would have the same form as the energy-weighted mass index, except that environmental impact of alternatives would be compared using an EI measurement scheme. Therefore this discussion of methodology will use energy as an example.

Like the value metrics above, which focused on the "value retention" or value saved due to material recovery, the energy metric for a facility would focus on the energy "saved" due to material recovery. However, whereas value does this implicitly, the energy (and EI) measure must do so explicitly. This "energy saved" is the reduction in total energy use if a recovered secondary material is used in place of a primary material in a new application. An example of this concept, from the point of view of the recycler, is illustrated below.

A recycler trying to determine the best way to recycle leaded glass from CRTs on the grounds of energy benefit would make the following comparison (illustrated in Figure 10). This leaded glass can (1) be sorted, broken into small pieces and cleaned, then sold for use to make new leaded glass products, or (2) be crushed and sold as-is to a lead-smelter as lead-containing flux. For option (1) the secondary material is replacing new leaded glass, thus the comparison is between the energy required to make the end-of-life material ready for use and the energy required to produce new leaded glass ready for the same use. For option (2) the secondary material is replacing other lead-containing silica wastes, such as contaminated dirt from superfund sites, or replacing sand from a quarry. In this case, the factors in the energy comparison are primarily transportation energy and any differences in smelter efficiency due to different feedstocks.

Note that the prior life cycle impacts of the product entering the recycling phase are not considered. In evaluating materials recovery, these impacts are essentially "sunk costs", which should be allocated to the product's initial use. On entrance to the recycling facility, the product is analagous to an ore, from which materials are extracted. Thus, the comparison is between the energy use of creating a marketable commodity out of this recycled ore, as compared to the energy use of creating a marketable commodity out of ore mined from the ground. However, these commodities are not identical. The value measure deals with this by assuming that substitutability will determine market prices. (Thus, if recycled commodity A is a good substitute for primary commodity B, their value should be similar, with a lower value reflecting poorer substitutability.) The energy and EI measures deal with the same issue by specifically comparing the secondary commodity with the primary commodity that would otherwise be used for a specific application (Figure 10).

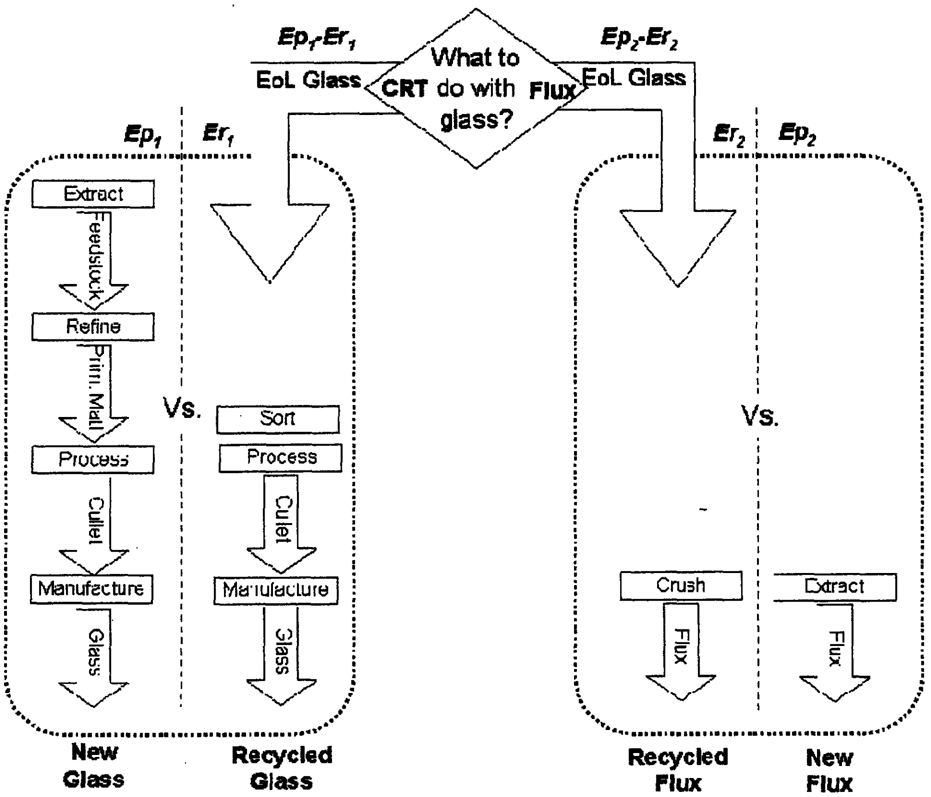

Figure 10: Recycler decision for EoL glass (Rectangles represent processes, arrows are material flows)

In the case of reuse, a similar comparison is made, however additional factors must be included. Product 1 can either be refurbished for reuse, or Product 1 can be recycled. If Product 1 is not reused, one can assume that another product will be used instead. This use is the "application" discussed in the material recycling example. The energy comparison is illustrated in Figure 11.

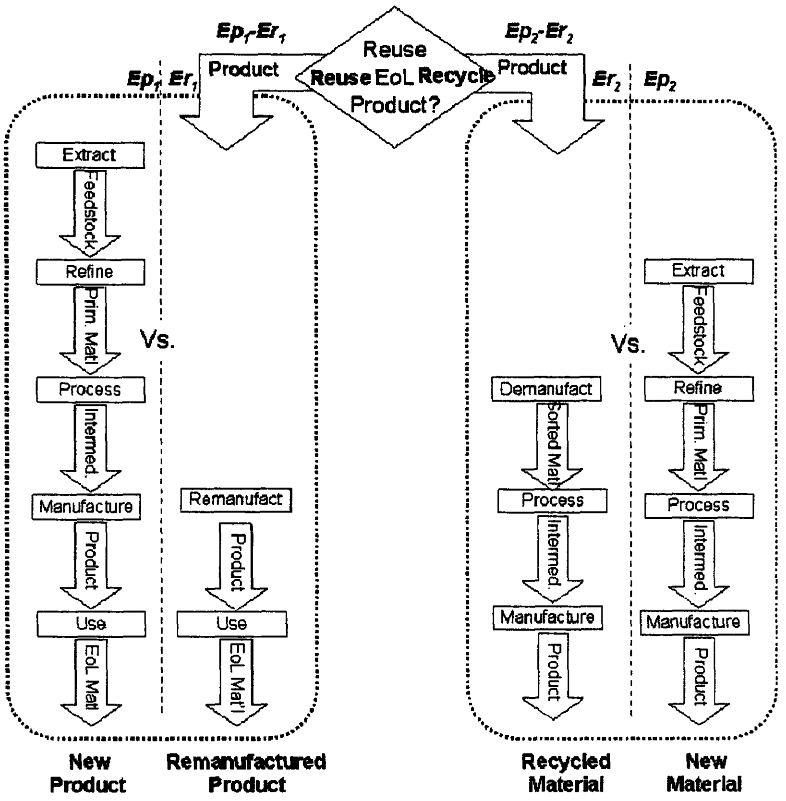

Figure 11: Recycler decision for product reuse

Note that in the reuse case, the use phase of the products is included. In fact, the difference in energy efficiency of the use phase between the new and old product could be a deciding factor on whether or not there is a net energy benefit from product reuse. The full calculation for product reuse would be:

$$EnergyRecovery = \frac{Eremanufacture + Euse}{Epremanufacture + Emanufacture + Euse} \qquad \textbf{(Eq. 7)}$$

Where *Epremanufacture* =the sum of the energy consumed in extraction, refining, and processing of all the materials used in manufacturing the product, and *Euse* = the energy consumed during the product's use phase. An important consideration is that *Euse* may differ substantially between the remanufactured product and the new product: while it is reasonable to assume the same hours of use, the efficiency of the two products may differ greatly due to design improvements in the new product.

Note also that the energy use from the product's first use phase, along with the energy use from the original manufacture of the to-be-refurbished product is excluded from consideration. As with the material recovery example, these impacts of the product's first life cycle are "sunk costs" that should not be included for consideration. It is only the energy savings going forward and not the energy use in the past, which determines the best approach for dealing with the product. In terms of computational effect, if the prior life cycle were not specifically excluded there is the possibility, if comparing two different EoL products, that the product with the greater prior life cycle energy use would be preferentially recovered, even if its recovery was less beneficial going forward.

Following this logic, the *energy-weighted mass recovery index* for a facility would be as follows:

$$EnergyIndex = \frac{\sum_{j}\sum_{k}(Ep_{kj} - Er_{kj})m_{kj}}{\sum_{i}\sum_{k} Emax_{ki}m_{ki}} \qquad \textbf{(Eq. 8)}$$

Where Ep= total energy use to make the primary commodity for use in application A, Er= total energy use to prepare the secondary commodity for use in application A, and $Emax$ = the total energy use to make the primary commodity which has the greatest energy use and for which a secondary commodity with energy use Er could be substituted (for instance, in Figure 10 and Figure 11 $Emax$ would be equal to Ep_1, rather than Ep_2).

The environmental impact, or *EI-weighted mass index,* parallels the energy measure. As with the energy measure, the EI measure is the EI weighted sum of the material flow masses based on the net EI benefits from making secondary commodities available and displacing use of the corresponding primary commodities. The metric used is as follows:

$$EIIndex = \frac{\sum_{j}\sum_{k}(EIp_{kj} - EIr_{kj})m_{kj}}{\sum_{i}\sum_{k} EImax_{ki}m_{ki}} \qquad \textbf{(Eq. 9)}$$

Where EIp= total environmental impact from making the primary commodity for use in application A, EIr= total environmental impact from preparing the secondary commodity for use in application A, and $EImax$ = the total environmental impact from making the primary commodity which has the greatest environmental impact, and for which a secondary commodity with impact EIr could be substituted, as described above for the energy measure.

The value, energy, and EI-weighted metrics developed above will be applied to the electronics recycling case study in Ch 6 and their efficacy will be assessed in terms of their usefulness, robustness, and feasibility. Primary consideration is given to the balance of their informative value and cost effectiveness. Informative value consists of their ability to provide additional resolution and clarity to the understanding of eco-efficiency for the system in question and to provide non-perverse results. An attempt will be made to identify whether measures such as mass or energy efficiency provide insights equivalent to those requiring more analytical synthesis (e.g., aggregate value retention, life cycle emissions or impact).

5. Case Study: Metrics Applied to Three Facilities

The preceding discussion highlights the conceptual advantages and disadvantages of a variety of performance metrics. To understand the practical value of these metrics for improving performance assessment, the value, energy, and environmental impact (EI) weighted measures were exercised against representative data for three recycling facilities. This information is based on data collected from recycling facilities operating in the United States. Subsets of these datasets are used here to protect proprietary information, but are illustrative of complete facility data.

As described in Chapter 4, mass flow data (facility inflows and outflows) is required for all measures. Attempts were made to collect data with as much resolution as possible concerning incoming material and product types by mass. Unfortunately, few facilities were able to correlate incoming to outgoing flows by lot. Of those that did, *none* recorded information about product distribution within lots. Because of this, it was not possible to perform an analysis of the recovered commodity streams by product or customer type. However, an outgoing mass by commodity type was obtained, and an overall understanding of facility mass flows was possible for the selected facilities.

Of the eight recyclers interviewed, only three had data of sufficient quality to enable a mass balance and useful analysis of material flows. The data required for this was 12 months of a facility's inflows and outflows by mass. It is telling that even this level of data collection was not consistently performed across facilities. Few facilities weigh all incoming and outgoing flows, despite the fact that this level of data collection is required to adequately measure even the simplest industry measure of "percent mass of material diverted from landfill".

Each of the three facilities studied provided a complete set for 2003 of one or both of outflows and inflows by commodity. This information generally included some indication of whether a commodity outflow was destined for product and part reuse, for material recovery, or for energy recovery.

Table 18 and Figure 12 below provide an overview of the characteristics of the material processed by the three study facilities.

Table 18: Facility profile (percent mass)

	Prompt focused	Reuse focused	Telecom focused
	1	2	3
Percent Reuse	2.8%	19.6%	2.2%
Percent Revenue from Reuse	23.7%	70.8%	17.13%
Outgoing commodities profile			
High Value, ($4.41/kg)	1.9%	17.3%	2.2%
Mid Value, ($0.88/kg)	15.3%	21.7%	44.4%
Low Value, ($0.24/kg)	67.7%	46.6%	31.7%
Zero-Neg Value, ($0.00/kg)	15.1%	15.0%	21.7%

The commodity flows of the three facilities are provided in Appendix D. Each facility has a distinct customer focus. Facility 1 attempts to maximize incoming manufacturing (i.e., prompt) scrap. Facility 2 focuses primarily on recovery for reuse, and has a higher proportion of incoming EoL products that are reusable. Facility 3 processes primarily telecommunication material and material with higher precious metal content. However, all three facilities do take in a full range of EoL electronic products and materials. Also, even the two facilities which have less than 3% of the mass of their material going for product or part reuse derive a significant proportion of their revenue from reuse sales (Figure 13).

Substantial differences exist between facilities in the value characteristics of the material streams (Figure 12, Table 18). Facility 2 derives 71% of their revenue from material destined for reuse, even though this material accounts for only 20% of the mass of material processed. In contrast, facility 1 derives the majority of its revenue from a large throughput of low value material. The lower processing requirements for these relatively homogenous commodity streams (i.e., from manufacturing scrap) or a higher charge on incoming material are likely what makes the approach viable for this facility. The telecom material processed by facility 3 is primarily mid value material (i.e. high value materials, but not reuse).

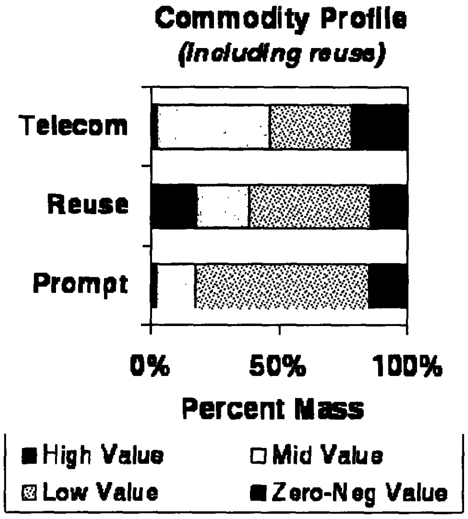

Figure 12: commodity profile by value

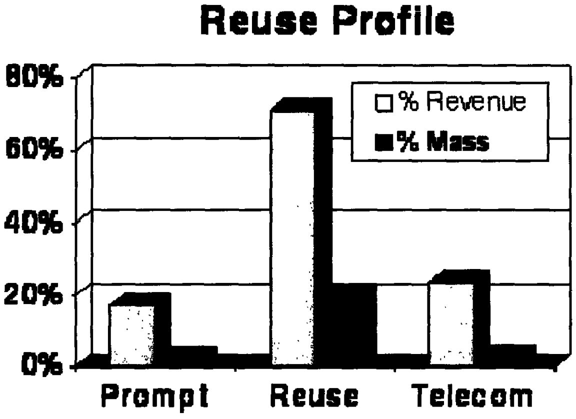

Figure 13: Reuse profile

For all three metric classes (value, energy, and environmental impact), information on the composition of the material flows is also required. To this end, a table of the average material composition of different incoming EoL products was developed from the literature (Appendix C), and the recycler's commodity streams were assigned the most relevant composition. The material composition of each facility's commodity mix is presented in Table 19. Notably, actual product composition varies widely and, thus, these compositional estimates represent the largest source of uncertainty in the work. Current industry efforts to develop a comprehensive compositional database for electronics products could significantly reduce this uncertainty.

Table 19: Material composition of commodities, by facility (percent mass)

Facility	Glass	Steel	Cu	Al	Plastic	Pb	Silver	Gold	Paper	Wood	Other
1	9%	34%	18%	7%	18%	0.8%	0.0101%	0.0013%	2%	0%	11%
2	6%	36%	15%	13%	14%	0.5%	0.2529%	0.0002%	9%	1%	7%
3	2%	26%	10%	23%	5%	0.6%	0.1485%	0.0125%	7%	10%	17%

These composition mixes do not correlate with the revenue profile of the three facilities much as one would expect. This difference arises because reused components provide such a high value and that value is not reflected by the product's material composition.

Each of the measures that are being investigated also requires a specific, unique set of data. The value-weighted measures require data on the incoming and outgoing price for each commodity. This data is already collected and readily available at each facility. For the purposes of this research, however, prices were normalized for all facilities as described below. The value-weighted measure also requires primary material prices. The energy and EI-weighted measures both require data outside the scope of a normal recyclers operations, which would, if used in practice, require availability of some standardized data. In these cases the data required was the energy used and environmental impact associated with refining the secondary material and with refining the primary material, which the secondary material would, in theory, replace.

5.1 Mass and Value indicators

The value-weighted indicators described in Chapter 4, value retention and value added, were calculated for the three recycling facilities. The diagram in Chapter 4 that graphically defines the factors *Vm*, *Vr*, and *Vp* is repeated below in Figure 14 to clarify the following discussion.

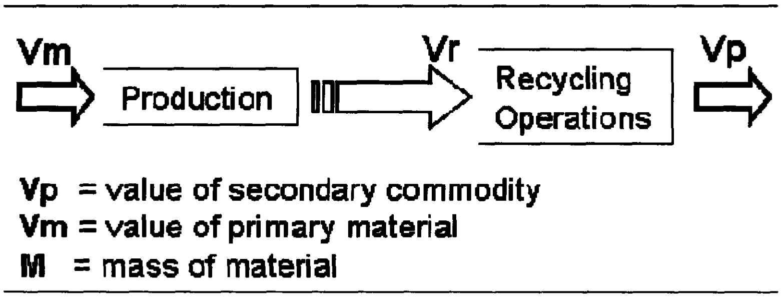

Figure 14: Value based recyclability (*Vr* is used only in the value added measure)

If the value-weighted metric calculations were done by a recycling facility, the specific incoming and outgoing prices (*Vr* and *Vp*, respectively) for each commodity would be used. However, for the purposes of this study, and to protect proprietary facility pricing data, incoming and outgoing commodities were assigned a value as shown in (Anonymous 1996; Anonymous 2003; Huisman 2003; Williams and Sasaki 2003). These pricing schemes represent the average value of the commodity streams from commodity pricing data collected from the three facilities for 2003 operations.

Table 20: Commodity pricing for Vr and Vp

Material Grade	Unit Prices		
	Incoming Products Vr ($/kg)	Incoming Materials Vr ($/kg)	Outgoing Commodities Vp ($/kg)
High	$1.65	$0.99	$4.41
Mid	$0.05	$0.29	$0.88
Low	($0.35)	($0.11)	$0.24
Waste			$0.00

To calculate Vm, each incoming and outgoing material was assigned a material composition based on compositional estimates for EoL Electronics and material scrap available in the literature, and provided in Appendix C. Primary material prices were collected from publicly available sources at the USGS and industry groups (USGS 1998; American Metal Market 2003; Plasticx Universe 2003). Value metric results for the three example recycling facilities are given in Table 21.

Table 21: Mass and value metric results

		Prompt focused	Reuse focused	Telecom focused
		1	2	3
A	Mass Recovery, 1st tier	97%	99%	99%
B	Value Retention (total) : Vp/Vm	48%	99%	27%
C	Value Retention (reuse)	366%	360%	211%
D	Value Retention (no reuse)	37%	32%	26%
E	Value Added (total): (Vp-Vr)/Vm	57%	78%	17%
F	Value Added (reuse)	347%	234%	203%
G	Value Added (no reuse)	47%	36%	9%
H	Relative Value Added (no reuse): (Vp-Vr)/(Vm-Vr)	42%	34%	11%

As shown in the mass recovery metric (row A) all facilities send 3% or less of the incoming material mass to landfill. As such, the mass recovery metric provides little information to distinguish among the three facilities. In contrast, the value metrics (rows B-H) show substantial differences between facilities.

For the value measures that include reuse, the largest distinction is between reuse dominated facility 2 and the other facilities as shown in Table 21. For the total material flow, facility 2 has twice the value retention (row B) and value added (row E) as facility 1 and over three times that of facility 3. This dominance is driven by the greater percent of material diverted for reuse, which is generally the highest value material (indicated by rows C and F).

The value difference between reuse and recycling indicated by the difference between row C and D is consistent with an analogous energy analysis by (Williams and Sasaki 2003). The authors' analysis found that the fraction of life cycle energy saved was 8.6% for resale, 5.2% for upgrades, and 0.43% for recycling. Thus, resale achieves an energy savings improvement of 2000% over recycling. The value retention metric gives improvement results for reuse over recycling of 1126%, 1078%, and 921% for the three facilities. Research on the environmental impact of the semiconductor industry suggests that these dramatic differences between value metric results for material recovery and product reuse are reflective of differences in the overall environmental impact. This difference is due to the significant consumption of materials and energy that goes into making the high purity materials used for components such as semiconductors that go into the useable product. Material recovery alone cannot recapture this energy, material, and financial expenditure (Williams, Ayres et al. 2002).

When material recovery is evaluated separately (i.e., excluding reuse, rows D, G, and H), facility 1 and 2 remain ahead of telecom dominated facility 3. The low value recovery for facility 3 is driven by a high value composition *(Vm)* without a proportionally high value of outgoing commodities. While facility 1 and 2 have comparable value retention results (row D) , facility 1 is found to dominate when using metrics that adjust for the higher incoming material value (*Vr*) of facility 2 (value added or relative value added) (rows G and H). With these adjusted metrics, facility 3 falls further behind, with little difference between value for incoming material (*Vr*), and the outgoing commodities (*Vp)*. These results would indicate that facility 3 does a lesser amount of disassembly and other processing, possibly due to a differing business focus. While facility 2 can use revenues from reuse to cover the expense of additional disassembly, the electronic recycling operations of facility 3 are a secondary business and so there may be less attention paid to value recovery.

5.2 Energy and EI indicators

Energy and EI-weighted mass recovery indexes were also applied to the three case facilities. While these measures are designed to investigate different recycling scenarios, data on the recycling process and ultimate fate of materials needed to support this analysis was lacking. Thus, the comparison made here assumed all three facilities use the same hypothetical recycling pathways for each material. Reflecting back to the discussion in Chapter 4 on the energy and EI-weighted metrics, all glass (or other materials) is assumed to be destined for the same "application", and thus has the same energy and EI measure per unit of mass recovered. If subsequent uses for these materials were known, this would be incorporated into the measure. For instance, separated plastic fractions destined to (1) energy recovery, (2) pure polymer application, or (3) mixed plastic products, could be assigned appropriate energy and environmental impacts. An additional simplifying assumption was that the energy and environmental impact of the facility operations and transport are minor and can be ignored. This is consistent with information from previous life cycle studies which included recovery stage energy consumption. Because direct facility impacts are ignored, the measure is more appropriately described as one reflecting the life cycle impact of operational decisions regarding material recovery pathways. As discussed, this should closely approximate the evaluation of the operations as a whole. The energy and environmental impact measures for the different facilities' recovery operations are thus a function of the composition of outgoing commodities. In accordance with the value measures, reuse applications were excluded.

The material compositions for each incoming EoL product and outgoing commodity that were developed for the value measures were also used in computing the energy and EI measures.

The energy used to produce primary and recycled materials(Ep and Er, respectively), including all upstream processing, was obtained from (K. Habersatter 1991; Keolian 1997; Graedel and Allenby 1998) and are listed in Table 22. An energy value for secondary gold and silver was not available and so the energy value for secondary copper was used because these materials are processed in the same smelting operation.

Table 22: Energy use to make primary and secondary materials

(MJ/kg)	Glass	Steel	Cu	Al	Plastic	Pb	Ag	Au	Paper	Wood	Other
Primary	7	40	100	196	111	41	2,292	181,654	18	18	91
Secondary	6	18	45	27	51	8	45	45	10	10	29

For the EI-weighted measure, the EPS life cycle analysis framework was used(Steen 1999); EPS calculates a single, aggregated environmental impact value. TRACI was also considered for use(Bare, Norris et al. 2003), however, TRACI provides separate impact results for different impact categories, and the single impact value was deemed a more appropriate comparison to the energy and value measures.

There is, however, a complication with use of EPS. EPS places a high value on "resource depletion" (ie: the consumption of, or "loss", of 1 kg of Iron, Al, or Cu in the making of a product). The effect of this is apparent in (Suner 1996), which calculates the EPS values for primary material including the loss of "resource value" of the product (ie: the "loss" of 1 kg of Steel, Al, or Cu in the making of that material). In Suner's thesis this results in a resource value contribution of 8.9% for aluminum, 98.8 % for copper, and 29.1% for Fe in steel to the total EI value. The extent to which inclusion of resource values could dominate EPS results in the calculations for this thesis is presented in Table 23, row C. The inclusion of resource depletion was not useful in the comparison of EI measures and so the "resource depletion" value of products and co-products was excluded from the final analysis. With resource depletion excluded, the next major contributor to EPS scores is energy-related (i.e.: the resource value and emissions related to the use of coal, gas, oil and electricity) as shown in Table 23, row D. For primary glass the major contributor is particulates (62%). For plastics the depleted resources are fossil fuels, which contribute to the making of the final product as both feedstock and energy source. From (Tillman, Baumann et al. 1991) it appears that approximately 50% of the fossil fuels used to make plastics are feedstock. For illustration purposes this value is presented in Table 23. However, it is the original EPS value of 2.05 that was used in the EI-weighted measure, as fossil fuel resources were included for all other EPS scores. Table 23 row D includes all fossil fuel consumption.

Table 23: Significant EI Contributors

	EPS values Primary Mat'l	Glass	Steel	Cu	Al	Plastic	Pb	Ag	Au	Paper
A	w/ resource depletion	0.49	1.88	211.14	3.09	2.05	175.37	54,286	1,269,175	0.46
B	w/o resource depletion	0.49	0.92	3.14	2.65	1.02	0.37	61	4,751	0.46
C	% resource	0.0%	51.0%	98.5%	14.2%	50%	99.8%	99.9%	99.6%	0.0%
D	% energy with out resource	34.5%	50.5%	59.1%	66.7%	94.7%	88.1%	79.2%	79.0%	33%

The life cycle inventory (LCI) data used for these analyses was collected from a variety of sources (Table 24). Where possible, LCI data from industry associations was used. LCI for primary material was available for steel, aluminum, and plastics; these sources did not provide an associated LCI for recycled material. Suner calculated an EPS score for both primary and recycled steel and aluminum, and for primary copper (Suner 1996). The EPS scores used in this thesis for recycled steel and aluminum were calculated by taking a ratio of the primary and secondary EPS values provided in (Suner 1996) and multiplying the ratio by the EPS value calculated in this thesis. However, Suner's EPS values for primary material included the loss of "resource value" of the material produced, as discussed above. This contribution was excluded from the primary EPS value before calculating a ratio.

Table 24: Life cycle inventory data sources

Material	Source (Primary)	Source (Secondary)
Steel	(IISI 2002)	Estimated, Ratio, (Suner 1996)
Aluminum	(Five Winds International 2003)	Estimated, Ratio (Suner 1996)
Copper	(ANL, NREL et al. 1998)	Estimated, Ratio
Plastic	(Boustead 2003)	(Tillman, Baumann et al. 1991)
Gold, Silver	(PRé Consultants B.V. 1997)	Estimated
Paper	(K. Habersatter 1991)	(K. Habersatter 1991)
Glass	(K. Habersatter 1991)	(K. Habersatter 1991)
Lead	(ANL, NREL et al. 1998)	(ANL, NREL et al. 1998)

For copper, the ANL LCI was used because the analysis is specifically for copper from primary ore, without recycling (ANL, NREL et al. 1998), whereas the Suner thesis assumes 20% recycling. Because there was no LCI for secondary copper and because copper recovery goes through a similar smelting process as steel recovery, the ratio of recycled/primary EPS values for steel was used to estimate an EPS score for secondary copper.

For plastics, the recycling destination was assumed to be new plastic applications via mechanical recycling (rather than feedstock recycling or energy recovery). As discussed in Appendix B, electronics contain many different plastics; however ABS and HIPS make up the majority. The energy use values for plastics refer to ABS, for which data was available. The LCI used for primary plastics was a weighted average of the LCIs for ABS and HIPS developed for the Association of Plastics Manufacturers in Europe (APME) by (Boustead 2003), assuming 75% ABS and 25% HIPS. The EPS value for ABS is 2.03 vs. 2.10 for HIPS, so the proportion used did not significantly impact the results. The EPS value for recycled plastics used the ratio of primary to secondary energy use for plastics. This ratio was similar to the impact ratio developed in (Tillman, Baumann et al. 1991). For gold and silver, LCI data for primary material was obtained from (PRé Consultants B.V. 1997). As was done with the energy measure, The EPS value used for recycled precious metals was the EPS value for secondary copper because these materials are obtained through the same smelting process. While an economic allocation would be appropriate, the secondary value for silver and gold is small relative to the primary number, and so there is no apparent resolution improvement from an economic allocation.

The EPS scores for recycled and primary paper and glass were developed using LCI data from (K. Habersatter 1991). For primary paper, the LCI used was an average of the LCIs for 4 primary paper sources. The data for both primary and secondary lead was obtained from (ANL, NREL et al. 1998).

The energy content listed in the LCIs was checked for consistency against energy numbers from (Keolian 1997), and other sources.

5.2.1 Energy and EI Results

Energy and EI-weighted mass index results for the three example recycling facilities are provided in Table 8, in addition to the relative value added and mass recovery measures. As shown, the energy and EI results are both significantly higher than either of the value measures, but are still lower than the mass recovery measure. Like the value metrics, the energy and EI metrics provide significant additional resolution between the three facilities. However, these measures do not show the same relative ranking of facilities that the value measures do. Facility 3, which showed the lowest value in both value measures, has the highest energy and EI results, whereas the energy and EI measures differ in which facility comes in second.

Table 25: Mass, value, energy, and environmental impact metric results

	Prompt focused	Reuse focused	Telecom focused
	1	*2*	*3*
Mass Recovery, 1st tier	97%	99%	99%
Value Retention (no reuse)	32%	33%	23%
Relative Value Added (no reuse): (Vp-Vr)/(Vm-Vr)	40%	34%	7%
Energy Measure (Ep-Er)/Emax	55.3%	65.3%	70.6%
EI Mueasure (using EPS) = (Ep-Er)/Emax	70%	67%	78%

There are a few different mechanisms which could explain these differences:

1. The relevance of particular materials differs between the perspectives of value, energy, and EI.
2. The EI and energy measures assume different processing (investment) than the processing that actually occurs (which is reflected in the value measure).
3. The EI and energy measures assume a single recycling pathway for each material, whereas the value measure captures the actual level of application for each commodity.
4. The EI and energy measures assume full recovery of materials, whereas value accounts for the degree of recovery actually occurring.
5. Loss of material properties is more readily accounted for in the value measure than in the EI or energy measures.
6. The value estimate for facility 3 may have been low if the value assigned to commodities was lower than the actual value.

Ideally, **Mechanism 1** would be the cause of the differences observed. Some materials, such as lead, may command a lower value in terms of recovery but represent real environmental risk. The rationale for using a set of operational metrics is that differences among these metrics could highlight different issues of concern. Unfortunately, it is not possible to directly assess whether mechanism 1 explains differences observed between the value-weighted mass index and the other measures. This is because the value weighted measure was calculated by commodity type, not specifically by product composition. For the energy and EI-weighted measures, however, Table 26 below gives the relative contribution of different materials to the facility recovery results. While the differences are not dramatic, these clearly could have some effect. Again, it is these differences that one would hope to discover as these reflect the rationale for using different measurement schemes in the first place; they are capturing different impacts. The fact that this difference is only minor suggests that, at least with EPS as the EI scoring system, the energy measure would be a reasonable proxy for EI, contributing at least 50% of the score for many materials. Table 23, row D, shows the degree to which this is true.

Table 26: Energy and EI percent contributions to recovery measure total

Energy						
Facility	Glass	plastic	silver	gold	Ferrous	NonFer
1	0%	22%	1%	6%	17%	52%
2	0%	15%	10%	1%	16%	55%
3	0%	4%	4%	28%	7%	55%

Environmental Impact (EI)						
Facility	Glass	plastic	silver	gold	Ferrous	NonFer
1	2%	14%	1%	5%	20%	56%
2	2%	11%	11%	1%	19%	52%
3	0%	3%	5%	32%	10%	45%

Mechanisms 2-5 all highlight one particular difficulty that is inherent to the EI and energy measures: the exact destination of each commodity must be known for these measures to accurately represent facility operations. It is presently highly difficult to obtain data on any of the degree of processing required, the application to which the material is applied, or the degree of quality degradation of the secondary material as compared to the primary material. Therefore, some assumptions must be made regarding these factors. As discussed above, this study assumed a single recycling pathway for each material, and 100% recovery of each material that is not categorized as "trash". It is likely that in some cases the recycling pathway modeled may result in greater energy and EI recovery than the actual level of application. It is also likely that the % of each material recovered is actually substantially lower than 100% due to the highly mixed nature of the material. For instance, small concentrations of plastics or of precious metals may end up destined for processes that recover a different material, thus those small fractions are lost. This could account for a significant amount of the recovery indicated. In contrast, the degree of processing required, the application for which secondary material is replacing primary material and the degree of quality degradation are all factors that are incorporated implicitly in the value measure.

To assess the impact of recovery pathway and processing, the sensitivity of the facility ranking to the degree of energy savings obtained by recovery of secondary materials was investigated (i.e. the difference between the energy use to make each material out of ore or scrap). Sensitivity to the energy savings for Al, Plastic, and precious metals was all investigated. Within a reasonable range of savings, changes in the percent energy savings for each of these materials did not alter the relative rankings of facilities.

The sensitivity of the facility ranking to the actual degree of material recovery was also tested for silver, gold, copper, aluminum, and plastic. The recovery effectiveness of silver, copper, and plastic had little impact on the relative rankings of the facilities. Figure 15 and Figure 16 show the impact of gold and copper recovery on the facility rankings. Figure 15 shows the change in last-place ranking based on the percent recovery of copper and gold, while Figure 16 shows the change in first-place ranking. The axes on the figures measure the actual percent of copper or gold recovered out of the total flow of these materials contained in the end-of-life electronics passing through a facility.It was found that facility 3 is particularly sensitive to the degree of recovery of gold (and also somewhat to recovery of aluminum) switching from 1st place to 3rd place as recovery of gold declined from 70% to 50%. The relative ranking of facility 1 and 2 was most sensitive to copper, switching places at 70%.

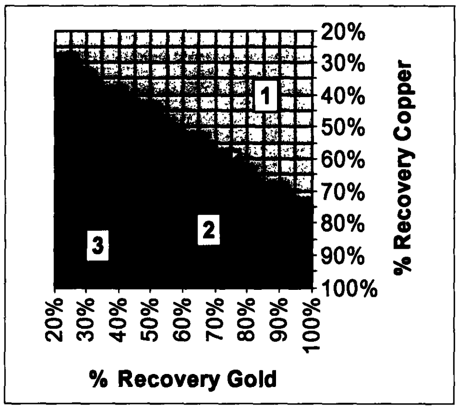

Figure 15: Worst facility ranking by % recovery of gold and copper

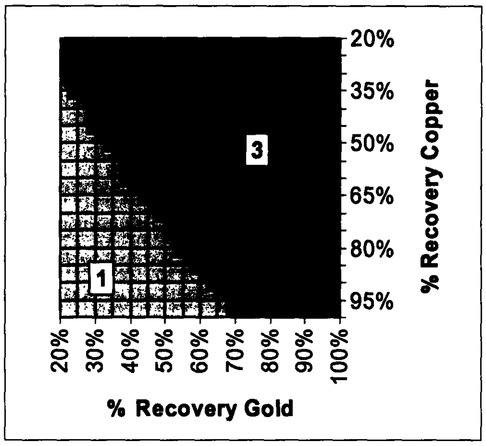

Figure 16: Best facility ranking by % recovery of gold and copper

Mechanism 6 may be one area where assumptions cause a problem for the value metrics. However, if this measure were done by a recycling facility this problem would not occur because they would be using facility pricing data. Thus, it is an artifact of the specific study constraints, not of the measurement methodology. In contrast, a facility is far less likely to have the level of information on downstream operations that would be required to avoid making the assumptions regarding material pathways that are required for the energy and EI measures.

This difference between the benefit of product reuse as compared to material recovery that was described in results from the value-weighted measure was not captured by the energy or EI-weighted measures presented here because the comparisons made accounted for material recovery only. In an alternative form of the metric, reuse was calculated as equaling 100%

energy recovery for the primary material commodities, but not greater. Thus, in either case, the extra energy required for preparing materials for high product-specific standards and for other intermediate processes leading up to and including manufacture was excluded. If the energy measure was done to examine reuse vs. recycling and incorporated these additional energy expenditures, the results of the energy measure would likely reflect those from the value retention measure.

At its most basic level, value-weighted mass recovery assessments, when compared against simple mass recovered, provide a better estimate of both environmental impact and retained quality. As discussed in Chapter 4, even with the omission of significant externalities, value does provide significant information about the effectiveness with which resources are reclaimed and returned to productive use. The energy and EI-weighted measures were developed to address externalities that are not embedded in market derived values (e.g., emissions). These measures, however, require full knowledge of downstream material recovery pathways; data which is often lacking. The effectiveness of the three measures applied to the case facilities is discussed in the following section using the criteria framework developed in chapter 2; effective metrics must fulfill a number of criteria that indicate a measure's usefulness, robustness, and feasibility for a particular system and application.

5.3 Assessing Measure Effectiveness

5.3.1 USEFULNESS & ROBUSTNESS: Informative value of metrics

One measure of metric usefulness is whether the metrics are associated with and support specific goals. For customers concerned only with liability, the existing mass-recovery measure (as well as the cost of services) may be sufficient. If the goals include landfill conservation, then a mass-only measure with an appropriate extension of scope to include all recycling operators could continue to be sufficient. However, if other goals are intended by the recycling activity (e.g., reduced environmental impact and resource conservation) then mass is a weak proxy. For these goals, the three additional metrics evaluated can provide a more comprehensive picture than the mass-based measure regarding the extent and kind of recovery taking place.

In addition to confirming the importance of reuse as a recovery strategy, the value-based metrics also differentiate the material recovery practices of the three operators. Although all three operators divert almost all material from landfill, not all of this material is repurposed as effectively. Based on the value retention measure, both facilities 1 and 2 generate material recovery streams retaining some 40% more value than those from facility 3. Considering the condition of incoming materials, this discrepancy is even greater. Facilities 1 and 2 add significantly more value to their incoming flows than does 3. In the end, the value based measures provide significant additional resolution concerning operator practices. Two facilities retain and add more value, preventing material down-cycling and, presumably, the attendant demand for additional primary material.

The extent to which measures track together is one indication of robustness. With this as a criterion, these metrics do not together appear particularly robust. As discussed above, the energy and EI measures also provide additional resolution but trend in the opposite direction, with facility 3 ranking first instead of last. This difference is likely due to a combination of assumptions that suggest facilities are recovering far more material than they are in reality. However, this could only be conclusively observed once all the mechanisms discussed above were fully examined. It does appear that while the energy and EI measures have the potential to be highly informative about the impact of different recycling choices, the extent to which the energy and EI measure results depend on assumptions of material pathways and degree of loss greatly reduces their robustness. In practice it would be difficult to ensure that these measures were calculated in a uniform way, and assumptions could dramatically influence results. Given the data that is likely to be available, the value measure appears to be significantly more robust. The values used are market-based with many factors inherent in the measure, instead of based on assumptions regarding material pathways..

Another measure of robustness is the potential for perverse results. The value-weighted measure is somewhat susceptible to this problem given that a higher "value" measure could be achieved by a low cost operator as well as a high-recovery operator. If the low cost is from lack of environmental controls or otherwise negligent or negligible processing, the goals for which the measure was originally designed would not be met. For this reason especially, the value measure alone is insufficient to clearly indicate recycling best practices. Better tracking of material mass through the recycling chain would be of value regardless of what combination of metrics was ultimately used.

5.3.2 FEASIBILITY: Cost effectiveness of metrics

In addition to assessing the informative value of the metric results, the metrics' practicality relative to data collection and analysis costs must also be considered. To this end, there is currently no standard recordkeeping by recyclers in the industry. Rather, the level of data collection appears to depend on operator preferences and cost structure. Nonetheless, it should be relatively simple for industry to move from a mass only metric to a value retention measure. All facilities already collect information on incoming and outgoing prices and outgoing mass flows. To this, facilities would need to add 1) incoming mass flows and types, 2) prevailing commodity prices (available from public sources), and 3) models of incoming product composition (rough values available in the literature, more accurate values may be compiled for RoHS compliance). In aggregate, value-based measures should allow for more targeted improvement without burdensome data requirements. A value retention measure weighted by processing costs should be very useful for operators.

Neither the energy nor environmental metric is able to inherently differentiate between subsequent uses in the way the value metric can. However, if subsequent uses are known, each of these methods can provide useful insights. Nonetheless, the data intensity required to do these measures well is a serous limitation for the use of these measures as operational metrics.

As compositional databases become more accessible and facility data collection is standardized, any of these weighting schemes should become more accessible.

5.3.3 Conclusions

Mass-only measures do not fully characterize the eco-efficiency of the recycling system. Detailed life cycle-based analyses provide useful insights to address some of this shortfall, but are not appropriate for making day-to-day evaluations. To meet this need, relevance-weighted mass recovery index measures of retained value, energy, and environmental impact should serve as a useful addition to the assessment toolkit. The efficacy of these measures has not been proven, however the study does give an indication that further development of these measures could improve on existing measures.

As a signaling mechanism, value provides insight to varying degrees into key eco-efficiency characteristics including material quality, processing, and reprocessing cost. As shown in the case above, value measures were able to provide significant additional resolution on the practices of three recycling operators. Although all three operators divert most material from landfill, the value-based analysis revealed that not all of this material is repurposed as effectively. Specifically, one operation was shown to both retain less value in and add less value to EoL product streams. In this case, the value-based metrics were able to identify operations that were retaining value, preventing down-cycling, and, thereby presumably, reducing the demand for additional primary material. Interestingly, the value added weighting methods were also able to provide unique insights in the effectiveness of individual operations in accomplishing these tasks.

The energy-weighted and EI-weighted measures were also better able than the mass-only measure to distinguish between facilities. However, these measures were sensitive to assumptions made regarding the level of next application, and data availability was a serious concern. For these measures to be practicably useful, life cycle impacts for a number of primary and secondary materials must be readily available, and also the application to which a secondary material is to be put must be known.

The significance of precious and light metals in all measures is telling, suggesting a focus on recovery of these materials is justified on multiple grounds. This reflects research done by (Huisman 2003) and others.

This work shows that the goals of recycling must be carefully defined and care must be taken to ensure that the metrics in common use provide direction toward those goals. If the purpose of recycling is to make the most of available resources rather than merely to reduce landfill consumption, then additional metrics are needed to evaluate progress toward that goal. The value recovery and other metrics described in this paper complement existing eco-efficiency analysis tools by providing operational metrics that can be used to assess real-time progress.

If companies are serous about both improving and reporting on their recycling effectiveness, there will have to be greater more consistent data collection. At the same time, developers of reporting requirements and metrics must be cognizant of data collection difficulties and the ratio of informative value to data collection expense of any chosen metric.

6. Conclusions and Recommendations

What are implications of this research for appropriate metrology, legislation, and product design?

While this research may not give definitive answers on either best practices for electronics recycling systems or for the measurement of them, it does indicate that additional measures to those used in practice today may be both necessary and feasible in order to improve system operation. The previous chapters laid out an approach for developing effective measures of sustainability, specifically for the recycling industry, and a characterization of the existing recycling system as a whole. From this understanding, it is possible to make some recommendations for system efficiency improvements and measurement improvement at the level of different actors.

6.1 Dispelling myths and lessons learned

Myth 1: Recycling electronics is inherently lucrative

Some electronics recycling does make a profit from the material by "cherry-picking" high value EoL material. This "cherry picking" includes: selective refurbishing and resale of newer products with high reuse value, selective recycling for precious metals from older electronics and military equipment which have a greater concentration of precious metals, or recycling of relatively pure manufacturing scrap (which is electronics recycling, but not of end-of-life material). However the current push for electronics recycling focuses on the majority of EoL material which has significantly less inherent value.

Policy makers and the public need to understand what recyclers understand all too well: electronics recycling in its current and foreseeable form occurs at a net cost; the recoverable value is lower than the cost of collection and processing. This fact alters what policies would be most effective, the ability of standard economics to drive the system, and the effectiveness of value measures in indicating effective recovery.

Lesson 1: Export may be inevitable

A simple mass balance would show that since much of manufacturing now takes place outside of the USA with completed electronics products entering the states, the USA does not have the capacity to absorb recycled material into production. This alone prevents the USA from effectively recycling its own waste. In addition to larger and potentially better markets, export happens because of inexpensive labor and lower environmental and other controls, which lead to lower costs.

To date, banning of export by other nations has not appeared to stop the flow of material. The ban is not well enforced, and nothing has been done to alter the strong economic driving force for export. In addition a ban on export in the USA may lead to less useful application of materials as non-optimal domestic sinks are found for materials.

Myth 2: 98 % of the material from a disassembly facility is recycled

This primary metric, as used by the first recycler in a recycling chain, only comments on the practices of that facility. As such, this metric omits the vagaries of the subsequent processing of the various streams that emerge from that recycler. The widespread use of this metric can be highly misleading as a measure of recycling system performance. Any reasonable measure of the effectiveness of the recycling chain would have to either (1) acquire direct reports from downstream recyclers, or (2) develop a proxy measure which more adequately indicates the downstream fate of materials. The extent to which downstream facilities practice "disappearing" of material is unknown, but it is known that there is a significant fraction of operators involved in this activity.

Lesson 2: Pay attention to detail: Zero-to-landfill may be counterproductive

While Zero-to-Landfill (Z-to-L) may be an appropriate goal to drive creative design, it is not an appropriate goal for the electronics recycling system as a whole or a sufficient metric for characterizing electronics recycling. Z-to-L neglects:

- The value of material (exergy retained, secondary markets, secondary application)
- The toxicity of material (thus, the value of harm avoidance)
- Processing costs
- Net environmental impact of secondary processing
- Added value of reuse

Thus, it creates goal-driven behavior that does not reflect the real impact of EoL material. In fact the focus on Z-to-L results in activities counter to underlying goals of resource recovery, cost effectiveness, and toxic waste reduction. Pure weight-based targets such as "percent diverted from landfill" are generally less useful than value- or environmentally-weighted targets. Value- or environmentally-weighted metrics give greater resolution and appropriate directionality by focusing efforts on the materials with greater impact.

From the analysis above, it is clear that measuring the percent diverted from landfill is both insufficient to characterize recycling facilities, and can be illusory in that it reflects only the destination of materials from the first recycler, not the fate of materials through the process chain. If material is simply passed on to a later facility where it is then disposed of, this occurs at both an economic and environmental cost to society as a whole. In addition, this metric does not indicate whether materials are well utilized, or whether recovery is sufficient.

There is no way currently to analyze whether reducing the mass percent recycled at a facility level, but focusing on harmful materials and valuable materials, rather than all materials, could lower costs and correspondingly improve collection. Additional data collection and measures are needed for this.

Lesson 3: Reporting is needed along the recycling chain.

While it may be possible to develop metrics, such as those discussed in this thesis which better assess the fate of materials destined for recycling, a truly viable understanding of the recycling system requires reporting by processors at all steps in the recycling chain. The value retention measure, for instance, can give deceiving results if material is sent to locations with exceedingly low costs (either due to low labor costs or lower environmental regulations). A recycling operation may be able to receive materials for a higher (or less negative) price – because operators are processing that material in a less conscientious manner rather than because they have found higher level applications. Effective monitoring is the only way to distinguish these.

Myth 3: "our" metric will transform the industry

In a system with small margins, where obfuscation may be fiscally beneficial, there is little incentive for most firms to add additional measures, regardless of the "quality" of those measures. Some in the industry feel that the standard mass measure is sufficient, that it is not worth the effort to collect more data, and that the client cares about liability more than environmental impact. Better metrics have a hope of transforming industry only if they affect the bottom line, if reasonable reporting requirements for feasible metrics are required by government or customer demand, or if recyclers positioning themselves as "best actors" choose to use and publicize metric results in such a way that this becomes a selling point.

Simply identifying better metrics is *not* likely to have significant effect without a market or regulatory driver to put those measures into practice and reduce the benefit of obfuscation.

Lesson 4: Additional metrics are vital, but should not be data intensive

As was explored in the case study, the existing mass recovery metric does not give sufficient characterization of electronics recycling effectiveness. Additional metrics that help to distinguish among recovery pathways and recycling processes would be beneficial; however measures that are overly data-intensive are unlikely to be used, and if applied, may be difficult to replicate. For example the energy and EI measures have the potential to be highly informative about the impact of different recycling choices. However in practice it would be difficult to ensure that these measures were calculated in a uniform way, and assumptions could dramatically influence results. Given the data that is likely to be available, the value measure appears to be significantly more robust, providing added insights with low data requirements. However, as some materials are net-negative (see Myth 1), these measures can also distort recovery results if disposal (or dumping, or burning) is cheaper than recycling.

Ultimately there must be a balance between metrics with reasonable data intensity on the one hand, and sufficient quality data collection on the other hand. More thorough and consistent tracking of material mass through the recycling chain would be of value regardless of what combination of metrics was used. In addition, as compositional databases become more accessible and facility data collection is standardized, any of the weighting schemes explored should become more accessible.

6.2 Recommendations:

6.2.1 Industry Level

There are a number of things the electronics recycling industry could do in order to improve performance and stabilize the recycling system. Most importantly, proactive actors in the industry could take it upon themselves to self-identify best practices and reporting mechanisms that can be used by all (or risk the legislation of less-preferable requirements). With regards to measurement, these best practices should include at least:

1. tracking the source and destination of inflows & outflows by mass and commodity
2. a mechanism for reporting the flows related to a facility in a transparent way.

There is no clear resolution to the question of how much operational metrics - metrics that are used regularly over time to indicate improvement - are worth in this industry, as compared to the current state of one-off studies. While the industry as a whole needs to be able to demonstrate effectiveness, for additional measurement to occur there must be real added value to operators from improving the level of data collection and using additional metrics. Intensive analyses such as LCA and QWERTY are valuable tools for projecting impacts of policy and design decisions, but are less effective at providing feedback regarding the results of earlier decisions.

In addition, as OEMS are increasingly pressured or required to take back electronics for recycling and answer questions about their environmental practices, it behooves OEMS to develop analyses of electronic recycling systems and develop means to report on effective recyclability. In terms of developing products with reasonable end-of-life costs, OEMS should initiate communication between designers and EoL processors of all sorts and be proactive about creative material choice for end-of-life. For certain products, this may include finding ways to capture the rent from material recovery and developing products with more expensive materials if those materials add multiple benefits. For instance, metallic covers are popular for cell phones – currently these are coated plastic. Making these out of aluminum may increase both their recyclability and consumer value. This would be more attractive to OEMs if they found a way to capitalize on that value.

For OEMs however, the most immediately valuable and feasible leverage point would be to require certain reporting or measurement methods of recyclers that work with them?

6.2.2 Legislative Level

In the USA, materials management is inconsistent at best, perverse and counterproductive at worst. There are currently nine primary federal materials policy legislative acts, twenty primary federal health and safety laws, and numerous state level regulations that affect materials use. Nevertheless, there is no consistent policy toward material systems. It would be worthwhile to revisit the efforts which originated in 1952 with the President's Materials Policy Commission (Geiser 2001) to develop a national materials policy. Along these lines, some of the approaches that may be worth further consideration include removing antiquated mining subsidies and eco-taxation reform, which is a revenue neutral shift of taxes from income to energy and material use(Vehmas, Kaivo-oja et al. 1999; Bosquet 2000). The international flow of materials complicates efforts to internalize the costs of material extraction and processing.

With regard to electronics recycling specifically, the numerous local and state level legislative efforts around the country, resulting in part from national level inaction, create a confusing regulatory maze. In addition, some well meaning regulations provide counterproductive results (at a national and international level). There is a need to assess the alignment of metrics and policies on whether efforts do match legislative goals, and whether they are effective.

Below are four specific policy regulations that could help create a stable working EoL Electronics recycling system. Together these four recommendations form a strategy aimed at internalizing the externalities from end-of-life electronics and coordinating policy at a national and international level to stabilize the recycling industry, simplify recycling, and create a funding mechanism for monitoring and enforcement of proper environmental controls for international recycling and disposal.

Policy Recommendation 1: Tax and monitor, not ban, international recycling

It is uncertain whether the USA will ever ratify the Basel Ban which restricts flow of hazardous waste from OECD to non OECD countries(Secretariat 1989). Concerns regarding ratification are that the ban would disrupt the flow of trade and compromise USA sovereignty while exacerbating the domestic waste problem. Additionally, rather than truly stemming trade, such a ban may create waste migration to the developing nation with poorest enforcement of the ban.

An alternative that could prove effective in creating a working system for international recycling would be to impose a tax on scrap export if participating countries agreed to impose similar taxes. Tax revenues could be distributed to regulating agencies in disposing and receiving countries to be used for monitoring and enforcement of an internationally defined standard of environmental protection for recycling facilities. Some of these fees could also be used for a technology assistance unit that provides grants, technical assistance and technology transfer for better environmentally friendly recycling technologies in the receiving country.

This process would internalize the costs of recycling while creating a funding mechanism for self enforcement. To be enforced, this system would have to be put into law by the majority of involved countries. This kind of agreement may be possible between China and the USA because: China is reconsidering its ban (Lin 2002), the USA is less likely to oppose a taxation solution than a ban, and there is significant NGO and international pressure to come up with an agreement. Development of this system could include regulations that would mandate a certain level of pre-processing or tax specific materials more highly, thus protecting local industries and bringing them on board without crippling the whole recovery system as an enforced ban is likely to do.

While this system does not eliminate the shadow market in electronics recovery, whereby disposal through illicit channels is the cheapest alternative, using tax dollars for monitoring and enforcement would be a significant improvement over a ban for which there are no funds for enforcement. There is a possibility that funds would be misused or diverted through a classic principle/agent problem and negotiating control and allocation of funds is likely to be a difficult task. Given concerns about sovereignty, creating an international monitoring agency is unlikely. Instead, funds would be distributed to national agencies, with occasional cross-nation spot checks of the use of those funds.

Policy Recommendation II: Internalize end-of-life costs in sale price

The solution in Recommendation I allows for international trade in end-of-life electronics. However, the cost of recovering electronics remains above the revenues achieved from the materials contained. Therefore, if recovery is to occur at a reasonable level, some form of subsidy is required. Currently, the final consumer pays the cost of recycling. This discourages recycling by those who are not either mandated to or predisposed to recycle. A number of voluntary systems (such as computer takeback) require payment at disposal, but these have consistently low participation. Rather, incentives for consumers to participate may be a critical component for high collection rates.

For collection, a mandatory deposit – refund system ("bottle bill",) such as the one that exists for lead acid batteries, may ultimately be the best method because of its simplicity and clarity. Like income taxes, this is one area where a legislative response to an Olsonian collective action problem could become accepted by the public. However, this only addresses the issue of collection.

The consequences of relying on an end-of-life disposal fee to fund the recycling were clearly apparent under Japan's first Specified Home Appliance Recycling ("SHAR") law. Because industry vehemently opposed internalizing takeback costs into upfront product price, financing was set up so the end-user paid a fee for recycling at the time of disposal. However, to avoid paying the fees, illegal dumping of WEEE by households increased by 25% the month after SHAR came into effect. Japan learned from this mistake and the second phase of compulsory recycling of PCs under the Electric Appliance Recycling Law charges consumers a recycling fee at the time of purchase instead of the time of disposal (Lin 2002). California recently adopted a similar approach.

If an upfront fee is charged, some mechanism needs to be put into place for maintaining and redistributing the funds. Debates over who maintains these funds and whether companies can still consider the funds part of their assets presents no end of complications. The National Electronics Product Stewardship Initiative (NEPSI) dialogue that started in April 2000 to develop a "system, which includes a viable financing mechanism, to maximize the collection, reuse, and recycling of used electronics, while considering appropriate incentives to design products that facilitate source reduction, reuse and recycling; reduce toxicity; and increase recycled content" (Staff 2004) floundered on the debate over a funding mechanism. In the fall of 2004, there was renewed speculation that NEPSI would reach a consensus recommendation by January 2005, however as of February 2005, that projection too appears to have slipped. According to Recycling Today Online (Staff 2004), a compromise funding system may include a fee at point of sale, but would allow manufacturers to choose whether to use collected fees to run independent take-back programs or join a pooled takeback program.

Policy Recommendation III: Coordinate local, state, and national regulations

Due to a current national regulatory climate favoring reduced regulation, states such as CA and MA are driving DfE and takeback legislation for the nation. National regulation is most likely to occur if manufacturers realize that the occasionally stringent patchwork method of regulation is to their detriment. When the NEPSI dialogue floundered, the EPA voiced a reminder of what would happen if a voluntary agreement was not reached:

> "The question you face today is very simple: does the electronics industry want to have a voice in designing that system? Or will you have to accept a system that is imposed on you by the states, one by one, or by the U.S. Congress through federal legislation? .... Today the solution to the problem of recycling electronics is in your hands. Tomorrow it might not be. You need to act now." (Horinko, 2003)

The extent to which this threat is viewed as real may determine the level of cooperation of the parties involved. The longer they wait, however, the more likely there will be another voice to contend with. Recyclers are consolidating and beginning to organize. This industry, which derives its primary revenues from fees collected rather than revenues from materials recovered, has different objectives than the OEMS and few other agendas to diffuse their lobbying efforts. This industry requires high volume in order to survive. Thus, domestic recyclers may favor landfill bans, export bans, cost internalization, and any other means to increase volume and funding for their services. This may not be the best for OEMS or recovery system efficiency.

Policy Recommendation IV: Design regulations with better metrics

Following the thrust of this research, it is important that policy requirements are designed with appropriate measures: measures that distinguish between materials and prioritize recovery on the basis of reduction of environmental impact and retention of value. The USA should not simply follow in the steps of the EU's WEEE legislation which measures recovery on a percent mass basis, but rather design any requirements and reporting mechanisms to allow for the fact that some materials are more important to recover than others.

6.2.3 Design Level: Insights in design for end-of-life

This thesis did not focus on product design and thus cannot suggest specific design improvements. However the work on metric development and the characterization of the electronics recycling system can provide some insights.

Designers also operate knowing that their products may be recycled with a very different technology than predicted. This makes DfR difficult. However, design for product and component reuse is supported by numerous studies indicating the superior environmental and economic value reuse over material recovery. In terms of material recovery, there are no easy answers for how to design products given uncertainty about ultimate disposal methods. However, creative consideration of end-of-life scenarios during the design phase would likely improve end-of-life handling. In doing so, attention should be paid to (1) the relative significance of different materials in terms of value and environmental impact, (2) existing patterns of product use and dispersion, (3) existing and emerging recycling process technologies, and (4) recycling economics including both processing costs and also the creation of markets for secondary materials.

6.3 Future Work

This thesis provided insights for both electronics recycling and the development of operational sustainability metrics. However there is much work left to be done. This includes a strengthening and expansion of the research done to date on electronics recycling which is outlined below. In addition, the methodology for developing operational sustainability metrics could be applied to most systems. Case study work similar to what was done in this thesis would be beneficial, however ultimately the work to incorporate sustainability into operational decision making must be done from within industry.

Case expansion and further metric analysis

The most immediate work would be a more thorough analysis of electronics recycling metrics using a broader set of operators, providing a more robust analysis of the criteria. Since the effectiveness of electronics recycling is not simply defined at the facility level, an investigation into metrics that would be effective at the system and facility level would be appropriate.

System-wide characterization of electronics recycling in practice

There is a need for a mass balance of electronics recycling material flows. Currently there exist only rough estimates of the material heading overseas and very little understanding of the material processing pathways or system economics. An adequate characterization has not yet been done, in part because it would involve acquiring an understanding of semi-elicit flows and characterizing flow pathways, information of which electronics recyclers are highly protective. A reasonable characterization would greatly help in any analysis of the electronics recycling system.

Recycling system modeling

With an improved metric set and characterization of electronics recycling in practice, it should be possible to develop a model of the recycling system to evaluate impact of changes in product design, regulation, or material economics.

The modeling work done by Huisman and Stevels (Stevels, Ram et al. 1999; Huisman 2003) is very useful to analyze best practices for recycling of individual products in Europe. There is a need for both a similar model for recycling in the United States, and for an economic/material flows model which is capable of assessing how material flows would change based on the above factors.

This model could ideally be integrated with optimization methods, allowing for an assessment of the best approach to achieving highest value retention with lowest LCA impact.

6.4 Final Comments

This thesis has sought to address three major issues; the development and application of operational sustainability metrics, the assessment of electronics recycling operations and systems, and improving the metrics in use for electronics recycling. This research provided a set of criteria for evaluating new sustainability metrics, and an overview of current developments for material specific metrics such as resource use and material cycling. Additional measures for resource recovery in the context of electronics recycling operations were developed and applied to three case study facilities. The results of this case study indicate that additional measures to those used in electronics recycling today may be both feasible and necessary in order to improve system operations and move toward sustainability. In addition, a characterization of the recycling system as a whole was presented, and recommendations were made for the industry and policy makers regarding appropriate use of metrics and improving system operations.

It is evident from this research that the goals of recycling must be carefully defined, and metrics designed to reflect those goals. Is the goal simply to remove material from landfill at any cost, as the current metrology would suggest, or is the goal to provide the greatest recovery of value and the greatest reduction in environmental harm at the lowest cost to operators, consumers, producers, and society?

More generally, unless stakeholders within society have a clear understanding of societal and stakeholder goals, along with metrics and incentives that move toward those goals, we are, as the proverb says, "likely to end up where we are [currently] headed", which most available indicators suggest is not toward greater sustainability.

The industrial revolution is 250 years old. The progress and the problems created in that time are astounding. In addition, the pace of change is accelerating rapidly. We will almost surely make equivalent or greater changes in upcoming years. The question is not whether change will occur but in what direction those changes will be made. It is our onus to review our goals and develop measures and policies to ensure that the human creative force, amplified by technology and harnessed by industry, moves us in the direction of sustainability instead of away from it.

Appendix A: Primary and Downstream Recycler Questionnaires

Primary Questionnaire

Code # ____

This is an example questionnaire for the electronics recycling material flows project. What follows is a guide. We look forward to talking with you in person.

Characterizing Supply (Inflow)

The first question will help us define your operations in general terms so that we can mask our results in a useful way.

1. Please rank your top three activities in terms of revenue generation and in terms of throughput.

Revenue, Throughput Categories:

______, ______ **Product Re-Use** as-is, surplus and refurbish

______, ______ **Parts Recovery & Re-Use** e.g. electronic, mechanical, electro-mechanical

______, ______ **Materials Recovery & Recycling** demanufacturing, separation, preparation for processing e.g. plastics, metals, precious metals, glass, other ______(circle material specialty)

______, ______ **Materials Processing/Refining** shred, grind, palletize, refine,

e.g. plastics, metals, precious metals, glass, other ______(circle material specialty)

______, ______ **Other** e.g. incineration, manufacturing, brokering, etc. If one of your primary activities is not among these categories, please describe it. ____.

In general we want to know how important electronics recycling is to your business, and whether electronics are your primary or a supplemental source of revenue.

2. What do you process aside from electronics?

____

3. What percent of your business revenue comes from the processing described in # 2 and from other activities that do not involve end-of-life electronics? ________________
4. What End-of-Life electronics do you process?

____

We are trying to understand what drives value for scrap electronics, particularly the material that is not resold as working units or parts. We want to focus on the most important incoming end-of-life items, and *then proceed to identify the important characteristics driving the material value. The next set of questions will help us assess these points.*

5. Estimate the quantity of electronics or electronic scrap that you accepted in 2002. If possible, estimate for each kind of incoming electronics listed in question # 4. *[number of units, tonnage].*
6. What form are these electronics in when you get them, and what percent is in each form? *[Whole units, components, etc.]*
7. Do you classify these incoming EoL electronics into different grades/categories? *[Y/N]*
8. If yes, what is the classification system, and what characteristics are used to assign grades?
9. Our focus is on the portion of end-of-life electronics that are not refurbished or resold as parts. For the remaining material, what characteristics make incoming EoL electronics more or less desirable, why? *[eg: mixed composition or contamination may effect scrap revenues.]*

	Primary Concerns					
Characteristic	Operating cost	Component value	Material value	Disposal cost	Liability	Other _______
Eg. *Age*		X	X			

10. For the most important items identified, what is the range you charge for processing (do you charge by product and/or grade)? *$_______to $______per _____[units, lbs,...]*

Processing

We want to understand what processing you do in house.

11. Do you use primarily automated or manual disassembly? ______________________________
12. What amount (by weight or by units) of the EoL electronics received in 2002 was refurbished/ reused?
13. Outline a typical processing sequence; what processing steps would incoming EoL electronic scrap go through in your facility *[assessment> disassembly> assay > shredding> sorting > sale]*
14. For each processing step,
    a. What is the form of the material before and after processing
    b. What equipment and additional materials are used in that step
    c. What is the cycle time for that process
15. What is the next piece of technology you are thinking of purchasing?

16. What is the sf of your plant? ____________________

Ouflow

We want to understand how revenue is generated in scrap electronics and the capacity of existing end markets. For this purpose we want to track the flow of the scrap and its form at each step in the recycling chain. As we did with the incoming scrap, we want to characterize the product streams after processing and identify what grades or measures of value you use to distinguish these. The following questions are similar to those we asked about incoming electronics.

17. After completing in-house processing, in what form is the electronic scrap/material shipped out? *[eg, baled plastic housing, ...]*
18. What grades/categories do you use to characterize outgoing parts and commodities?
19. What characteristics are used to assign these grades?
20. For outgoing commodity grades, what contamination and/or co-mingling is acceptable?
21. Who takes the processed EoL materials? *[your vendors, downstream processors]*
22. How much of the commodity do they take?
23. What do they charge or pay to take the material?

Please feel free to use the following list, if it helps you to organize your response. These questions will be explored during subsequent data collection that will follow selected lots of end-of-life electronics.

Outflow

	Material Form[5]	**Company Name[6]**	**Quantity 2002[7]**	**Transfer Price[8]**
Whole units [with working value]	1.			
	2.			
	3.			
Components [Hard drives, memory, etc.]	1.			
	2.			
	3.			
Monitors, CRTs, CRT glass	1.			
	2.			
Ferrous metal scrap	1.			
	2.			
Nonferrous metal scrap	1.			

---

[5] The physical form, or identifying category of the material at the time it was sold /transferred to another company.

[6] The name of the company that received the end-of-life material.

[7] The amount of the material transferred to that company in 2002.

[8] The price charged or paid to transfer that material, either per unit or for the whole shipment.

	2.			
	3.			
Precious metal scrap [obsolete CPUs, etc]	1.			
	2.			
	3.			
Plastic Scrap	1.			
	2.			
	3.			
Cu wire, tubing				
Batteries, Hg switches				
Packaging waste				
Other				

Regulations

We want to understand the perspective of recyclers regarding current regulation and regulatory options.

24. What regulations most effect operations of your business?

25. Are you subject to regulations on transport of material?

26. What environmental permits/certifications does your company hold?

27. Are there specific changes to these regulations that would benefit your operations?

Downstream Recycler Questionnaire

Code # ______________________________

This is an example questionnaire for the electronics recycling material flows project.

While we would appreciate any information you would be willing to share about how your processes operate, our primary objective is to correlate material inflows with outflow composition to determine the fate of materials originating from end-of-life electronics and how value for those materials is generated through processing.

What follows is a guide. We look forward to talking with you in person.

Characterizing Supply (Inflow)

28. What material do you process?
29. What are your primary sources of scrap material?
30. What percent of the material that you process comes from electronic scrap?
31. What forms of electronic scrap do you receive?
32. Do you classify this incoming scrap into different grades/categories?
33. If yes, what is the classification system, and what characteristics are used to assign grades?
34. How is scrap of these different grades used in your operations?
35. What is the range that you charge or pay to take the scrap material (by grade)? *$______ to $_____ per ton*
36. What was the quantity electronic scrap of each category that you accepted in 2002?

Processing

We want to understand what processing you do in house. In particular, we would like to correlate inflows to outflows for electronics scrap. We recognize this may be difficult if electronics are a small fraction of your total material flow.

37. Outline a typical processing sequence; what processing steps would incoming electronic scrap go through in your facility?
38. Is there a flow chart available of the process?
39. Do you record composition of specific incoming, intermediate, and outgoing material flows? Which flows?

40. What is the next piece of technology you are thinking of purchasing?

Ouflow

We want to understand how revenue is generated in scrap electronics and the capacity of existing end markets. For this purpose we want to track the flow of the scrap and its form at each step in the recycling chain. As we did with the incoming scrap, we want to characterize the product streams after processing and identify what grades or measures of value you use to distinguish these. The following questions are similar to those we asked about incoming electronics.

41. What are the outgoing products and waste streams resulting from in-house processing?
42. What grades/categories do you use to characterize outgoing commodities?
43. What characteristics are used to assign these grades?
44. Who takes the processed materials?
45. What do they charge or pay to take the material?

Regulations

We want to understand the perspective of recyclers regarding current regulation and regulatory options.

46. What regulations most effect operations of your business?
47. What environmental permits/certifications does your company hold?
48. Are there specific changes to these regulations that would benefit your operations?

Appendix B: Material Issues – Material Pathways and Economics

Modern electronics contain a wide variety of materials, including metals, plastics, and ceramics. Not surprisingly, the eventual recovery pathways for these materials can be substantially different). This appendix summarizes the common processing routes and associated issues for major categories of EoL materials. These materials and their typical destination are listed in Table 27.

Table 27: EoL Electronics material pathways

Material/Parts	**End Uses, processing**
Reuse, refurbish Reuse, parts	Reuse markets, overseas, donation Repair, refurbish, manufacture of lower-end product
CRT Glass	New CRT glass, fill material, flux for smelters, other shielding applications
Non-Ferrous metals	Remelt, or primary or secondary smelters
Ferrous metals	Steel recovery
Precious metals	PM recovery in smelter
Toxics (batteries)	Specialized recovery (lead, cadmium) or hazardous waste disposal
Plastics	New polymer, non-polymer product applications, road grade, waste-to-energy, disposal

Reuse - Subsidizing an Industry

Reuse is a significant income source for the majority of dismantlers and other operators early in the recycling chain, even if it represents only a small fraction of the incoming material mass. The reuse value of a computer can be significantly higher than the value of the embedded materials (Table 10). Thus, most recyclers have some way to assess and refurbish computers and components. Reuse of components can extend far beyond the technological life of the product; chips, storage devices, fans, and other components from obsolete equipment can go into lower end products like electronic toys or ATM machines. This reuse market is likely to be stronger in locations with more extensive manufacturing of such products.

Reuse provides additional economic and environmental benefits beyond material recovery, as much of the environmental burden of electronics products is not from the raw materials, but rather the intensive refining and manufacturing process that enable modern electronics (Williams and Sasaki 2003). Thus, any attention paid to remanufacture (Williams and Shu 2001) and strengthening the reuse market, is justified. Unfortunately, the rapid obsolescence of electronics means that there is only a limited window of opportunity for the reuse market, and the amount of material that is destined for material recovery or disposal is inevitably bound to increase. The reuse market is also hindered by the legacy problem. Old computers that are sold or donated to overseas markets or schools and charity organizations inevitably must be disposed of – at a fee. Thus, some typical donation facilities, such as the Salvation Army, have started refusing to take electronics, in order to avoid the expense of disposing of unsold products. This and other issues would be somewhat alleviated by an advanced recovery fee where the cost of recycling is paid at purchase, making ultimate disposal free to the final owner.

Glass/Lead:

Recycling of cathode ray tubes (CRTs) from computer monitors and TVs has become an area of much concern, because CRTs, like printed wire boards (PWBs or PCBs), do not pass the federal government's Toxicity Characteristic Leaching Procedure (TCLP) Leachate test. The debate over the significance of this was previously discussed in Chapter 3. However, the result is that CRTs are more heavily regulated than other end-of-life material, with CRTs in TVs and monitors specifically banned from landfills in some states.

The major (existing and potential) domestic markets for EoL CRT glass are reprocessing into new CRT glass and use of the glass as flux in Pb or Cu smelters. There is a wide array of other small niche markets, many of which take advantage of the lead in the glass in some way, and most of which use the glass to replace low-grade sand or silica requirements. These include: mine filling material, sandpaper, matchbox striking surface, sand-blasting material for removing lead paint (Menad 1999), as well as projected uses in x-ray shielding, decorative tile, decorative glass, construction aggregates, highway reflective products, fiberglass, and glass bottles for pesticides (Dillon 1998).

A major market overseas is remanufacture for use in TVs. This would be the environmentally preferable destination; however, it is unclear what happens to unacceptable material or material at the end of its second lifetime. On a related note, the environmental requirements for domestic smelters are generally greater than those for smelters in less developed nations. This is a significant factor in smelter competitiveness, environmental implications, and price of goods sold.

Closed Loop Glass-to-Glass Recycling

The EPA has encouraged closed-loop glass recycling of EoL CRTs into new CRTs, however this preferred market is limited by a number of factors including purity of the recycled glass "cullet" and a diminishing amount of CRT glass manufactured in the USA. The percent of CRT glass sales from USA CRT manufacturers decreased from 1995 to 2000 from 63% to 46% (Monchamp, Evans et al. 2001) and is likely to decline further. In addition, the transition from leaded panel to unleaded panel CRTs and from CRTs to LCDs both act to further limit the market. Mr. Dlubak of Dlubak Glass, one of the two primary collectors of glass for glass-to-glass recycling, has been quoted as saying "There may not be a CRT or TV industry in the US in a few years", and others in the industry have made similar comments.

A survey conducted by the Electronic Industries Alliance (Monchamp, Evans et al. 2001) found that the capacity of the glass-to-glass recycling pathway was 125,100 tons annually using the present system, with a conservative estimate of 161,600 ton capacity with better technology for glass sorting. In 2000, US CRT manufacturers used 43,800 Tons of recovered glass, including manufacturing scrap, meeting 28% and 56% of the capacity for recycled funnel and panel glass respectively (using current technology). As recently as 1990 the USA CRT glass industry used no recycled glass in their operations. The industry's manufacturing scrap at this time was also sent to local landfills or to smelting operations (Magdits 2004). Outside pressure has caused the industry to begin to include new and old scrap material in their operations. The market value of CRT glass cullet averages 180$/ton, however cleaning and sorting costs can outweigh the revenue to be gained from the high level re-application.

The effect on recycling of the shift to LCDs from CRTs is unclear. LCDs have mercury lamps which are of concern to recyclers. However there is not currently sufficient volume or regulatory attention for recycling pathways to have developed. It is unclear the extent to which CRTs will continue to be made and used in LDCs or for alternative applications like ATM machines, thus extending the life of this recycling application.

Glass in Smelters

For CRT glass, the end-use with the largest capacity is its use as a fluxing agent in lead or copper smelting. While lead, copper, and other metals may be recovered in the process; the content of these metals in the CRT is small. Although the lead content is minimal, the lead is not the only reason for its use in a lead smelter; the silica content of CRT glass is used as a fluxing agent in both primary and secondary lead smelters. The information in this section is primarily from an interview with Louis Magdits from Doe Run (Magdits 2004).

Primary Smelter

Primary lead smelters around the world use essentially the same pyrometallurgical process to smelt lead-containing ores, which are often high in sulfates and sulfides. The process involves sintering, a roasting operation that uses silica and iron ore as fluxing agents to convert lead sulfides into lead oxide and SO_2 gas which in many cases is converted to produce sulfuric acid. The product of this process is sinter which contains lead oxide, iron and silica. The sinter is combined with additional silica and fluxing agents and reduced in a blast furnace to produce lead bullion.

CRT glass can be used as a fluxing agent in both the sinter plant and the blast furnace. Substitutes for this use of CRT glass include any number of silica bearing materials including crushed soda bottles, sand, etc. The lead yield in the process is at least 99%.

Secondary Smelter

Secondary lead smelters use a variety of methods to recover and refine lead from a wide variety of lead bearing materials. Materials processed by secondary smelters include manufacturing plant scraps, (dross, residues, etc), end-of-life consumer products such as lead-acid batteries from automobiles, CRTs, and also lead contaminated material such as lead paint, leaded soil from Superfund sites, rifle and skeet range cleanups, and other decontamination efforts. Since secondary smelters do not have to convert lead sulfide type materials a sintering process is not used. Secondary plants typically use rotary (common in the EU), reverbratory, or blast furnaces. Some will use an electric arc furnace.

Typically the rotary and blast furnaces use silica as a fluxing agent. In this process, fluxes such as silica re used to modify the metallurgical properties of the slag. Characteristics such as melting temperature, pH, viscosity, and other factors are modified to achieve optimal smelting efficiencies. Reverbratory furnaces typically do not require silica as an added fluxing agent. Some secondary and primary smelters can recycle the silica bearing slag produced so silica is reused in the process multiple times.

Virgin silica is relatively inexpensive, (5$/ton delivered), however there are alternative substitutes for the material used in both primary and secondary smelters, such as soil from superfund sites as well as sand and soil from rifle and skeet ranges, for which the supplier's alternative is disposal at a substantial cost. Thus, while silica is a necessary input, CRT glass is competing with other negative value materials. For this reason there is generally a charge to take CRT glass.

Metal Scrap (Cu, Fe, Al)

The majority of metals in E-waste is easily recovered by either hand sorting (for metal housings and large components) or through a mechanical process consisting of shredding, magnetic separation of ferrous material, and eddy current separation of nonferrous metals from plastics and other non-metals. The eddy current can separate Al, Zn, Ag, Cu, Brass, Pb because of differences in material density and electrical conductivity (Kang and Schoenung 2004). Pure metal streams, typically from manufacturing scrap, can often be remelted for reuse, but lower purity metal streams, such as the majority of EoL electronics scrap, will be smelted in primary or secondary smelters.

Copper

While Cu is a valuable metal and electronics representing a significant demand for the material, recovery of Cu remains quite low. This low recovery is primarily because of the low Cu concentration in electronics scrap.

> "These metals would be worth recovering by existing methods if the quantities were large enough and if the scrap were uniform enough in quality, but neither is true." (Ayres, Ayres et al. 2003)

The majority of Cu in electronics (as well as in appliances and auto scrap) is low grade scrap which is processed like ore in primary or secondary smelters. The scrap is fed into a blast furnace to produce 70-80% wt% "black copper", which is oxidized to 95% wt% "blister copper", which is melted in an anode furnace where 99.99% pure copper is deposited on cathodes (Kang and Schoenung 2004). High grade Cu Scrap (No. 1, consisting of wire, cable and copper tubing, and No. 2, consisting of unalloyed scrap with minimum 94% Cu, typically from manufacturing scrap) commands a high price and is simply re-melting not smelted.

There is currently no commercial demand in developed nations for low grade Cu scrap (scrap with a copper content of less than 30% in US and EU, or 50% in Japan). In Japan, where recovery is relatively high, Cu recovery from electrical and electronic appliances is roughly 20%, the lowest for all Cu products. This low grade Cu scrap may be recovered for the value of commingled precious metals (PWBs, for example, which have only 10-20% Cu scrap, are processed for precious metal value).

While manufacturing scrap is typically well recovered, the domestic recovery of secondary (old) scrap is declining. Three trends are suggested to account for this (Ayres, Ayres et al. 2003):

1. increased exports to less-developed-nations (China and Taiwan)
2. consumption patterns shifting toward infrastructure uses (with a long useful lifetime)
3. increased complexity and spatial dispersion of Cu products such as appliances and electronics. (Waste electronics account for 50% of copper waste (Ayres, Ayres et al. 2003)).

According to (Ayres, Ayres et al. 2003), the ratio of old to new copper scrap in the US has declined as has secondary processing of copper, from a high of 31 processors in 1976, down to 8 in 1985, with only one remaining today. As with lead smelting, increasingly stringent environmental compliance costs and declining metal prices have driven scrap processing overseas, with China the biggest importer of this scrap (Ayres, Ayres et al. 2003).

Precious Metals, Printed Circuit Boards, and Toxics

Precious metals account for a significant fraction of the recovered value from electronics scrap and very little of the WEEE mass. The recovery of light and precious metals is the most well defined recycling process, and the most valuable product, after reuse.

Precious metals are found primarily in printed circuit boards and connectors. Ultimately, precious metals such as gold, silver, palladium, and platinum, are recovered in a precious metal refinery through a series of smelting, electrolytic refining, and leaching processes (Kang and Schoenung 2004), which is generally described in any metallurgy text. While some dismantlers send precious metal bearing material as-is to smelters, others engage in wet or dry separation methods (like leaching) to get concentrated precious metal material that reaps a higher price for the refinery.

The recovery of precious metals overseas is of concern in that methods using cyanide to leach precious metals can be environmentally damaging. These methods also may result in incomplete recovery, as precious metals that are not directly exposed (for instance, encased in plastic) will not be recovered. Recovery in a smelter results in higher recovery levels. However, for low grade material, there is the risk that it may not be able to be processed in a smelter: a smelter has to show that they are taking a positive-value raw material – otherwise it is classified as hazardous-waste, and they have to go through a different permitting system. Currently some precious metal containing electronic material is approaching that limit

Plastics

A topic of much consternation in the electronics recycling field is what to do with the plastics from EoL electronics. According to the American Plastics Council there are 15 prevalent types of plastics used in all electronic applications (Figure 17).

In consumer electronics, High Impact Polystyrene (HIPS) and Acrylonitrile-butadiene-styrene (ABS) dominate the plastics recovered. For TV's the plastic content is over 80% HIPS whereas for computers the plastic content is approximately 40% ABS (Figure 18). However, it is, ultimately, small quantity plastics that present the greatest recycling difficulties. While pure plastics can command a high price, mixed plastics typically have a zero to negative value, and a cost effective means of separating plastics, while a topic of significant research, has not been found.

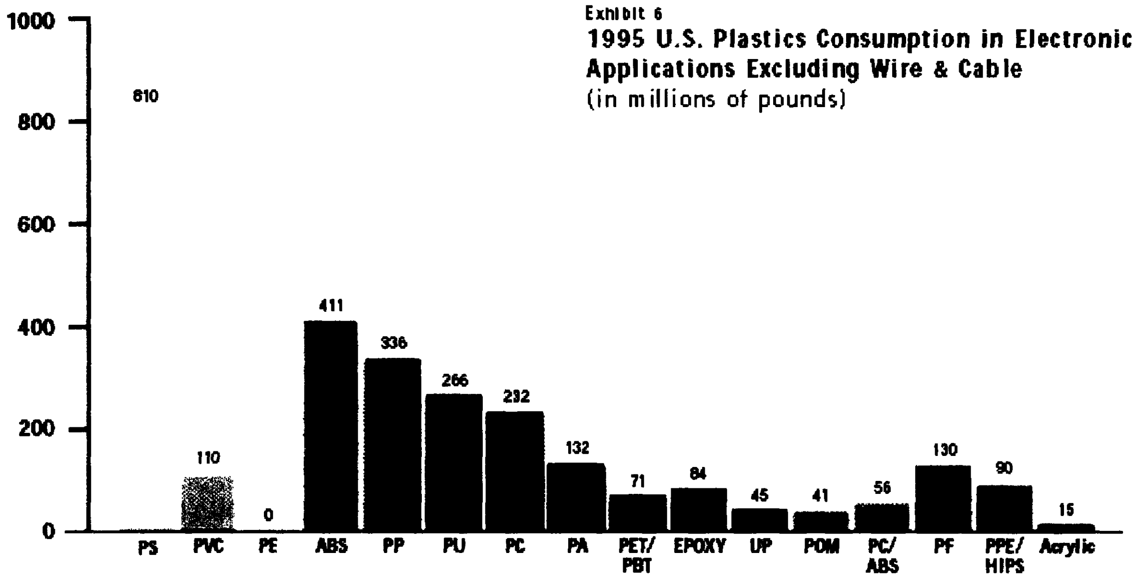

Figure 17: Plastics used in electronics (APC 2000)

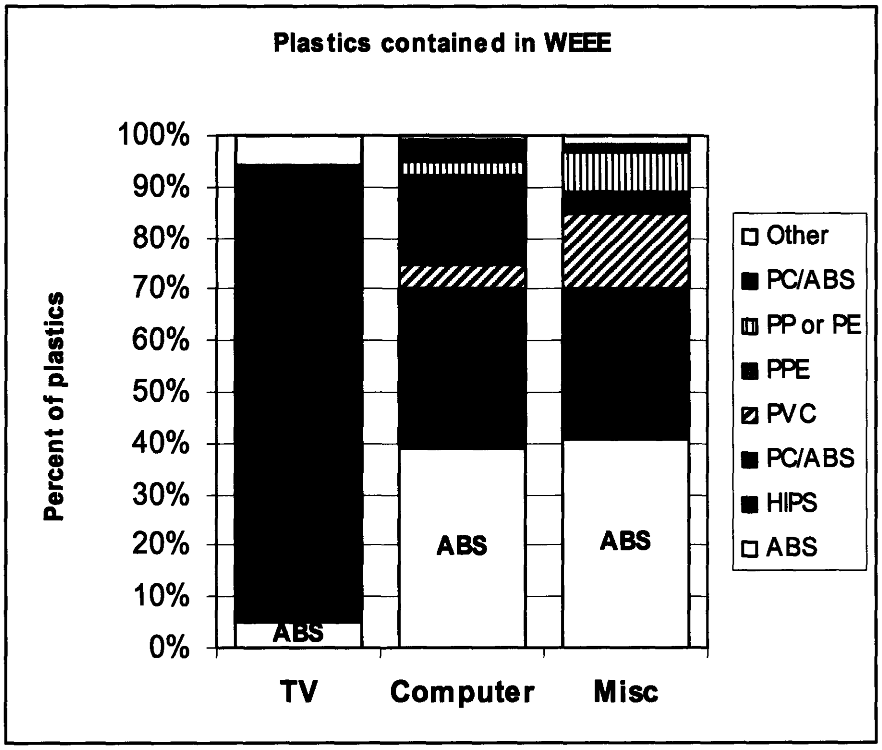

Figure 18: Minnesota Study on plastics recovered from Consumer Electronics (Tony Hainault 2001)

EoL plastics can follow any of four major material pathways for recovery (Patel, von Thienen et al. 2000). These are:

Mechanical Recycling:

- for recovery in like-grade applications (Back to Polymer, BTP)
- Recovery in applications that substitute non-polymer materials (plastic lumber, etc)

Feedstock Recycling:

- Recovery as feedstock, a substitute for virgin petroleum feedstock (Back-to-Monomer, BTM)

Energy Recovery:

- Energy recovery (in an incinerator, cement plant, or smelter)

A study on the energy savings from plastics recovery found that recovery to like grade applications (BTP) had a much greater energy savings than other recovery options (Patel, von Thienen et al. 2000). In addition the potential value for separated plastics can range from $265/t for flaked polypropylene to $900/t for pelletized ABS (USGS 2001) or even, according to the American Plastics Council, up to $1 per pound (APC 2003). Clearly, BTP is the ideal recovery option. However, while the plastics industry professes that recovery back to polymer is plausible and economic (APC 2003), net positive profits for mixed, post-consumer plastics recovery are rarely (if ever) achieved. The fundamental issue is that a minimal level of contamination between plastic types can ruin a batch of material, and even mixing of compatible plastics leads to downgrading of material to a polymer with the lower performance specifications.

Recycling operations in LDCs have the potential to recover plastics to a higher level for a number of reasons: lower labor costs allow for a higher degree of manual sorting, and also there is a higher tolerance for the potential processing complications arising from contaminants. In addition there are better markets for lower grade recycled material.

Another issue with plastic recovery is the impact of plastic coatings and Brominated Flame Retardants (BFRs). Plastic coatings can make even same-grade plastics incompatible, while BFRs are banned from new electronics in the EU– thus further hindering closed loop recycling. Plastics have an average calorific value of 40 MJ/kg, the same magnitude as oil and currently represent about 4% of annual oil consumption (Menad, Bjorkman et al. 1998). However some BFR's create dioxins and furans when incinerated, and incomplete combustion can create additional harmful emissions. The extent of environmental impact from different EoL options for different plastics and additives is still not well known (Menad, Bjorkman et al. 1998).

A Delphi study of recycling technology (Boks and Tempelman 1998) found no consensus about the processing mechanism most likely to dominate in the future. However many felt that the chosen processing mechanism would depend on the plastic type, while others felt that the mechanism would depend more on economics. These are not necessarily mutually exclusive, and this remains an area for which there are many alternatives, none of which seem truly optimal.

Appendix C: Product compositions and data sources

All product compositions are listed as percent of the total material in the product (out of 100).

Table 28: Product compositions used in case study (based on the compositions listed in Table 29)

	Product material compositions								
	Glass %	Steel %	Cu %	Al %	Plastic %	Pb %	Ag %	Au %	Other %
cpu tower		67	7	5	19	0.299	0.015	0.004	1
monitor	44	18	5	2	24	3.863	0.008	0.002	
Data Processing Equip	19	35	10	10	22				5
Offices & Services	0	62	13	13	10				1
Telecom	0	28	8	8	55				2
Video & Sound	30	20	3	3	25				19
Household Appliances	2	53	3	3	19				20
Equip, (for hotels restaurants)	2	77	3	3	10				6
Cables	0	4	27	27	38				5
Lamps	86	5	3	3	1				2
Circuit Boards (CBS)	30	8	10	2	30	2.000	0.600	0.050	

Table 29: Product compositions found in the literature

(Smith 1996)

	CRT galss	**CRT steel**	**Cu**	**Al**	**ABS plastic**	**PS**	**POM Plastic**	**Sheet metal**	**CBS**	**Card board**
Monitor	38	8	8	5	15	0	0	6	10	10

(Williams and Sasaki 2003)

	glass	**steel**	**Cu**	**Al**	**plastic**	**epoxy**	**tin**	**pb**	**Ni**	**Ag**	**Au**	**Ferrite**	**other**
CPU tower		67	7	5	7	12	0.5	0.3	0.2	0.015	0.004		1
Monitor	44	18	5	2	23	1	0.1	3.9		0.008	0.002	3	

(Huisman 2003)

	Glass	**Ferro**	**Cu**	**Al**	**Plastic**	**Pd**	**Ag**	**Au**	**Other**
audio	0	26	11	1	57				6
dvd		72	4	1	18	0	0	0	6
17" crt	64	9	6	0	18		0	0	3
cell phone	6	2	27	2	44	1	0	0	18

(Ayres, Ayres et al. 2003)

	Glass	Ferro	NonFe	Plastics	Other
Data Processing	19	35	19	22	5
Offices & Services	0	62	27	10	1
Telecom	0	28	15	55	2
Video & Sound	30	20	6	25	19
Appliances	2	53	6	19	20
Equipment	2	77	6	10	6
Cables	0	4	53	38	5
Lamps	86	5	6	1	2

Table 30: Metal composition of printed circuit board (PCB) scrap

	Avg metal content (kg) of 1000 kg PCB scrap (kg)											Total	
	Cu	Fe	Ni	Tin	Pb	Al	Zn	Sb	Ag	Au	Pd	(kg)	%)
Arpaci 1992	100	0	12	20	0	12	0	0	6	1		151	15
Poetzschke 1991	200	80	20	40	20	20	10	4	1	0.5	0.005	395	40

Table 31: Plastic content of WEEE (% of plastics)

	ABS	HIPS	PC, ABS	PC	PPO	PM MA	SAN	PVC	PPE	PP,P E	No ID
(Tony Hainault 2001)											
TV	5	82	1					1	7	0	6
Computer	39	25	10					5	17	3	1
Misc	41	22	8					15	4	8	2
(Anonymous 1999)											
Computer	35	10	30	5	12		2	5			3
Fans	7	35	58								
Stereos	6	28		12	19	12	4	2			18
TV housings	14	73			5	2		4		2	
Vacuum Cleaners	48	14		12			6	20			
(APC 2000)											
Fans	7	35	58								
Stereos	5	24			16	11	3	1			16
Vacuum Cleaners	30	19		16			8	27			2
TV	8	75			12					3	1
Computer	57	5	2		36						

Appendix D: Commodity Compositions and Value Category for 3 Case Facilities

	Quantity (lbs)		Value		Commodity Compositions											
Facility 1	In	Out	Category		glass	steel	cu	al	plastic	pb	silver	gold	Ferrou	NonFe	Paper	other
Commodity			In	Out)	%	%	%	%	%	%	%	%	%	%		%
			(Vr)	(Vp												
PREPREG FIBERGLASS	398,532	799,985	3	3												100%
IC TUBES	12,443	11,778	4	3												100%
MIXED OFFICE PAPER		8,878		4											100%	0%
FIBER/OTHER	19,724	15,503	5	4												100%
FEMIX	427		3	3									60%			40%
STAINLESS STEEL 18/8 S	196	521	3	2		100%										0%
STEEL	928,462	54,635	5	3		90%									10%	0%
IC CHIPS	3,397	15	1	1												100%
OCC LOOSE	578	0	5	4											100%	0%
OCC BALED	19,943	164,504	5	4											100%	0%
TONER CARTRIDGES	11,631	40,814	6	2					50%							50%
HIGH GRADE BREAKAGE	270,340	112,765	4	3	30%				25%				20%	6%		19%
LOW GRADE BOARDS	38,267	706	3	4			10%	2%		2.0%	0.600%	0.050%	8%	17%		60%
HIGH GRADE BOARDS	19,631	10,519	2	2			10%	2%		2.0%	0.600%	0.050%	8%	17%		60%
PRECIOUS METAL GERA	2,700	10,942	2	4			10%	2%		2.0%	0.600%	0.050%	8%	17%		60%
MEDIUM GRADE BOARD	7,688	126,479	2	2			10%	2%		2.0%	0.600%	0.050%	8%	17%		60%
TIN/LEAD BOARDS	55,082	121,797	5	3			10%	2%		2.0%			8%	20%		58%
COPPER YOKES	1	8,400	4	3			40%		20%							40%
TUBES	59,830	238,404	6	4	44%	18%	5%	2%	24%	3.9%	0.008%	0.002%		3%		0%
COMPUTER MONITORS	489,934	224,907	6	4	44%	18%	5%	2%	24%	3.9%	0.008%	0.002%		3%		0%
TV SCRAP	402,490	131,352	6	2	44%	18%	5%	2%	24%	3.9%	0.008%	0.002%		3%		0%
COPPER FOIL CONTAMI		3,990		2			70%									30%
COPPER BREAKAGE	11,462	13,482	3	3			70%									30%
MODULES	21,440	101,227	4	3		50%	10%	2%		2.0%	0.600%	0.050%	8%	17%		10%
COMPUTER BREAKAGE	139,606	106,873	4	3	19%				22%				35%	19%		5%
CONTAMINATED PLASTI	80,604	36,470	5	4					80%							20%
MIXED PLASTIC	23,570	99,889	5	3					80%							20%
TIN/LEAD SOLDERS	9,032	25,486	2	2						80%				20%		0%
COPPER #3	2,082	8,616	3	3			90%									10%
COPIERS	1,277,707		6	3	0%				10%				62%	27%		1%
COPPER LAMINATE SCR	5,511	11,151	2	2			95%									5%
COPPER #2	1,084	730	2	2			96%									4%
AUPINS Total: v1,849	1,849		2	2			95%					0.500%				5%
CU1 Total:	558		2	2			100%									0%

	Quantity (lbs)		Value		Commodity Compositions											
Facility 1 continued	**In**	**Out**	**Category**		**glass**	**steel**	**cu**	**al**	**plastic**	**pb**	**silver**	**gold**	**Ferrou**	**NonFe**		**other**
Commodity			**In**	**Out)**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**		**%**
			(Vr)	**(Vp**												
COPPER PINS	4,223	330	3	2			100%									0%
CUPINSC Total:	84		3	4			100%									0%
RED BRASS		465		2			100%									0%
YELLOW BRASS TURNS		7,369	4	3			100%									0%
YELLOW BRASS	11,844	25,243	3	3			100%									0%
COPPER FOIL	31,821	143,002	2	2			100%									0%
COPPER EDGE TRIM	742,374	2,036,297	3	3			95%		5%							0%
EMIX	3,791		4	3	0%				55%				28%	15%		2%
EELOWGR	29,523		6	3	0%				55%				28%	15%		2%
LOW GRADE BREAKAGE	434,703	275,999	6	3	0%				55%				28%	15%		2%
CUINSL Total:	3,211		3	3			60%		40%							0%
COPPER INSULATED WI	33,760	40,468	3	3			60%		40%							0%
CONSUMER ELECTRONI	35,723	46,938	4	2	30%				25%				20%	6%		19%
COMPONENTS (WT OR units	1,797	115,654	1	1			10%	2%		2.0%	0.600%	0.050%	8%	17%		60%
GOLD TRIM	7,898	38,219	3	3					99%			0.100%				1%
ABS		46,700		4					100%							0%
POLYSTYRENE	43,765	73,601	5	3					100%							0%
PLASTIC TRAYS	62,869	126,817	3	2					100%							0%
REUSABLE MONITORS		7,460		2	44%	18%	5%	2%	24%	3.9%	0.008%	0.002%		3%		0%
REUSABLE ELECTRONIC		681		2	19%				22%				35%	19%		5%
COPPER ALUMINUM	16,405	212,065	3	2			80%	20%								0%
ALUMINUM BREAKAGE P*	108,076	41,796	3	3				70%								30%
CONTAMINATED ALUMIN	61,033	66,394	3	3				80%								20%
CAST ALUMINUM	38,775	194,066	3	3				98%								2%
AL3003 Total:	627		2	2				100%								0%
ALUMINUM FOIL		2,018		3				100%								0%
ALUMINUM BRONZE	825	4,634	3	2				100%								0%
WASTE	185,395	185,395	5	4					80%							20%

	Quantity (lbs)		Value		Commodity Compositions											
Facility 2	**In**	**Out**	**Category**		**glass**	**steel**	**cu**	**al**	**plastic**	**pb**	**silver**	**gold**	**Ferrou**	**NonFe**		**other**
Commodity			**In**	**Out)**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**		**%**
			(Vr)	**(Vp**												
OTHER HIGH	9,215		5	3												100%
TEST	14,066		6	3												100%
GRANITE	29,324		5	3												100%
HOSE W/CON	36,934		5	3												100%
SAMPLE	38,427		5	3												100%
BLOWERS	41,639		5	3												100%
SILICONLOW	41,823		5	3												100%
SOFT FOAM	62,330		5	4												100%
OTHER MIX	68,021		5	3												100%
WOOD	285,034		5	4											100%	0%
STAIN HIGH	16,793		3	2		100%										0%
MAGNETS	159,496		5	3		100%										0%
PAPER C	25,188		5	3											100%	0%
PAPER W	94,505		5	3											100%	0%
VRS PAPER	757,213		5	3											100%	0%
CARDBOARD	1,349,623		5	3											100%	0%
STEEL	7,766,861		5	3		90%								10%		0%
CLARKBOARD	5,196		3	3			10%	2%		2.0%	0.600%	0.050%	8%	17%		60%
FLATSCREEN	63,403		6	4	50%				40%							10%
SOLDER	25,324		3	2						100%						0%
GLASS	11,143		6	4	44%	18%	5%	2%	24%	3.9%	0.008%	0.002%		3%		0%
CRTS	18,356		6	4	44%	18%	5%	2%	24%	3.9%	0.008%	0.002%		3%		0%
DISPLAYS	2,509,120		6	4	44%	18%	5%	2%	24%	3.9%	0.008%	0.002%		3%		0%
CU NVCARDS	35,169		5	3			50%			30%						20%
MACHINE	4,883		4	3		67%	7%	5%	19%	0.3%	0.015%	0.004%		0%		2%
STAIN MIX	34,067		3	2		80%								20%		0%
MEDIA	327,968		6	3					50%						50%	0%
PENT3FAIL	612		4	2	0%				10%				62%	27%		1%
MEMFAIL	244,669		6	3	0%				10%				62%	27%		1%
MODS	667,202		5	2	0%				10%				62%	27%		1%
COAX	24,333		5	3			30%		60%							10%
CD S	48,244		5	3					90%							10%
PLASTIC	368,502		5	4					90%							10%

	Quantity (lbs)		Value		Commodity Compositions											
Facility 2 continued	**In**	**Out**	**Category**		**glass**	**steel**	**cu**	**al**	**plastic**	**pb**	**silver**	**gold**	**Ferrou**	**NonFe**		**other**
Commodity			**In**	**Out)**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**		**%**
			(Vr)	**(Vp**												
PLASTIC B	1,153,124		5	4					90%							10%
GND STRAPS	46,085		2	2			100%									0%
CU FOIL	79,686		3	2			100%									0%
CU TRIM	37,613		3	2			98%		2%							0%
FANS	259,070		6	2	2%				19%				53%	6%		20%
PUMPS	352,231		6	3	2%				19%				53%	6%		20%
CU MIX	2,965,550		3	3			80%							20%		0%
ANIXTER	42,878		4	2	19%				22%				35%	19%		5%
TDC	2,560,312		4	2	19%				22%				35%	19%		5%
RETURNS	450		4	3	0%				10%				62%	27%		1%
HFLEX	55,649		6	1	0%				10%				62%	27%		1%
UPS	245,327		6	3	0%				10%				62%	27%		1%
NCR	316,342		4	2	0%				10%				62%	27%		1%
CABLES	599,103		5	3	0%				38%				4%	53%		5%
ALUM NOVAL	888,672		5	3				50%								50%
ALUM MIX	1,230,848		3	2				70%								30%
WIRE AG	87,564		5	2			20%				80.00%					0%
ALUM HIGH	67,530		3	2				100%								0%
ALUM TURN	879,172		3	2				100%								0%
HAZARDOUS	90,015		5	4												100%
TRASH	314,500		5	4					80%							20%
W2ENERGY	334,647		5	4					80%							20%

	Quantity (lbs)		Value		Commodity Compositions											
Facility 3	**In**	**Out**	**Category**		**glass**	**steel**	**cu**	**al**	**plastic**	**pb**	**silver**	**gold**	**Ferrou**	**NonFe**		**other**
Commodity			**In**	**Out)**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**		**%**
			(Vr)	**(Vp**												
Toner Cartridges	672		5	4												100%
Foam	7,869		5	4												100%
Wood	344,768		5	4											100%	0%
Stainless Steel	74,427		2	2		100%										0%
Clean Steel	409,630		5	3		100%										0%
Cardboard	227,711		5	4											100%	0%
CBS	855,884		2	2			10%	2%		2.0%	0.600%	0.050%	8%	17%		60%
Monitors	111,449		6	4	44%	18%	5%	2%	24%	3.9%	0.008%	0.002%		3%		0%
CPUs	27,350		4	3		67%	7%	5%	19%	0.3%	0.015%	0.004%		0%		2%
Contaminated Steel	335,218		5	3		80%								20%		0%
Trash	43,318		5	4					80%							20%
Copper Laminates	33,539		2	3			95%									5%
Plastics	8,969		5	4					90%							10%
Copper	27,503		3	2			98%									2%
Resale	76,062		1	1	19%				22%				35%	19%		5%
Transformers	733		3	3					38%				4%	53%		5%
Lead Batteries	4,003		5	4					38%				4%	53%		5%
Li Batteries/ Hg Relays	2,811		6	4					38%				4%	53%		5%
Power Supplies	45,946		5	3	0%				38%				4%	53%		5%
Insulated Wire	186,869		5	3	0%				38%				4%	53%		5%
Mixed Al	60,843		3	3				80%								20%
Clean Al	205,082		3	2				90%								10%
High Grade Al	375,006		2	2				98%								2%
Au on Al	1,849		3	2				99%				0.100%				1%

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