Title of Publication *Edited by*
TMS (The Minerals, Metals & Materials Society), 2007

CHARACTERIZING SUSTAINABLE MATERIAL RECOVERY SYSTEMS: A CASE STUDY OF E-WASTE MATERIALS

Jeremy Gregory[1], Elisa Alonso[2], Frank Field III[3], Randolph Kirchain[2,3]

[1]Laboratory for Energy and the Environment
[2]Department of Materials Science and Engineering
[3]Engineering Systems Division
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Keywords: Recycling, electronics, cathode ray tubes, leaded glass, sustainability

Abstract

This paper presents a sustainability assessment of the material recovery system for leaded glass from cathode ray tubes (CRTs). In particular, the global mass flow of primary and secondary CRT glass and the theoretical capacities for using secondary CRT glass to make new CRT glass are analyzed. The global mass flow analysis indicates that the amount of new glass required is decreasing, but is much greater than the amount of secondary glass collected, which is increasing. The capacities for using secondary CRT glass to make new CRT glass were analyzed using a linear optimization model with the capability to analyze a statistical distribution on the incoming secondary material composition. The analyses showed that as the variation in secondary material composition increased, secondary material consumption decreased. The comparison of the ratio of secondary glass collected to the amount of new glass required from the mass flow analysis and the theoretical capacities for using secondary glass in new glass production indicate that the material recovery system is sustainable for the foreseeable future. However, a prediction of the time at which the market for secondary glass will collapse due to excess capacity is not possible at the moment due to several sources of uncertainty.

Introduction

End-of-life (EoL) electronics, or e-waste, have garnered international attention in recent years due to several notable characteristics of the waste stream. First, e-waste represents the fastest growing segment of waste, growing at three times the rate of general waste [1]. Second, electronics goods typically comprise numerous valuable non-renewable materials, such as precious and heavy metals, some of which are toxic materials including lead, arsenic, and mercury. Third, few US states have controls on the disposal of EoL electronics, resulting in low reclamation and recovery rates with most products either remaining in storage or being landfilled or incinerated [2]. Fourth, the intimate commingling of materials requires intensive processing to sufficiently separate and recover materials. Generally, this processing leads to expenses that exceed revenue from the recovered materials [3]. The high cost of processing e-waste has led some recyclers to send EoL electronics to industrializing countries where they are manually dismantled at a low cost, but in unsafe labor conditions [4]. These experiences have made the practice of exporting e-waste controversial.

Devices with cathode ray tubes (CRTs), such as televisions and computer monitors, have received particular scrutiny because they contain large amounts of leaded glass, which has a low value and is considered toxic. Furthermore, many barriers exist that make it challenging to reuse the glass from EoL CRTs in other applications (including new CRTs). These barriers are related to glass material content and value, a shift in global manufacturing locations and markets, glass reuse requirements, and limitations on the classification and export of hazardous waste.

This paper seeks to examine the CRT-glass material recovery system and the challenges it faces by exploring aspects of the system that impact its sustainability. The specific aspects of this system that are evaluated include the global mass flow of primary and secondary CRT glass and the theoretical capacities for using secondary CRT glass to make new CRT glass. Background is presented on CRTs and the CRT glass material system, followed by analyses of the two aforementioned aspects of the system. The paper concludes with a sustainability assessment that combines the analysis components.

It should be noted that the use of the expression "sustainability" in this paper is not in the strict sense of the word (i.e., consumption in relation to a carrying capacity). Rather, the term is used as an indication of whether an activity is moving toward or away from sustainability when compared to performance over time or performance against similar activities. Furthermore, there is a perspective of economic sustainability for the CRT glass manufacturers and EoL CRT processors. They must assess the long-term risks associated with the supply and demand of primary and secondary CRT glass and the impacts they may have on their business prospects.

Cathode Ray Tube Composition and End-of-Life Processing

Figure 1 depicts the major components of a "bare" CRT; that is, a CRT that has had its housing and other exterior components removed. The glass typically accounts for over half of the weight of the monitor and the panel, or screen, glass accounts for over half the weight of the CRT [5]. The panel glass contains small amounts of lead, on the order of 0-4% by weight, whereas the composition of funnel and neck glasses are on the order of 22-28% and 30% lead, respectively [6]. The panel glass also contains significant amounts of barium and strontium, up to 14% and 12%, respectively [7]. The panel glass and funnel glass have coatings on their inner surfaces: a phosphor coating and a conductive coating, respectively. The entire tube is a sealed vacuum, which must be compromised to remove the shadow mask and electron gun.

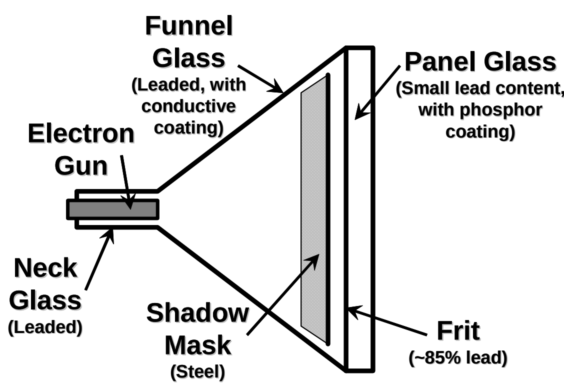

Figure 1. CRT Composition.

CRT recycling can be accomplished using one of two major alternatives: shredding or dismantling. The former refers to shredding the entire monitor or television, typically minus the cord. The metals are separated using standard electro-magnetic and density methods, leaving two remaining material streams: glass and electronics shredder residue (ESR). ESR is predominantly plastics and as such, it can be sent to a processor who will recover most of the plastics, or it is landfilled or incinerated. When shredded, the glass stream is a mixture of panel and funnel glass, making it difficult for reuse in new CRTs. Firm-specific glass specifications vary considerably [8], driving strict uniformity constraints on secondary cullet, particularly for use in panel glass. As a result, the glass from the shredder is often (although not exclusively) sent to smelters for use as a flux.

Dismantling first involves removing housings (typically plastic) and the exterior components such as the yoke (coils of copper wire around the neck that act as an electromagnet) and banding (metal reinforcement around the funnel), leaving the bare CRT. If the glass will be used in new

CRTs, the vacuum in the CRT is compromised and the panel is typically separated from the funnel. The glass is then crushed, cleaned, and sorted in an automated process that produces separate streams of glass that can be used in new CRTs. (In some instances, however, the CRT is crushed to make it easier to transport, but the glass is not separated.) Some processors can produce several streams that vary according to glass composition and manufacturer type.

Several issues surround CRTs that create barriers to increased recovery of the glass; most are related to the fact that the glass contains lead. The lead in the glass prevents it from being used in other glass products such as containers or windows. The lead content can also lead to the glass being classified as a hazardous material, which can complicate and increase the cost of transportation. Concerns over the leaded-glass have led some groups to propose stronger regulations on the export of CRTs and CRT glass, particularly to developing countries [9].

Another barrier to increased recovery of CRT glass is its relatively low value, which is of particular importance given that the glass represents a significant fraction of the weight of the CRT. This leads to the cost of processing being greater than the value of the materials in the TV or monitor as scrap. In fact, depending on the degree to which the glass has been separated and cleaned, processors will often have to pay a downstream recipient, such as a smelter or a CRT glass manufacturer, to accept the glass cullet [10]. Alternative applications for secondary CRT glass have been proposed including decorative tile, nuclear waste encapsulation, construction aggregates, and sandblasting medium. However, in all cases (including smelting and primary glass production) the secondary CRT glass is being used as a substitute for other low cost materials: usually sand and primary glass (leaded or unleaded).

Strict compositional specifications from CRT manufacturers also limit the degree to which secondary cullet is used in making new CRT glass, particularly when the composition of the incoming cullet is unknown. Manufacturers make use of “prompt” scrap (rejects from the manufacturing process) because the composition is known, but glass from EoL CRTs presents a greater challenge. The capacity for the use of secondary cullet in making new CRT glass is explored below.

The final barrier to using secondary CRT glass is related to trends in the global marketplace for manufacturing and selling CRT-containing devices. On the manufacturing side, there are no manufacturers of CRT glass in North America, as of this year. Similarly, nearly all CRT glass manufacturers have left Europe as well; they are now located almost exclusively in Latin America and Asia. However, North America and Europe are still generating e-waste and there is still demand for CRTs all over the world. The disparities between manufacturing, e-waste generation, and sales demand locations necessitate a global flow of secondary CRT glass if they are to be used in manufacturing new CRTs. The next section examines the flow of new CRTs and the expected amounts of secondary CRT glass that could be used in new CRTs.

Primary and Secondary CRT Glass Mass Flow

The popularity of flat panel displays (FPD) for televisions and computer monitors has led to the assumption that CRTs are a dying technology. Although the total number of CRTs manufactured is decreasing, they still represent the majority of televisions sold worldwide (76% in the first quarter of 2006), primarily due to strong demand in the industrializing world [11]. Still, the expected increase in the amount of EoL CRTs expected to enter the secondary glass market and the decrease in the number of CRTs manufactured motivates a comparison of the expected demand for secondary cullet and the amount of cullet that will be available.

A model is presented here that combines global population, CRT sales, and EoL collection rates with product characteristics to determine the amount of secondary CRT glass that will be available in comparison to the amount of glass that will be required to manufacture new CRTs. This comparison is a key element of the material recovery system for CRT glass.

Table 1 lists the key inputs for the model and the sources of the data. The parameters dependent on time range from 1990 to 2010 and the parameters dependent on location include the regions of Africa & the Middle East, Asia Pacific, China, Europe, Latin America, and North America. The relatively long time period considered in the analysis necessitated the estimation of some trends within any dataset that was dependent on time. These estimations were based on information in the literature and discussions with manufacturing and recycling experts. The ranges of weights in Table 1 represent data for the range of years (1990-2010) and were determined using product weights and sales data; increasing weights reflect larger products purchased by consumers over time.

Table 1. Types of input data and sources for mass flow model.

Geographic		**Product**		
Parameter	**Source**	**Parameter**	**Range**	**Source**
Population, $P(l,t)$	[12]	Average TV funnel glass weight, $W_{F,T}(t)$	5.7 – 7.5 kg	[5]
TV sales, $S_T(l,t)$	[5, 13, 14]	Average TV panel glass weight, $W_{P,T}(t)$	11.4 – 15.0 kg	[5]
Monitor sales, $S_M(l,t)$	[5, 13, 14]	Average monitor funnel glass weight, $W_{F,M}(t)$	2.8 – 4.2 kg	[5]
Collection rates, $C(l,t)$	E	Average monitor panel glass weight, $W_{P,M}(t)$	4.9 – 7.8 kg	[5]
		Average TV lifetime, L_T	14 yr	E
		Average monitor lifetime, L_M	9 yr	E

Notes: E = Educated estimate based on literature review and discussions with manufacturing and recycling experts.
l = location, includes: Africa & Middle East, Asia Pacific, China, Europe, Latin America, North America
t = time (annual): 1990-2010
Collection rate = the ratio of EoL units collected to generated, where "generated" indicates that a product has reached the end of its useful life and is ready for disposal or recycling

All of the values used as inputs are not presented here due to space constraints. However, a sample of population, $P(l,t)$, and collection rate (the ratio of EoL units collected to generated, where "generated" indicates that a product has reached the end of its useful life and is ready for disposal or recycling), $C(l,t)$, data is listed in Table 2 for the year 2005 to provide a sense of the relative magnitudes of the values. Collection rate values are assumed to increase, but the rate at which they increase is dependent on location.

Table 2. 2005 Population and collection rate input data.

Region	Africa & Middle East	Asia Pacific	China	Europe	Latin America	North America
Population (1,000)	1,189,774	2,331,288	1,323,345	728,389	561,346	330,608
% of population	18%	36%	20%	11%	9%	5%
Collection rate	0.05%	1.00%	0.25%	40.00%	0.50%	17.50%

Estimates for TV and monitor sales ($S_T(l,t)$ and $S_M(l,t)$, respectively) are presented in Figure 2 and reflect the assessment of a future decrease in CRT sales, particularly in Europe and North America and in monitor sales. Nonetheless, the overall demand for CRT glass will exist for the foreseeable future, primarily due to demand from industrializing countries. This demand is depicted in the plots as the increase in market share of the industrializing countries.

The calculated total amounts of secondary CRT glass collected worldwide and the total amounts of CRT glass required to satisfy production demands for the years 2005 to 2010 are shown in Figure 3. The decrease in the required amounts of glass is driven by the decrease in expected sales, but the increase in the amount collected is driven by two effects. First, the number of units generated will increase because this behavior follows the sales trend when the devices were purchased (9 years ago for monitors and 14 years for TVs), which was increasing. Second, collection rates increase in each region each year.

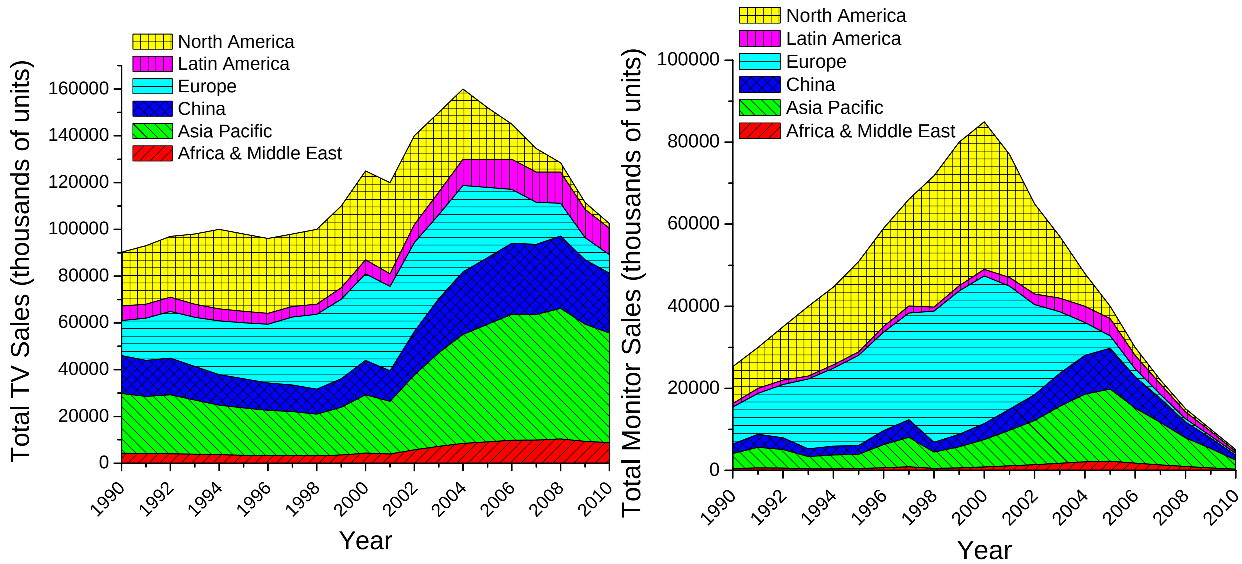

Figure 2. TV and monitor sales data that are input to the model.

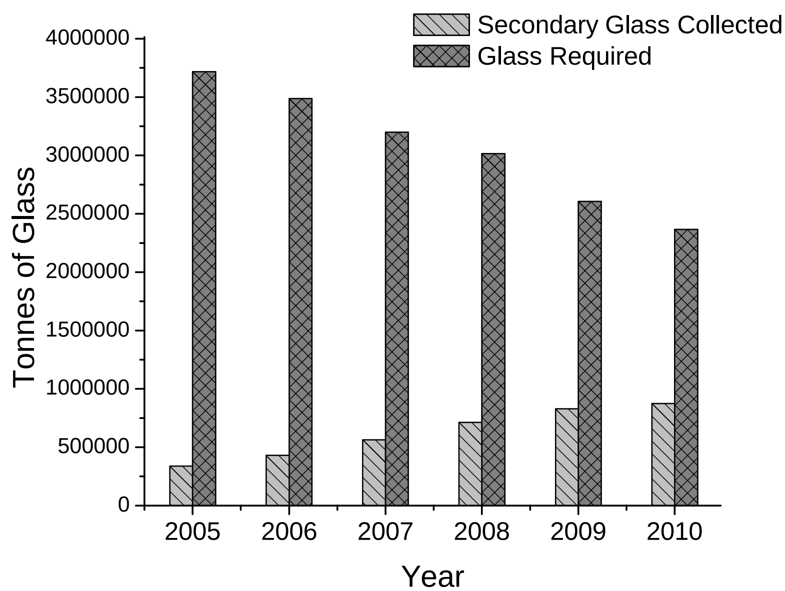

Figure 3. Secondary glass collected and new glass required.

The ratio of the secondary glass collected to the amount of glass required is plotted for the years 2005 to 2010 in Figure 4. The increase in this value over time reflects the increase in the numerator (amount collected) and the decrease in the denominator (amount required). This is a key metric for evaluating the sustainability of the system because it characterizes the availability of secondary material in the system. It will be compared with the analyses of the capacity for secondary glass use in new CRT glass production outlined in the next section.

It should be noted that the results in Figure 4 are directly proportional to the collection rates. If all collection rates increase by 25%, then the ratio of secondary glass collected to the amount of glass required also increases by 25%. Since the collection rates represent an area of uncertainty, one can assume that the uncertainty in the collected/required ratio is the same as the uncertainty in the collection rates. (There is a complicating factor that the uncertainty in collection rates will vary by region – European and North American collection rates will be known to a higher degree of certainty.)

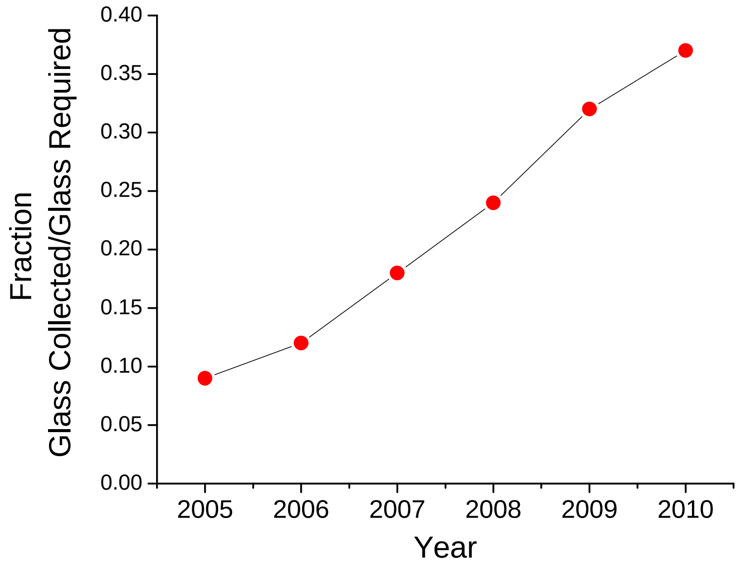

Figure 4. Ratio of secondary glass collected to new glass required.

It is interesting to examine the regional breakdown of material collected and generated, as is plotted in Figure 5. Even though Europe and North America represent approximately 15% of the population, they generate over 50% of the EoL units. However, they also represent over 95% of the material collected (this amount decreases slightly with time as other regions' collection rates increase).

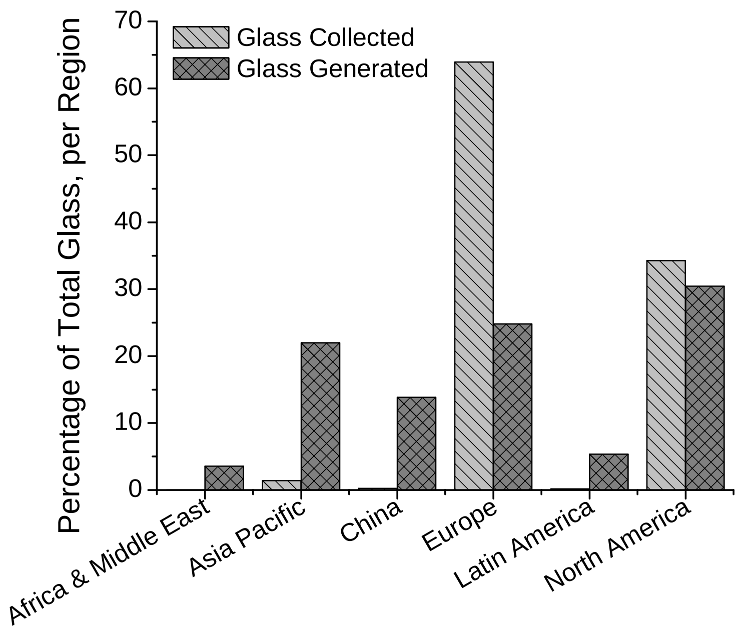

Figure 5. Regional breakdown of material collected and generated.

Capacities for Secondary Glass Usage in CRT Glass Manufacturing

Linear optimization modeling tools are often applied to improve decisions of secondary batch planners in both metals [15, 16] and electronics recycling [17, 18]. These models can also be applied to problems beyond batch mixing such as purchasing, upgrading, and sorting of secondary materials [19, 20]. A linear optimization model with a chance constrained modification was used here to estimate the theoretical maximum capacity of secondary glass usage in CRT glass manufacturing. Previous work has demonstrated potential for improving batch planning decisions, specifically, increasing automotive scrap consumption in secondary aluminum production [21].

The model was designed to minimize the cost of producing 100 tonnes each of two types of CRT glass, new panel and new funnel, subject to meeting their compositional constraints through use of primary and secondary materials. For mathematical details of this model, please refer to [21]. Specifically, for these compositional constraints, six oxides were tracked: alumina (Al_2O_3), barium oxide (BaO), calcium oxide (CaO), sodium oxide (Na_2O), potassium oxide (K_2O), and lead oxide (PbO). The model could make use of ten different raw materials to produce the new glass: three secondary CRT glasses and seven primary pure oxides, all of which are listed in Table 3. Secondary materials were set lower in price in order to maximize scrap use.

Table 3. Raw material inputs to optimization model.

Secondary CRT Glass	Primary Pure Oxides
Dismantled panel glass ($200/t)	SiO_2, Al_2O_3, BaO, CaO, Na_2O, K_2O, PbO (all $300/t)
Dismantled funnel glass ($200/t)	
Mixed glass ($150/t)	

Data on typical secondary glass and new glass compositions and a range of different new glass compositions for panel and funnel glass were taken from published literature and are listed in Table 4 [7]; the final four columns of the table are provided for informational purposes only and were not used in the model. While it was assumed that the primary materials were of specified pure oxides, secondary CRT glass was assumed to have compositional variability. This was captured by the coefficient of variation (COV), which is defined as the standard deviation (or the variance) divided by the mean. The compositions for secondary panel and funnel were assumed to represent the mean composition of dismantled and separated panel and funnel, respectively (the first two columns of data in Table 4). The mean composition for the mixed glass was approximated by the weighted average of secondary panel and funnel compositions, assuming a 2:1 weight ratio of panel to funnel for a typical CRT.

Table 4. Chemical compositions of different types of CRT glasses (SiO_2 not listed) [7].

Weight Fractions	**Typical Composition for Secondary Glass**		**Typical Composition for New Glass**		**Range of Compositions for New Manufactured CRT Glass**			
	Dism. Panel	**Dism. Funnel**	**Panel**	**Funnel**	**Panel Min**	**Panel Max**	**Funnel Min**	**Funnel Max**
Al_2O_3	0.021	0.028	0.017	0.018	0.0175	0.0365	0.011	0.05
BaO	0.097	0.028	0.099	0.008	0.022	0.139	0.0005	0.037
CaO	0.01	0.035	0.001	0.035	0.0005	0.0435	0.0105	0.0445
K_2O	0.072	0.083	0.069	0.082	0.06	0.085	0.061	0.103
Na_2O	0.076	0.020	0.086	0.007	0.0515	0.0945	0.053	0.083
PbO	0.003	0.175	0.0001	0.22	0	0.028	0.11	0.236

Two different scenarios were run using the model to explore capacities for using secondary CRT glass. First, the new glass composition was set in the model so that 99.99% of the time, it would fall within +/- 25% of the typical compositional specifications for new glass (the third and fourth columns of data in Table 4) and the COV of the secondary glass was varied between 0 and 50%. The new glass composition was different from the secondary glass composition because the secondary glass comes from many manufacturers, each having a different "recipe" for making CRT glass, while the new glass must be made to satisfy a given set of material properties.

The output from this scenario, the tonnage of each of the secondary glass materials used to produce new glass, is plotted in Figure 6. Over the full range of COVs more recycled material was used in new funnel glass than in new panel glass. Moreover, dismantled glass was generally selected over mixed glass, with secondary panel being used in new panel and secondary funnel being used in new funnel. The use of secondary material in new panel was limited by the maximum allowable PbO, whereas the use of secondary material in new funnel was limited by the maximum allowable BaO. As the COV increased, the amount of recycling decreased due to increasing uncertainty of the composition of the secondary material. Interestingly, at higher values of COV, the chance constrained model began to use secondary mixed glass in the funnel, which is likely to lower costs. This use of different types of scrap material where possible, or diversification, is a characteristic of results from chance-constrained optimization.

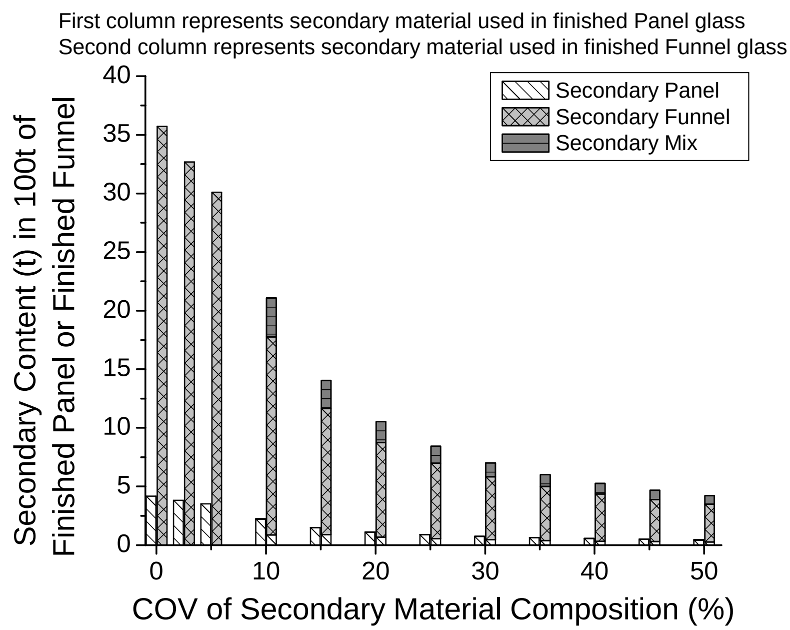

Figure 6. Secondary glass content in finished panel or funnel for typical secondary and new glass compositions and +/- 25% new glass compositional specifications.

The second scenario involved secondary baseline material compositions that are identical to the new glass composition. This is the case of a "pure" incoming waste stream (perhaps entirely of prompt scrap, or manufacturing rejects), but varying the COV of the secondary material composition enables an analysis of the impact of adding other cullet with different compositions. The new glass composition in this scenario was set so that 99.99% of the time it would fall within +/- 10% of the mean scrap compositions.

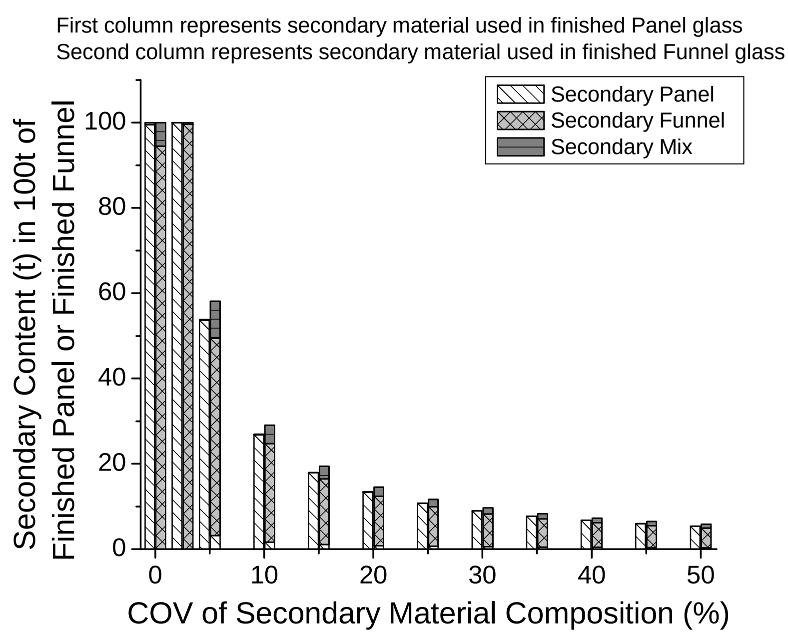

Figure 7. Secondary glass content in finished panel or funnel for identical baseline secondary and new glass compositions and +/- 10% new glass compositional specifications.

The results from this scenario are depicted in Figure 7. As expected, at very low COVs, the recycling rate is equal to 100%. However, as COV increases, the recycling rate decreases. This shows that the uniformity of the secondary material can greatly increase the recyclability of the EoL CRT glass. As with the previous scenario, there is more mixed scrap being used in the funnel, which suggests that the cost savings of using secondary materials in new funnel glass may be higher than those in new panel glass. Also, more secondary glass is used in new funnel glass than in new panel glass, although the difference is smaller than the previous scenario. Another similarity with the previous scenario is that the PbO content in panel and BaO content in funnel limited the amount of secondary material used. In particular, the high PbO content in funnel discouraged the use of secondary funnel or mixed glass in making new panel glass and the high BaO content in panel discouraged the use of secondary panel or mixed glass in making new funnel glass.

Sustainability Assessment of the CRT Glass Material Recovery System

The sustainability of the CRT glass material recovery system from an availability standpoint is strong. Figure 3 indicates that collection amounts are increasing in the short-term; this will continue for the foreseeable future. The real question lies in the demand side. The values of the secondary glass collected to new glass required ratio in Figure 4 are increasing. The market for secondary glass will collapse when this ratio approaches the capacity of new CRT glass manufacturers to use secondary glass. An assessment of when this will happen is extremely difficult because of uncertainty related to regional collection rates, the variation in incoming secondary glass composition, and the variation in capacities for the use of secondary glass among CRT glass manufacturers.

Capacities as high as 38% for funnel and 15% for panel have been reported [22], but there has been speculation that those rates could go as high as 60% and 30%, respectively [22]. Indeed there is one source that specifies a range of 30% to 80% when using prompt cullet [5]. All sources in the literature mention higher capacities for funnel glass than panel glass, which is consistent with the analyses presented here. In addition, other values for capacities listed in the literature, generally less than 30%, are consistent with the range values calculated in these analyses. Thus, the modeling framework is sound, but the question regarding typical COVs for the incoming secondary material remains. Furthermore, it is unclear how many CRT glass manufacturers are actually capable of meeting these capacity targets. Fortunately, the secondary glass collected to new glass required ratios in Figure 4 are all under 40%, but the trend is quickly moving beyond that range, which would push the limits of secondary glass capacities in manufacturing.

The sustainability outlook of the CRT glass material recovery system can be improved through a few key actions. First, improving regional collection rates, particularly in the industrializing world, would increase the amount of secondary glass available for use in new CRT glass. Second, tailoring new glass compositions to make them more amenable to the use of secondary glass would relax some of the constraints on the usage of secondary glass and increase capacities. Third, improving sorting of EoL panel and funnel glass by composition would decrease the COV on the secondary glass stream and increase capacities for new glass.

It is also clear that the sustainability of the secondary glass recovery system will be heavily dependent on the export of EoL CRTs or EoL CRT glass in order to effectively utilize available materials. Even if the industrializing world improves its collection rates within the next few years, the number of EoL CRTs being generated there will still be small compared to Europe and North America because of the much larger legacy of old equipment in the industrialized world. Thus, for the foreseeable future, the EoL material will have to flow from Europe and North America to the glass manufacturing locations in Latin America and Asia.

Acknowledgements

Gabrielle Gaustad's assistance with the chance constrained optimization model is acknowledged and greatly appreciated.

References

1. Crowe, D.M., Elser, D.A., Gopfert, B., Mertins, L., Meyer, J.S., Spillner, A., and Strobel, R. (2003). Waste from electrical and electronic equipment (WEEE) – quantities, dangerous substances and treatment methods.
2. US EPA (2002). Municipal solid waste in the United States: 2000 facts and figures. EPA530-R-02-001
3. International Association of Electronics Recyclers (2003). IAER electronics recycling industry report 2003.
4. Basel Action Network and Silicon Valley Toxics Coalition (2002). Exporting Harm: The High-Tech Trashing of Asia.
5. Monchamp, A., Evans, H., Nardone, J., Wood, S., Proch, E., and Wagner, T. (2001). Cathode Ray Tube Manufacturing and Recycling: Analysis of Industry Survey.
6. Lee, C.-H., Chang, S.-L., Wang, K.-M., and Wen, L.-C. (2000). Management of scrap computer recycling in Taiwan, *Journal of Hazardous Materials*. **73**(3): p. 209-220.
7. Hreglich, S., Falcone, R., and Vallotto, M. (2001). The recycling of end of life panel glass from TV sets in glass fibres and ceramic productions, in *Recycling and Reuse of Glass Cullet: Proceedings of the International Symposium organised by the Concrete Technology Unit and held at the University of Dundee, Scotland, UK on 19-20 March 2001*.
8. Lee, C.H. and Hsi, C.S. (2002). Recycling of scrap cathode ray tubes, *Environmental Science & Technology*. **36**(1): p. 69-75.
9. Smith, B. (2006), Talking Points: Cathode Ray Tubes - E-waste rules fall short, in *E-Scrap News*. 2006. p. 17-19.
10. Materials for the Future Foundation (2001). CRT Glass to CRT Glass Recycling.
11. Anonymous (2006), CRT Still Rules TV Market, iSuppli Says, in *Electronic News*. 2006.
12. United Nations (2004), World Population Prospects: The 2004 Revision. 2004.
13. Menad, N. (1999). Cathode ray tube recycling, *Resources Conservation and Recycling*. **26**(3-4): p. 143-154.
14. U.S. Environmental Protection Agency (1998). Computer Display Industry and Technology Profile.
15. Rong, A. and Lahdelma, R. (2006). Fuzzy Chance Constrained Linear Programming Based Scrap Charge Optimization in Steel Production. 742
16. Cosquer, A. and Kirchain, R. (2003). Optimizing The Reuse of Light Metals from End-of-Life Vehicles: Lessons from Closed Loop Simulations, *TMS: The Minerals, Metals, and Materials Society*. **AA3**.
17. Lund, J.R., Tchobanoglous, G., Anex, R.P., and Lawver, R.A. (1994). Linear Programming for Analysis of Material Recovery Facilities, *Journal of Environmental Engineering*. **120**(5): p. 1082-1094.
18. Stuart, J.A. and Lu, Q. (2000). A Model for Discrete Processing Decisions for Bulk Recycling of Electronics Equipment, *IEEE Transactions on Electronics Packaging Manufacturing*. **23**(4): p. 314-320.
19. Gesing, A., Stewart, C., Hopson, G., Costello, S., Lambert, S., Good, T., Grieve, R., Dalton, R., Wolanski, R., and Berry, L. (2001). Separation of Wrought Fraction of Aluminum Recovered From Automobile Shredder Scrap, in *TMS*. New Orleans, LA: TMS.
20. Shih, J.S. and Frey, H.C. (1995). Coal blending optimization under uncertainty, *European Journal of Operational Research*. **83**: p. 452-465.
21. Gaustad, G., Li, P., and Kirchain, R. (2006). Managing Raw Materials Compositional Uncertainty: Chance Constrained Modeling for Alloy Production, in *Materials Science & Technology: Green Engineering for Materials Processing Symposium*. Cincinnati, OH.
22. Doring, E. (2003). Recycling of post consumer special glass, present situation and possibilities, in *Recycling and Reuse of Waste Materials, Proceedings of the International Symposium, Sep 9-11 2003*. Dundee, United Kingdom: Thomas Telford Services Ltd, London, E14 4JD, United Kingdom.