Evaluating the Economic Viability of a Material Recovery System: The Case of Cathode Ray Tube Glass

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This paper presents an analysis of the material recovery system for leaded glass from cathode ray tubes (CRTs) using a dynamic material flow analysis. 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 comparison of the ratio of secondary glass collected to the amount of new glass required from the mass flow analysis indicates 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

Devices containing cathode ray tubes (CRTs), such as computer monitors or televisions (TVs), represent a significant and challenging fraction of the end-of-life (EoL) electronics waste stream. In Europe, where regulated EoL electronics, or e-waste, includes nearly every product with a cord or battery, CRT devices represented approximately 22% by weight of e-waste generated in 2005 (*1*). In the U.S., where regulated e-waste typically includes only computing equipment and TVs, this figure climbs to 58% (*2*). The leaded glass in the CRT is the cause of several EoL treatment challenges. Furthermore, both economic and technological barriers exist to reuse the glass from EoL CRTs in other applications (including new CRTs). Fortunately, two viable uses for EoL CRT glass (also known as secondary CRT glass or CRT glass cullet) exist: raw material for the production of new CRTs and fluxing agents in smelters (*2*). Of these two, the environmentally preferred, higher value, and historically predominant sink has been the former.

There is a sentiment in the developed world that the CRT is a dying technology (*3*). Indeed, CRT sales for monitors and televisions are markedly down in the U.S. as costs for more compact, liquid crystal displays (LCDs) have decreased (*3*). Although inexpensive CRTs remain popular in the developing world (*4*), it is clear that, even for those markets, CRTs will eventually be supplanted. Inherently, a shift to new display technologies will also drive an increase in CRT device retirement. These coupled trends directly call into question the ongoing viability of the economically and environmentally preferred material recovery pathway: the reuse of CRT cullet into new CRTs. Will the supply of EoL cullet outstrip the capacity of new production? Information about the timing and extent of this oversupply should help stakeholders identify the need for developing or facilitating other sinks for CRT cullet. The issue has urgency due to the rapidly changing nature of the CRT market and regulatory climate.

To explore this issue, this paper develops and exercises a dynamic material flow analysis model of the global mass flows of primary and secondary CRT glass. Specifically, by simultaneously comprehending global trends in sales, retirement, and production technologies for CRTs, the model projects the relative supply of and demand for CRT cullet and ultimately estimates the time until supply of CRT cullet exceeds demand. The results of the work provide insight into the factors that will have the greatest impact on the economic viability of the CRT glass recovery system. Furthermore, the methodology is a broader example of applying material flow analysis to identify market vulnerabilities in a material system. The case analysis is relatively unusual in that it evaluates a material system with rapidly declining consumption. Thus, the methodology may be of particular value in the analysis of systems with similar characteristics.

The paper continues with a review of previous research on the modeling of secondary materials systems as well as background on the CRT glass system. This is followed by a description of the specific elements of the model, the methods used to characterize the CRT glass system, and the case analysis.

Literature Review. Material flow analysis (MFA) has been used extensively to quantify the nature, magnitude, and drivers of resource use (*5*); waste generation (*6, 7*), and the mobilization of effluents (*8*). MFA studies have been broadly developed to support decision-making concerning waste and secondary resources policy. Although MFA-based forecasting does exist (*9*), MFA studies do not typically include comparisons of future, global supply and demand in secondary material streams because such studies are either regional (*10, 11*), static (*11*), or historical (*11, 12*). Furthermore, MFA studies quantify actual material flows but do not generally evaluate technological capacities to use secondary streams.

A few exceptions to this exist in the literature. Several studies have utilized MFA to estimate how characteristics of secondary materials streams will evolve (*13, 14*) and eventually be limited (*15, 16*). Being regionally focused, these studies attempt to characterize only technological limitations due to changes in patterns of consumption and trade. Furthermore, all of the above cases rely on statistical projections of observed material flows. Because materials flow responds to derived demand, this approach is appropriate only where driving direct demand patterns are expected to pattern historic trends (a plausible assumption for large, diverse materials markets like steel). Examples of dynamic MFA based around direct product demand are found in a set of work by Reuter, van Schaik, and others who have used simulation models to characterize fundamental physical recycling limits for closed-loop recycling within specific product sectors (e.g., automobiles) (*17–20*). Although they provide key insights, these papers do not explicitly explore how technological characteristics and supply/demand dynamics can convolve

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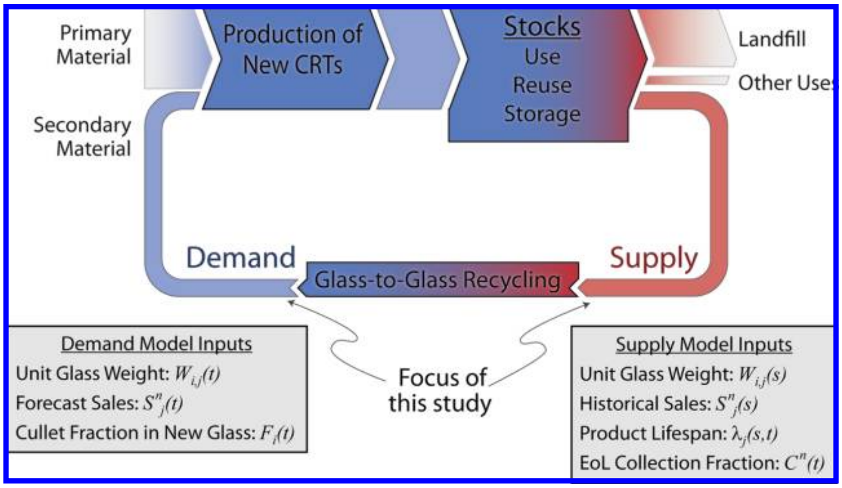


FIGURE 1. CRT glass material system flow. Arrow width is representative of the relative magnitude of the material flow.

to bound long-term capacity for reuse. From a methodological perspective, this study attempts to complement and extend these examples of dynamic-MFA by demonstrating the value of explicitly modeling evolution in technology (i.e., the capacity to use cullet in new products), the underlying product demand (i.e., the size and composition of CRT demand), and the underlying supply (i.e., market and regulatory driven product retirement and disposal) to study vulnerabilities in a materials system.

From a case perspective, several studies have estimated the amount of end-of-life CRT devices generated regionally in the U.S. (*2, 21*), Europe (*1*), and South Africa (*22*). In addition, Linton has forecast the amount of CRT waste that will be collected in the U.S. for the next fifty years (*23*). Finally, Weitzman correctly identified that there would be decreasing demand for CRT cullet in the U.S. because U.S. manufacturers were producing a smaller share of the CRT market (assuming that CRT cullet generated in the U.S. would only be used in CRT glass manufacturing in the U.S.) (*24*). Although each of these provides important insights into the problem, no single study is able to answer the questions posed because the examined scope was limited temporally, geographically (only a single region), and/or sectorally (i.e., demand or supply). The research presented in this paper addresses these gaps for this case.

Primary and Secondary CRT Glass Material Systems. There are two types of glass used in CRT devices: panel glass (used in the front screen showing an image) and funnel glass (used in the funnel-shaped component behind the panel that prevents emission of X-rays). The glass in a monitor typically accounts for over half of the product weight and the panel glass accounts for over half the weight of the CRT (*21*). The panel glass contains small amounts of lead (0−4 wt%), whereas the funnel and neck glasses contain 22−28 wt% and 30 wt% lead, respectively (*25*). Owing to their different chemical compositions, CRT glass cullet must generally be separated into panel and funnel glass to be used extensively in the production of new CRTs.

Several barriers exist to increasing the recovery of CRT cullet. First, the lead in the glass precludes its use in high-volume glass products such as containers or windows. The lead content can also lead to the glass being classified as a hazardous material, thereby complicating logistics, particularly internationally (*26*).

Together, these factors mean that CRT glass has relatively low value. This creates situations where the materials in an EoL TV or monitor are worth less than the cost to recover that material. In fact, depending on the degree to which the glass has been separated and cleaned, processors will often have to pay a downstream recipient to accept the cullet (*24*). Alternative applications for secondary CRT glass have been proposed including bricks, decorative tile, nuclear waste encapsulation, construction aggregates, fluxing agent, and sandblasting medium (*27, 28*). Several projects are working to reduce the barriers to use in these applications (*28*), nevertheless, in all cases identified to-date secondary CRT glass substitutes only for other *low cost* materials (usually sand). 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 (*21, 28*).

The final barrier to using secondary CRT glass is related to trends in the global marketplace for manufacturing and selling CRT-containing devices. CRT glass production used to take place all over the world (*29*), but today production is located exclusively in Asia, particularly China and India (*30*). Nevertheless, North America and Europe are still generating e-waste and there is still demand (albeit sometimes small) for CRTs all over the world. The disparities between the locations of waste generation and potential consumption necessitate a global flow of secondary CRT glass if it is to be used in manufacturing new CRTs.

Models of Supply and Demand in the Secondary CRT Glass Material System. The multiple potential pathways of material flow for CRT glass throughout its life are depicted in Figure 1. The focus of this study is on CRT glass cullet that is used to produce new CRTs, as highlighted in the lower portion of the figure. In particular, the analysis focuses on the *supply* and *demand* for cullet. The use of CRT glass cullet in the production of new CRTs is the focus of this analysis because it is the economically preferable alternative (the only cullet destination that is revenue-generating for the recycler), the more common alternative (approximately 75% of CRT cullet in the U.S. (*2*)), and the only closed-loop alternative.

The inputs for the supply and demand models are also shown in Figure 1. Specifically, the supply model combines four elements to estimate annual CRT glass cullet collection: unit glass weights, historical sales, product lifespans, and EoL collection fractions. Supply flows, Y, for each year, t, are separately tracked for two product types, CRT TVs (T) and monitors (M), indexed on $j \in \{T,M\}$, and in terms of funnel cullet (F) and panel cullet (P), indexed on $i \in \{F,P\}$. Additionally, cullet generation is modeled for a set of N regions, indexed on n. CRT glass cullet collection amounts are calculated using the following relationship:

$$Y(t) = \sum_{i\in\{F,P\}} \sum_{n=1}^{N} (Y_i^n(t)) = \sum_{i\in\{F,P\}} \sum_{n=1}^{N} ((\sum_{j\in\{T,M\}} (\int_{s=-\infty}^{s=t} W_{i,j}(s) \cdot S_j^n(s) \cdot \lambda_j(s,t) ds)) \cdot C^n(t)) \quad (1)$$

The cullet *generated* in region n in year t is the weight of glass in a model unit product (average over all product sizes) in the year the product was sold (indexed on s), $W_{i,j}(s)$, multiplied times the number of products sold in region n in year s, $S_j^n(s)$, multiplied times the probability that a product sold in year s reached the end of its life in year t, $\lambda_j(s,t)$, integrated over all sales years prior to t in one-year increments. The cullet *collected* in a region n in year t, $Y_i^n(t)$, is the amount generated multiplied times the fraction of EoL products collected in a region in a given year, $C^n(t)$. The total supply of cullet for a given year t, $Y(t)$, is the sum of the panel and funnel cullet collected in all N regions.

The demand model combines two elements to estimate the annual capacity for using CRT glass cullet in new production: forecast sales and the average process capacity (i.e., the fraction of new CRT glass that may be made from cullet). Potential cullet consumption is calculated using the following relationship:

$$D(t) = \sum_{i\in\{F,P\}} (D_i(t)) = \sum_{i\in\{F,P\}} (\sum_{n=1}^{N} (\sum_{j\in\{T,M\}} W_{i,j}(t) \cdot S_j^n(t)) \cdot F_i(t)) \quad (2)$$

Demand for panel or funnel cullet in a given year t, $D_i(t)$, is calculated by multiplying the weight of glass (funnel or panel) sold worldwide in the year t times the fraction of new glass that may be made from cullet, $F_i(t)$. The weight of glass sold worldwide is the weight of glass in a unit product sold in the year t, $W_{i,j}(t)$, multiplied times the number of products sold in region n in t, $S_j^n(t)$, summed over all N regions. The total demand for cullet for a given year t, $D(t)$, is the sum of the demand for the panel and funnel cullet.

The supply and demand of CRT glass cullet can be compared over time to determine relative trends and, in particular, estimate when supply will exceed demand. It is important to note that here demand represents the amount of cullet that *could* be used in the production of new CRT glass. Actual consumption may be limited by supply availability. However, the economic viability of the system will be adversely impacted when supply exceeds demand because the alternative applications for CRT glass cullet have limited value at present.

Data Sources for Model Inputs. The temporal span of the analysis and data used in the analysis were dictated by the need to forecast trends sufficiently into the future to capture potential critical events. Forecasting trends up to the year 2025 was estimated to be sufficient. Historical product sales data were required back to 1990 in order to estimate the e-waste collected.

For the two model parameters that are a function of location—sales and EoL collection fraction—the analysis is broken into four world regions: North America; Europe, the Middle East, and Africa (EMEA); Latin America; and Asia (including Australia). These regions were selected based on the resolution of available sales data.

Annual sales data for CRT TVs and monitors were estimated using various sources (*2, 21, 29, 31*–*33*) because no single source of publicly available data was comprehensive. Gaps in historical data were estimated using interpolation based on known trends in other regions. Gaps in forecasts were estimated using extrapolation based on media reports of market forecasts (e.g., ref *4*). No information was available on sales numbers beyond 2011 due to the inherent challenges of forecasting. Although there is widespread agreement that there will be a significant decrease in worldwide CRT sales in the next decade, the timing and nature of the sales peak are unknown (*3*). Given this uncertainty, sales data beyond 2011 were assumed to follow the downward trend plotted in Figure 2. Sensitivity analyses were completed to examine the effect of the uncertainty in these assumptions. It is clear from Figure 2 that future sales will be dominated by TV sales in Asia. Thus, three scenarios for TV sales in Asia were selected to use in sensitivity analyses: high, medium (baseline), and low sales (see Figure 2a).

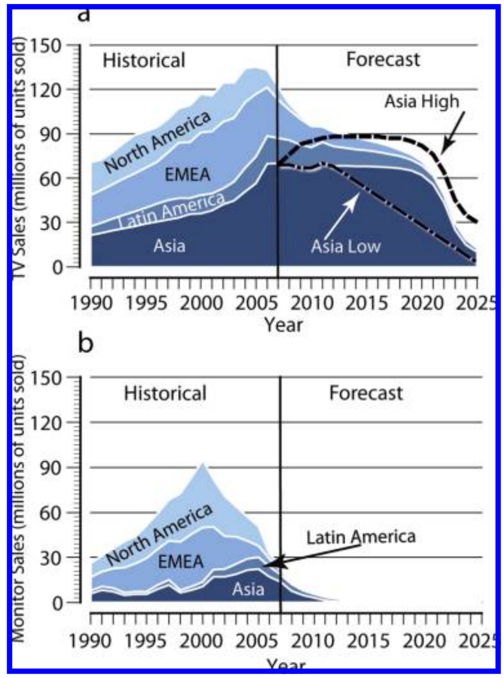


FIGURE 2. Annual (a) TV and (b) monitor sales for four locations. The TV sales plot in (a) shows three scenarios for future TV sales in Asia used in sensitivity analyses including the baseline.

TABLE 1. Sales-Weighted Average Funnel and Panel Glass Weight for a Unit TV and Monitor in 1990 and the Annual Increase in Unit Weight Thereafter

glass type	average unit weight in 1990 (kg/unit)	annual unit weight increase 1991–2000 (kg/unit)	annual unit weight increase 2001–2025 (kg/unit)
TV funnel	5.68	0.11	0.07
TV panel	11.36	0.23	0.14
monitor funnel	2.82	0.09	0.05
monitor panel	4.89	0.20	0.09

The increasing demand for larger TVs and monitors has meant that the average weight of glass in these devices has increased over time. A sales-weighted average funnel and panel glass weight for a unit TV and monitor was determined from (*21*) across the analysis period and for a wide range of TV and monitor sizes. (See Table 1.)

Studies on the age of e-waste returned for recycling have indicated that there is a wide distribution in the product lifespan (*2*). In this study, TV and Monitor lifespan characteristics $\lambda_c(s,t)$ were derived from (*2*) by convolving the information from that report weighted in accordance to the sales fractions of products with specific attributes in the following manner:

$$\lambda_T(s,t) = \lambda_{T,\text{small}}(s,t)\cdot\Lambda_{T,\text{small}} + \lambda_{T,\text{big}}(s,t)\cdot\Lambda_{T,\text{big}} \quad (3)$$

$$\lambda_M(s,t) = \lambda_{M,\text{res}}(s,t)\cdot\Lambda_{M,\text{res}} + \lambda_{M,\text{com}}(s,t)\cdot\Lambda_{M,\text{com}} \quad (4)$$

$\lambda_{c,k}(s,t)$ is the retirement probability function for products with specific attributes (k for TVs is *small* or *big*, indicating less than or greater than a 19″ display; k for monitors is res for residential sales and com for commercial sales; s is the year the product was sold; t is the year of the analysis). Λ_{jk} is the sales fraction for the associated products: $\Lambda_{T,\text{small}}$ is 43%, $\Lambda_{T,\text{big}}$ is 57%, $\Lambda_{M,\text{res}}$ is 48%, and $\Lambda_{M,\text{com}}$ is 48% (*2*). The two derived product lifespan functions are shown in Figure 3 as cumulative probability distributions.

Beyond constituents of municipal solid waste, data on EoL collection rates are scarce. Recent studies from the European Union (*1*) and the United States (*2*), have estimated CRT collection rates of approximately 30% and 15−20%, respectively. To the authors' knowledge there are no known estimates of how these rates vary over time or in other regions of the world.

EoL collection fractions, $C^n(t)$, in this analysis were assumed to follow an "S-curve" behavior over the period of the analysis as defined by the following expression:

$$C^n(t) = \frac{\alpha}{1 + e^{\left(-\frac{(t - t^n_D) - \Delta}{\tau}\right)}} \quad (5)$$

where α defines the range of collection fractions that will be observed and Δ is a time shift parameter:

$$\alpha = C^n(\infty) - C^n(-\infty) \quad (6)$$

$$\Delta = t^n_0 + \tau\cdot\ln\left(\frac{\alpha}{C^n(t^n_0)} - 1\right) \quad (7)$$

where τ is a time delay shape parameter and t^n_D is a time delay shift parameter. The limits of the curve are defined by α, the midpoint of the curve is defined by $C^n(t^n_0)$ at the reference time t^n_0, and τ determines the shape or steepness of the curve.

Because Europe has the most extensive collection experience, a collection rate S-curve was defined for Europe to serve as a reference. The limit, reference, and shape parameters for the European curve are listed in Figure 4. The reference point was based on (*1*), but the upper limit and the time delay shape parameter τ were estimated. Sensitivity analyses will explore the impact of the value of τ.

Curves for other locations were assumed to have the same limits, reference point, and shape as the European curve, but are offset by the time delay shift parameter t^n_D; values for this parameter for each location are listed in Figure 4 and are estimates, with the exception of North America (*2*). Sensitivity analyses will test the impact of the assumed values for this parameter.

Notably, two of the four locations are separated into "sublocations" in Figure 4: EMEA is separated into Europe and MEA and Asia is separated into Asia Pacific and China. This is due to current differences in policy and market conditions within these regions. The aggregate trend represents the weighted (by sales) sum of the sublocation trends. For example, the sales data collected for this research indicate that China represented approximately 42% of CRT-device sales in Asia in 2005 and this is estimated to decline nearly linearly every year until reaching 32% in 2025. Europe's fraction of CRT sales within EMEA was nearly 90% in 2005 and this is estimated to hold steady for approximately five years and then decrease to 70% by 2025. The final EoL collection fraction curves are shown in Figure 4, including

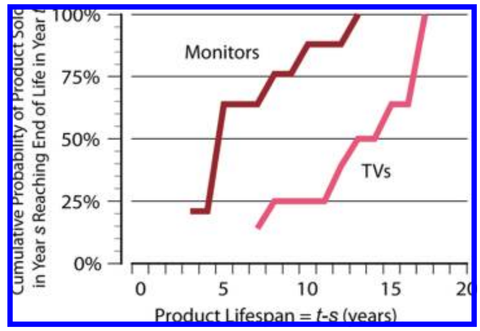
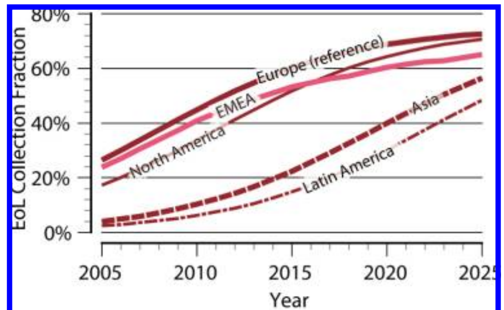


FIGURE 3. Cumulative probability functions of product lifespan for CRTs and TVs.



Collection fraction curve parameters for all regions

$C^n(-\infty)$	$C^n(\infty)$	t^n_0	$C^n(t^n_0)$	τ
0%	75%	2006	30%	5.00

Time delay shift parameter values (t^n_D)

Europe	MEA	North America
0	14	3

Latin America	Asia Pacific	China
14	10	14

FIGURE 4. Parameter values to define annual EoL collection fractions and the resulting-curves for the four locations in this study and for the reference curve, Europe only. Based on the time delay shift parameters, Europe and MEA combine to form the EMEA curve and Asia Pacific and China combine to form the Asia curve.

the European reference curve. Inflections in the EMEA curve reflect the decreasing sales fraction of Europe within EMEA over time.

In addition to sales forecasts, the demand model requires data on the capacity for using CRT glass cullet in the production of new CRT glass. Unfortunately, there is limited information in the literature on such capacities. One study from 2002 estimated this capacity to be 20% for panel glass and 40% for funnel glass (*34*). Another study from 2004 listed capacities of 30% for panel glass and 55% for funnel glass (*28*).To update those figures, the authors surveyed current CRT glass manufacturers. Collecting such data proved to be difficult for several reasons (e.g., they are several levels removed from monitor and TV manufacturers in the product supply chains, language and cultural barriers, unwillingness to share data), but two manufacturers shared data on their cullet capacities and use. Their capacities were significantly higher than the aforementioned values, but they could not collect enough cullet to meet their capacities. Additional discussions with stakeholders in the primary and secondary CRT glass industry indicated that not all CRT glass manufacturers are using cullet in manufacturing.

In light of these differences, a constant value of 50% was used as a baseline fractional capacity for the use of CRT funnel and panel glass cullet in the model. Although the manufacturers who shared data on cullet use provided

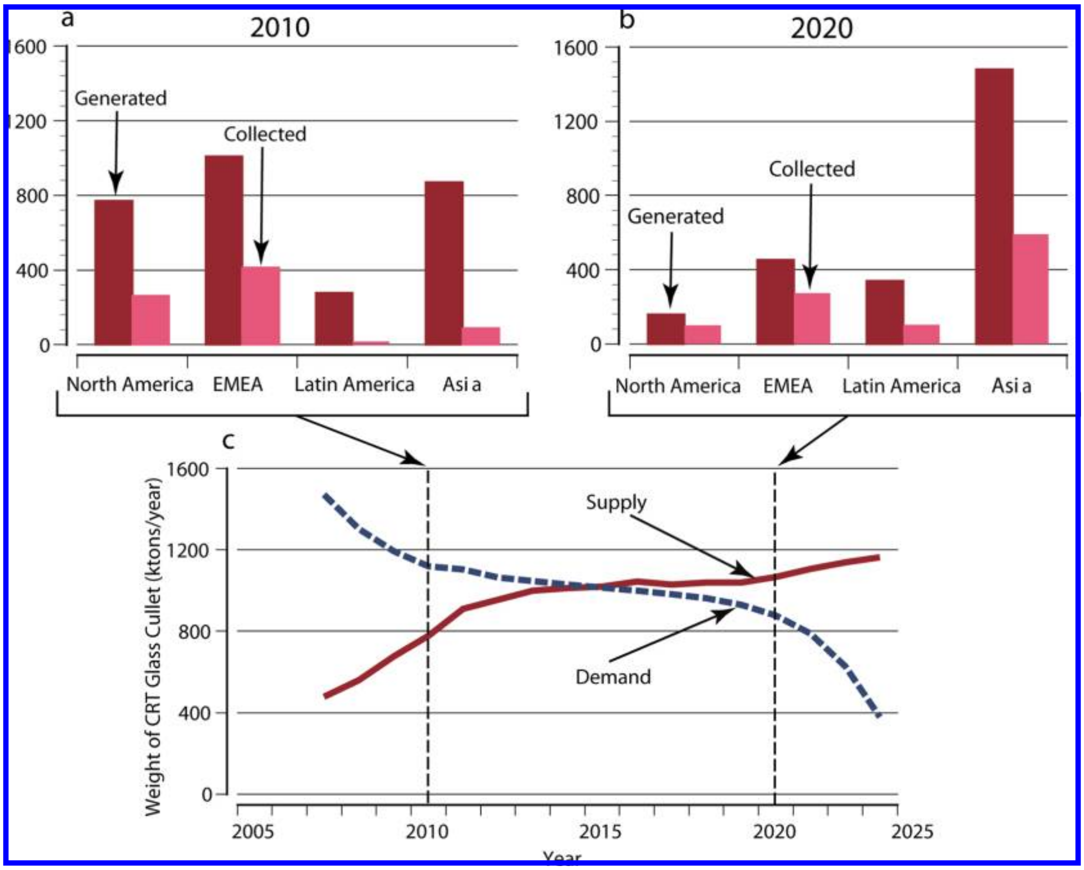


FIGURE 5. Weight of CRT glass cullet generated and collected in the four regions in (a) 2010 and (b) 2020, and (c) supply and demand curves for CRT glass cullet using baseline assumptions.

capacities higher than 50%, this value attempts to represent an average for the entire industry, even those not using cullet. Sensitivity analyses will be conducted on these assumptions.

Analysis and Discussion. It is interesting to compare the modeled weight of CRT glass cullet generated and the amount of CRT glass collected in each region as it evolves over time. Figure 5a and b show these amounts for the four regions in 2010 and 2020 (weights are in metric tons, as in all plots). The projected amounts generated in North America and EMEA decrease over time as sales decrease, whereas the projected amount generated in Asia increases by almost a factor of 2. Furthermore, the modeled collection fraction is almost nonexistent in Latin America and Asia in 2010, but increases significantly by 2020.

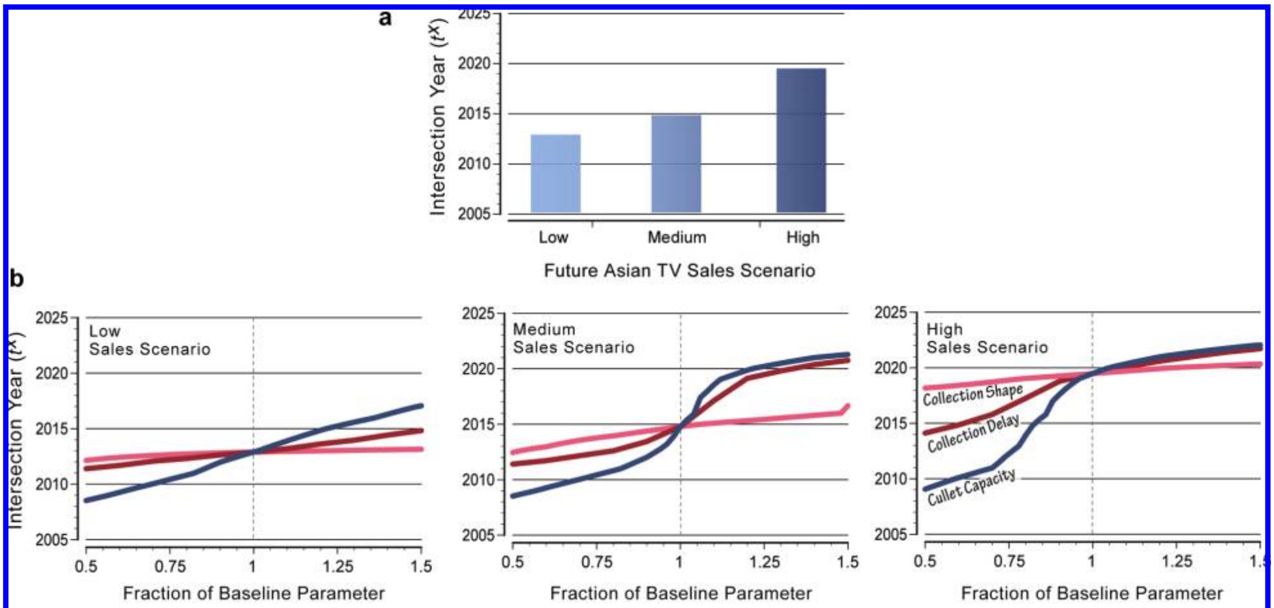
Predicted supply and demand behavior for CRT cullet using baseline inputs in the models are plotted until the year 2025 in Figure 5c. As expected, cullet demand decreases over time as product sales decrease and cullet supply increases as more products reach EoL. The intersection of the curves, when supply begins to exceed demand, occurs in approximately 2015 for the baseline conditions.

Given the uncertainty in several inputs, it is important to examine the sensitivity of the results to these key assumptions. The areas of highest uncertainty include sales forecasts ($S^n{}_j(t)$), collection rates, and the capacity for glass manufacturers to use CRT cullet ($C^n(t)$). With regard to future sales, TV sales will clearly dominate monitor sales and Asia will represent the largest market for TV sales. Thus, the three future Asian TV sales scenarios described in Figure 2 were tested. The implication of collection rate was explored in terms of both the shape parameter, τ, and the delay parameter, t^n_D. Given the importance of the Asian market, only changes to collection in that region were explored.

Figure 6 plots the modeled time to intersection (t^x) at which supply exceeds demand for CRT cullet under various conditions. Each of these plots represents a single parameter sensitivity, evaluated holding all other parameters constant. Figure 6b plots the impact of changes in the three parameters, $C^n(t)$, τ, and t^n_D, for each of the sales scenarios. In each plot in Figure 6b, the x-axis represents the fraction of the baseline value at which each factor was evaluated, ranging from 0.5× to 1.5× baseline.

Figure 6a shows that the modeled supply/demand intersection year is moderately sensitive to the TV sales scenario, increasing by over four years for the high scenario and decreasing by two years for the low scenario. The results shown in Figure 6b suggest that cullet capacity, $C^n(t)$, has the strongest effect on t^x. The parameter τ, generally, has an intermediate impact, while t^n_D has little impact on t^x, irrespective of demand conditions. Of these factors, only cullet capacity appears to have the leverage to drive t^x to occur quite soon. If most CRT glass manufacturers are using cullet in high fractions, then the intersection easily stretches to 2020. Low cullet usage, however, means oversupply could occur eminently.

To more thoroughly characterize the impact of these factors a full-factorial numerical experiment was executed across all four factors. For each quantitative factor, twenty levels were chosen randomly from a uniform distribution spanning from 0.5× to 1.5× of the baseline value. Based on the set of results from these experiments, an analysis of variance was carried against a mixed effects model fitted to the observed t^x using the restricted maximum likelihood (REML) method. All main and interaction effects were statistically significant ($p < 0.0001$); however, interaction effects were not explored in detail because none accounted for more than 1.1% of the variance in the model. The results of this analysis are shown in Figure 6c. The scaled coefficient estimates confirm that changes in cullet capacity, $C^n(t)$, have the strongest effect on t^x. Proportionately, $C^n(t)$ has nearly



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Summary of Fit

R-square	0.864
Adjusted R-square	0.864
Root Mean Square Error	1.69
Mean of Response	2014
Observations (or Sum Wgts)	24000

Parameter Estimates

Parameter	Coefficient Estimate	Standard Error	t-Ratio	p-Value	Scaled Estimate†
Intercept	2000	0.06	31500	<0.0000	2020
Capacity for Cullet use (2007)	25.8	0.08	340	<0.0000	6.06
Future Asian TV Sales Scenario[-1-0]	-2.00	0.03	-75	<0.0000	-2.00
Future Asian TV Sales Scenario[0-1]	-1.87	0.03	-70	<0.0000	-1.87
t_D (Asia Pacific Collection Delay)	0.44	0.00	120	<0.0000	2.22
τ (Time delay shape)	0.26	0.01	40	<0.0000	0.61

† Continuous factors centered by mean, scaled by range/2

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob > F
Model	5	435300	87000	30400	<0.0000
Error	23994	68700	2.9		
Corrected Total	23999	504000			

Effect Tests

Source	DF	Sum of Squares	Variance Component	F-Ratio	Prob > F
Capacity for Cullet use (2007)	1	331000	665.7	115000	<0.0000
Future Asian TV Sales Scenario	2	59600	n/a	10400	<0.0000
t_D (Asia Pacific Collection Delay)	1	39900	0.2	13900	<0.0000
τ (Time delay shape)	1	4820	0.1	1680	<0.0000

FIGURE 6. Sensitivity analyses. (a) The impact of variation in future Asian TV sales scenario on supply and demand intersection year t^x. (b) The impact of variation in cullet capacity ($C^n(t)$), collection rate shape (τ), and collection delay$_{(t_D^n)}$, on t^x. x-axis represents fraction of baseline parameter at which analysis was executed. (c) Summary of analysis of variation for main effects of the four factors explored in (a) and (b) on model response.

three times more leverage on the modeled result than either the sales scenario or t_D^n (collection delay). τ has only a small effect on the modeled intersection year. Consistent with these coefficient results, the effects tests suggest that of the three random effects factors, nearly ninety percent of response variance is attributable to $C^n(t)$.

Predicting the exact year when supply will exceed demand is not possible, but these analyses indicate that it could happen within the next 10 years. The intersection year under the baseline scenario was predicted to be nearly 2015, but this intersection could be sooner if there are low TV sales, particularly if there are high collection rates in Asia and if CRT glass manufacturers maintain low usage of CRT cullet. Notably, the supply and demand curves depicted in Figure 5c shift depending on the modeled assumptions (vertically or horizontally), but the shapes essentially remain the same. Thus, a shift in a curve changes the position of the "knee" in each curve, which can have a significant impact on the supply and demand intersection point.

There are two major implications of this research. First, more data needs to be collected on the current and expected capacity of the entire CRT glass manufacturing industry to use CRT cullet because this has a significant impact on the demand curve. Second, more research is needed in the area of alternative value-driven applications for CRT cullet. Others have called for such research (*35*) and while there has been research into alternative applications for CRT cullet (*28, 36, 37*), the applications are generally low or negative value for cullet. The breakthrough that is needed to create a viable value-driven market for CRT cullet is either the capability to extract lead and other "undesirable" elements such that the cullet can be used in other common applications (e.g., architectural, automotive, and packaging glass) or the development of glasses for common applications which can accommodate these elements. Such technologies are beginning to emerge (*35*). Now, research efforts should focus on transforming CRT cullet into a commodity that is valuable.

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