Supply and demand in the material recovery system for cathode ray tube glass

Supply and Demand in the Material Recovery System for Cathode Ray Tube Glass

Jeremy Gregory, Marie-Claude Nadeau, and Randolph Kirchain

Abstract— **This paper presents an analysis 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 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.**

Index Terms— **Cathode ray tube, e-waste, glass, recycling.**

I. Introduction

DEVICES containing cathode ray tubes (CRTs), such as computer monitors or televisions (TVs), represent a significant and challenging fraction of the electronics waste stream. In Europe, where regulated 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 US, 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 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 US [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 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 particular urgency due to the rapidly changing nature of the CRT market and the emergence of government-mandated e-waste recycling systems.

To explore this issue, this paper develops and exercises a dynamic materials 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 glass cullet.

This model is used to compare trends in supply and demand and, ultimately, estimate the time until the supply of CRT glass cullet exceeds the demand. The results of the work provide insight on 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 material systems with similar characteristics.

From a case perspective, several studies have estimated the amount of end-of-life CRT devices generated regionally in the US [2, 5], Europe [1], and South Africa [6]. In addition, Linton has used forecast the amount of CRT waste that will be collected in the US for the next fifty years [7]. Finally, Weitzman correctly identified that there would be decreasing demand for CRT cullet in the US because US manufacturers were producing a smaller share of the CRT market (assuming that CRT cullet generated in the US would only be used in CRT glass manufacturing in the US) [8]. Although each of these provides important insights into the problem, no single study is able to answer the questions posed in that the examined scope was limited temporally, geographically (only

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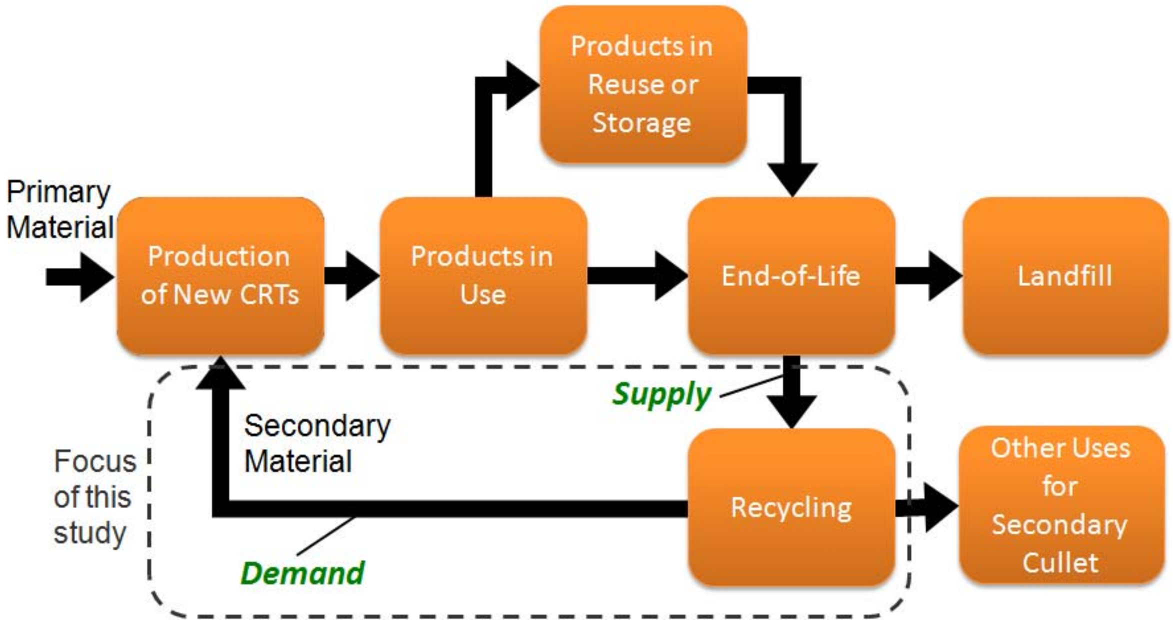

Figure 1. CRT glass material system flow.

a single region), and/or sectorally (i.e., demand or supply). The research presented in this paper addresses these gaps for this case.

II. 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 of CRT glass cullet, represented by the arrow from “End-of-Life” to “Recycling”, and the demand for CRT glass cullet, represented by the arrow from “Recycling” to “Production of New CRTs”. 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 CRT cullet destination that is revenue-generating for the CRT recycler), the more common alternative (approximately 75% of CRT cullet in the US is estimated to be sent to CRT glass manufacturers [2]), and the only closed-loop alternative.

The inputs and outputs for the supply and demand models are shown in Figure 2. Specifically, the supply model combines four elements to estimate the annual amount of CRT glass cullet collected worldwide: historical sales, glass weights per product, product lifespans, and EoL collection fractions. Flows, Y, for each year, t, are separately tracked for two product types CRT TVs (T) and monitors (M), indexed on $c\in\{T,M\}$, and in terms of funnel cullet (F) and panel cullet(P), indexed on $\xi\in\{F,P\}$. 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 (variables are defined in Figure 2):

$$Y(t)=\sum_{\xi\in\{F,P\}}\sum_{n=1}^{N}\left(\left(\int_{s=-\infty}^{s=t}\sum_{c\in\{T,M\}}\left(W_{\xi,c}(s)\cdot S_c^n(s)\cdot\lambda_c(s,t)\right)ds\right)\cdot C^n(t)\right) \tag{1}$$

The cullet generated in region n in year t, $Y_\xi^n(t)$, is the sum of the weight of glass in a unit product in the year the product was sold (indexed on s), $W_{\xi,c}(s)$, multiplied times the number of products sold in region n in year s, $S_c^n(s)$, multiplied times the probability that a product sold in year s reached the end of its life in year t, $\lambda_c(s,t)$, integrated over all sales years prior to t in one-year increments. The cullet collected in a region 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 the production of new CRT glass: forecast sales and the percentage of new CRT glass that may be made from cullet. Potential cullet consumption is calculated using the following relationship:

$$D(t)=\sum_{\xi\in\{F,P\}}\left(\sum_{n=1}^{N}\left(\sum_{c\in\{T,M\}}W_{\xi,c}(t)\cdot S_c^n(t)\right)\cdot F_\xi(t)\right) \tag{2}$$

Demand for panel or funnel cullet in a given year t, $D_\xi(t)$, is calculated by multiplying the weight of glass (funnel or panel) sold worldwide in t times the fraction of new glass that may be made from cullet, $F_\xi(t)$. The weight of glass sold worldwide is the weight of glass in a unit product sold in the year t, $W_{\xi c}(t)$, multiplied times the number of products sold in region n in t, $S_c^n(t)$, 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.

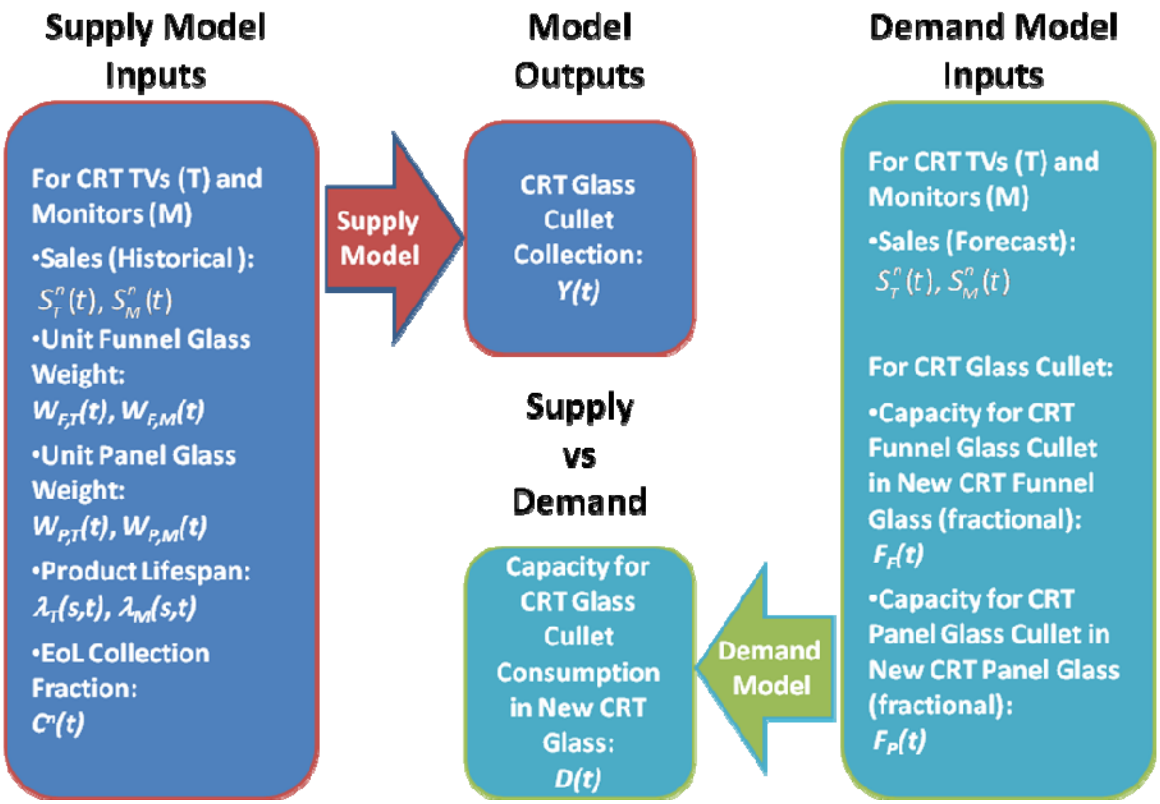

Figure 2. Supply and demand models inputs and outputs. Within the functions, *n* represents region, *t* represents the year of the analysis, and *s* represents the year in which products are sold.

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 demand represents the amount of cullet that *could* be used in the production of new CRT glass. Actual consumption of CRT glass cullet may be limited by supply availability. However, the economic viability of the system will be in jeopardy when the supply exceeds the demand because of the limited-value alternative applications for CRT glass cullet.

III. Data Sources for Model Inputs

The complete details on data sources and methods for model inputs are presented in [9]; an overview of the methodology is presented here.

The temporal span of the analysis and data was dictated by the need to forecast trends sufficiently into the future to capture potential points where supply would exceed demand. Forecasting trends up to the year 2025 was estimated to capture such crossover points. Historical product sales data were required as far back 1990 in order to estimate the amount of e-waste that could be 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, 5, 10-13] because no single source of publicly available data existed that was comprehensive. Gaps in historical data were estimated using interpolation or mapping from trends in other regions where data were available. Gaps in forecasts were estimated using media reports of market forecasts [e.g., 4] and extrapolation. 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. Given this uncertainty, three scenarios for TV sales in Asia (the dominant factor in future sales) were selected to use in sensitivity analyses: high, medium (baseline), and low sales.

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 [5] across the analysis period.

Studies on the age of eWaste 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 with the sales fractions of specific product types (small and large TVs and residential and commercial sales). The result is probability distributions for TVs and monitors that a product sold in year *s* reached the end of its life in year *t*.

Once a product is ready for EoL management, it can either be landfilled or recycled, as depicted in Figure 1. Data on EoL collection rates (the fraction of EoL products generated that are collected for recycling) are extremely limited. 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 in this analysis were assumed to follow an "S-curve" behavior over the period of the analysis: collection rates begin at a low plateau, then increase rapidly until reaching an upper plateau. Several parameters define the shape and values of the function including a reference collection fraction value at a reference year, an upper limit, and a shape parameter.

Since Europe has relatively high collection rates and a sizable population, a collection rate S-curve was defined for Europe that could act as a reference for other regions. The reference point was based on the aforementioned EU study [1] (30% in 2006), but the upper limit (75%) and the time delay shape parameter were estimated. Sensitivity analyses will explore the impact of the value of the shape parameter.

Curves for other locations were assumed to have the same limits, reference point, and shape as the European curve, but are offset by a time delay shift parameter. Estimated shifts range from 3 years for North America to 14 years for Latin America.

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 [10]. 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 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.

IV. 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 3 shows 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 two. Furthermore, the modeled collection fraction is almost nonexistent in Latin America and Asia in 2010, but increases significantly by 2020.

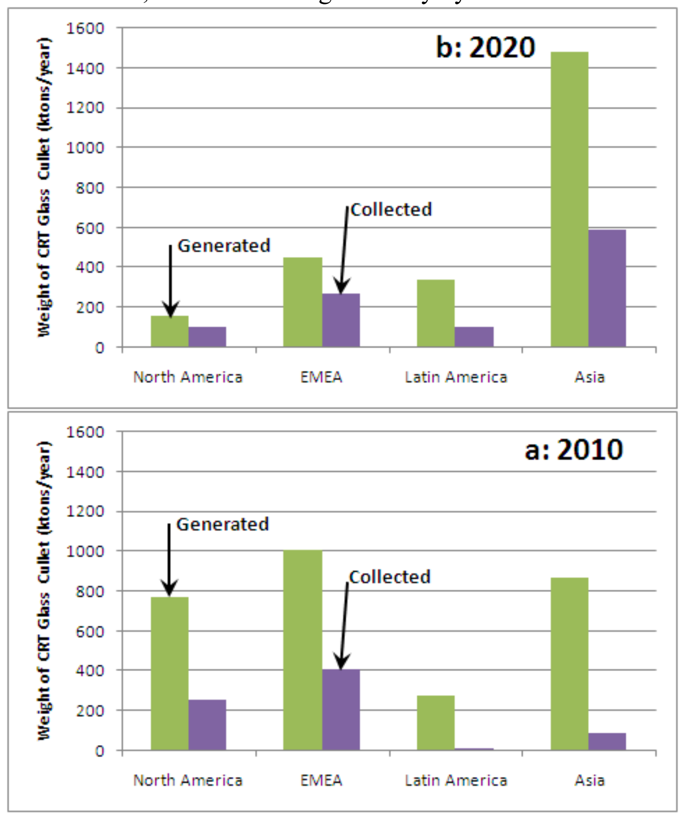

Figure 3. Weight of CRT glass cullet generated and collected in the four regions in a) 2010 and b) 2020.

Predicted supply and demand behavior for CRT cullet using baseline inputs in the models are plotted until the year 2025 in Figure 4. 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 2014 for the baseline conditions.

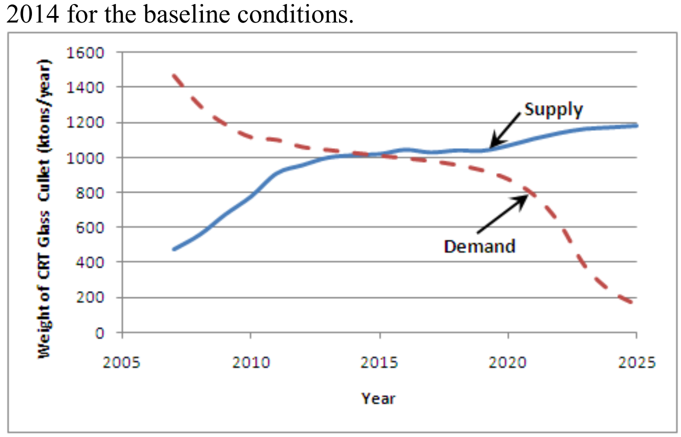

Figure 4. Supply and demand plots of CRT glass cullet using baseline inputs.

Given the uncertainty in several inputs, it is important to examine the sensitivity of the models to these key assumptions. The areas of highest uncertainty include sales forecasts, collection rates, and the capacity for all CRT glass manufacturers to use CRT cullet. The impact of variation in these inputs on the year in which supply and demand intersect is depicted in Figure 5 to Figure 7. With regard to future sales, TV sales will clearly dominate monitor sales and Asia will represent the largest market for TV sales. Thus, three future Asian TV sales scenarios were used in the model. Figure 5 shows that the supply and demand intersection year calculated by the model is moderately sensitive to the future TV sales scenario, increasing by two years for the high scenario and decreasing by two years for the low scenario. The intersection year is also only moderately sensitive to variation in the collection time delay shape parameter (which determines the shape of the collection fraction S-curves), as depicted in Figure 5.

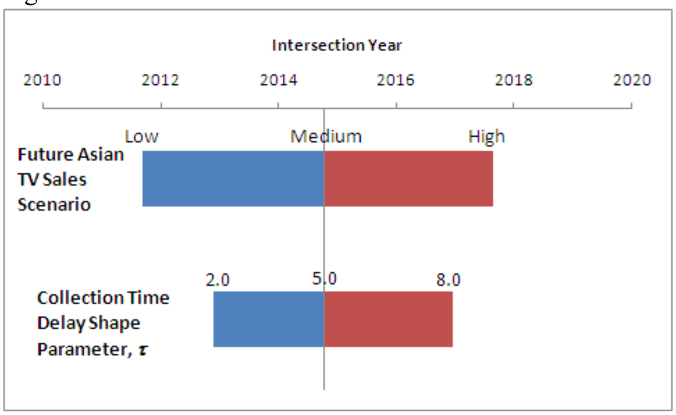

Figure 5. The impact of variation in future Asian TV sales scenario and the collection time delay shape parameter, on supply and demand intersection year. Baseline parameters result in the intersection year of 2014.

Another important parameter that defines collection rates as a function of time is the time delay shift of the collection fraction S-curves with respect to Europe. Variation in the shift parameter for Asia Pacific and China, which collectively are Asia, the region that will be generating the most CRT cullet, can have a significant impact on intersection year, as depicted in Figure 6. If Asia has a short lag behind Europe in its collection efforts (five to ten years), supply will intersect demand in a few years. However, if the lag is significant (on the order of 15 years), then the intersection point could extend to 2020.

The capacity for all CRT glass manufacturers to use CRT cullet also has a significant impact on the intersection year, which is illustrated in Figure 7. It is important to remember that the capacity for cullet us is an industry-wide parameter; it could include some manufacturers who are using no cullet and others who use cullet extensively. If most CRT glass manufacturers are using cullet in high fractions, then the intersection will be later than the baseline prediction of 2014. However, low usage of cullet means the intersection could occur quite soon.

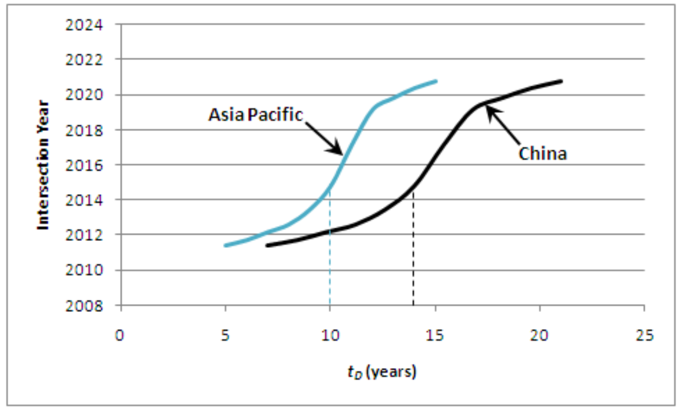

Figure 6. The impact of variation in t_D, the collection delay with respect to Europe, on supply and demand intersection year. t_D=10 is the baseline for Asia Pacific; China is always 1.4 times Asia Pacific's delay.

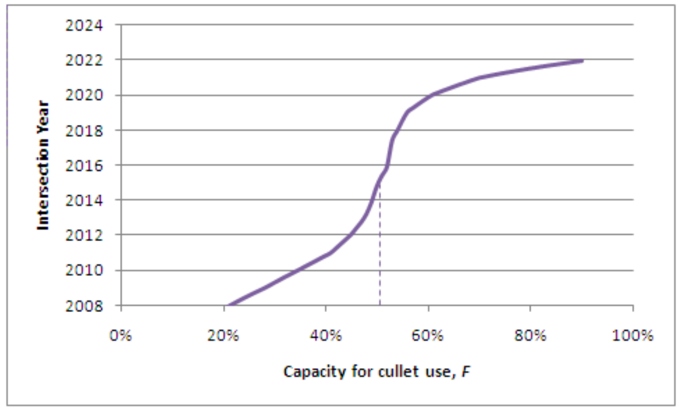

Figure 7. The impact of variation in the fractional capacity for cullet use (panel and funnel are equal). The baseline value is 50%.

Predicting the exact year when supply will exceed demand is not possible, but these analyses indicate that it could happen within the next ten years. The intersection year under the baseline scenario was predicted to be 2014, but this intersection could be sooner if there are low TV sales, but 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 4 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 need in the area of alternative value-driven applications for CRT cullet. Others have called for such research [11] and while there has been research into alternative applications for CRT cullet [12, 13], the applications are generally low or negative value for cullet and are unlikely to meet the supply of CRT cullet generated. The breakthrough that is needed to create a viable value-driven market for CRT cullet is the capability to extract lead and other undesirable elements from the cullet such that it can be used in the same applications as other glass cullet, such as architectural, automotive, and packaging applications. Although technologies exist to remove lead from CRT cullet [11], the cullet is still only accepted in low-value applications. Thus, research efforts should focus on transforming CRT cullet into a secondary commodity that is valuable.

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