Material Flows and Energy Analysis of Glass Containers Discarded in New Jersey, USA

Ching-Ling Tsai and Uta Krogmann

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Supporting information is available on the *JIE* Web site

Summary

The use of glass cullet (crushed recycled glass containers) as aggregate in construction projects and landfills has increased rapidly even though the use of cullet as feedstock in new glass container and fiberglass production is energetically more sound. The effect of increased use of cullet as aggregate has not yet been thoroughly assessed. The objectives of this study were to model and quantify glass container flows across New Jersey and the associated life cycle energy consumption, and then compare life cycle energy consumption for two different recycling scenarios and three different end-use/disposal scenarios. The results of a material flow analysis showed that in 2008 only about 11% of the glass containers consumed in New Jersey were used as glass container or fiberglass feedstock, while five times more were used as construction aggregate. However, a lower system energy requirement can be achieved by increased use of cullet as container feedstock compared to construction aggregate, even when the cullet is transported 1,600 miles to a glass container manufacturer. Based on the uncertainty analysis, there is about an 80% probability for the scenario with increased use as container feedstock to have a lower system energy requirement when compared with all other scenarios. To achieve increased use of cullet as glass container feedstock in New Jersey, the quality of the cullet must be improved.

Introduction

In 2008, 10.2 million tons[1] of municipal solid waste (MSW) were generated in New Jersey (NJDEP 2010), the most densely populated state in the United States. Of this, 3.9 million tons, including 317,000 tons of glass containers, were processed in recycling facilities (NJDEP 2010). The importance of improving recycling and minimizing MSW disposal has long been recognized. Recycling is defined as "any process by which materials that would otherwise become solid waste are collected, separated or processed and returned to the economic mainstream in the form of raw materials or products" (NJDEP 2009). In New Jersey, the Statewide Mandatory Source Separation and Recycling Act (1992) requires a 50% recycling rate for MSW.

Glass container recycling in New Jersey is dominated by commingled dual-stream curbside collection. Some municipalities also have access to drop-off centers, where residents can bring their glass containers. In dual-stream recycling, used glass containers are collected at the point of generation, commingled with other containers such as high-density polyethylene (HDPE) and polyethylene terephthalate (PET) containers and aluminum, tin, and bimetal cans, but separate from the paper fraction. Recently dual-stream recycling is being replaced by single-stream recycling, where the container stream is

Address correspondence to: Uta Krogmann, Rutgers University, Department of Environmental Sciences, 14 College Farm Rd., New Brunswick, NJ 08901-8551, USA. Email: krogmann@aesop.rutgers.edu

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collected commingled with the paper fraction. This trend has resulted in higher breakage rates and elevated contamination of the glass containers (CRI 2009; Eureka Recycling 2002; Jamelske and Wessling 2005; Morawski 2009; Smith-Teutsch 2010). Broken glass containers are difficult to cost-effectively separate by color, which is necessary if the cullet is to be used in new glass container production. The higher contamination rates also complicate the separation to meet cullet specifications for glass container production. The specifications for glass container production require less than 0.4% by mass of paper and plastic materials in the cullet, less than five particles of metal and less than one particle of all other contaminants per truckload of cullet (CWC 1997; ISRI 2009). As a result, use of cullet for alternative applications that do not require high quality or color separation (i.e., daily landfill cover, drainage layer, or road pavement) has grown rapidly (Reindl 2003).

Studies assessing the life cycle environmental impacts of the glass container recycling system with increased use as aggregate are currently lacking. Two case studies conducted in Manchester, United Kingdom, and Ontario, Canada, have found that the life cycle energy savings for cullet used as aggregate were one order (Morris 1996) or two orders (Butler and Hooper 2005) of magnitude lower than that for cullet used in new container production. However, the Canadian study covers several materials and does not provide many details, while the UK study is more a feasibility study. In the UK study, Butler and Hooper (2005) indicated that even long-haul of cullet for use in glass container manufacturing in France can provide more energy savings than its use as aggregate substitute within the United Kingdom. However, the distances and conditions in the United States might be different than in Europe.

Based on these studies and the increasing trend of no color separation and single-stream recycling, it is important to assess the life cycle energy consumption of glass container recycling in New Jersey. The first objective of this study was to understand, quantify, and model glass container flows in New Jersey and the associated life cycle energy consumption from the extraction of raw materials to collection and processing of recycled glass containers, to final use and disposal. The second objective of the study was to compare energy consumption for two different recycling scenarios (i.e., current recycling practice and single-stream recycling), and three different end-use/disposal scenarios (i.e., increased use for higher beneficial uses such as glass container manufacturing, dominant aggregate use, and curbside recycling replaced with MSW disposal). Based on the findings, implications for glass container recycling will be discussed.

Materials and Methods

A material flow analysis (MFA) and an accompanying energy analysis were conducted to track the life cycle of glass packaging containers discarded in New Jersey and the associated life cycle energy use. Glass containers are used for packaging of foods and beverages (i.e., jars and bottles). MFA is a method for investigating complex material flows to better manage resources, environmental impacts, and wastes (Ayres and Simonis 1994; Baccini and Bader, 1996; Baccini and Brunner 1991; OECD 2001). In the case of glass containers, MFA tracks and quantifies glass packaging container flows throughout the entire life cycle following the rule of a simple mass balance where input minus change in stock equals output.

Energy analysis, which has been used to assess energy consumption patterns and impacts on energy resources (Boustead and Hancock 1979; Michaelis and Jackson 2000; Sundin et al. 2002), was used to calculate system energy requirements associated with the life cycle of the material (glass container) flow. System energy requirements in this study include (1) primary fuel consumption (i.e., combustion of the primary fuel—coal, natural gas, diesel, and nuclear—used for producing electricity or for direct power generation) and energy consumption for producing the primary fuels (i.e., energy consumption for extraction, refining and processing, and final delivery of the primary fuel to the customer [Franklin Associates 2004]), and (2) energy credits (energy savings due to use of cullet instead of virgin raw materials). To ease the comparisons between processes, specific energy consumption is reported (i.e., energy consumption per ton of used and discarded glass containers).

Glass Container Recycling in New Jersey

Except for glass containers collected via bars and restaurants (2.6% by mass), glass containers collected via dual-stream curbside collection (85.7% by mass), single-stream curbside collection (9.3% by mass; Hourihan 2009) and drop-off centers (2.4% by mass) are not color separated and require further processing in one of the 32 material recovery facilities (MRFs).

Glass containers in MRFs are predominantly separated by negative sorting (i.e., glass containers are left on the conveyor belt while other recyclables are removed) rather than positive sorting (whole bottles are manually separated by color). Typical process equipment in MRFs for handling glass containers from single- and dual-stream recycling systems includes screens, conveyor belts, glass crushers, and air classifiers. However, processing glass containers from a single-stream recycling system requires more processing steps (e.g., more air classifiers and screens) to remove the paper fraction, and therefore more energy (an approximate 13% increase; 18.1 kilo-British thermal units per ton [kBtu/t]) compared to processing glass containers from dual-stream recycling (Joseph Vinyard, Hatch Mott McDonald 2009, personal communication).[2] Cullet from MRFs intended for higher beneficial uses is sent to intermediate cullet processing facilities for further processing to optically separate cullet by color and to remove additional contaminants. Due to the high quality, cullet from bars and restaurants needs only limited processing in intermediate processing facilities and is easily accepted by glass container manufacturers (Morawski 2009).

System Boundary and Scenarios

System Boundary in Space and Time

All upstream and downstream flows and processes associated with glass packaging containers consumed and discarded within the geographical boundary of New Jersey in 2008 are within the system boundary in this study. The year 2008 was chosen because the data from that year were the most recent available data. It is considered a representative year based on the fact that both the recycling rate (38%) and the percentage of glass containers in the recyclables (57%) in 2008 fell within the ranges for the past 10 years (recycling rates of 33% to 40% and percentages of glass containers in the recyclables of 49% to 63% [NJDEP 2010]). Based on a review of previous studies (Dacombe et al. 2005; Gaines and Mintz 1994; Morris 1996; Ruth and Dell'Anno 1997), the following processes were included in the system boundary: glass container raw material extraction, glass container production, glass container wholesale and retail distribution, collection of recycled glass containers, processing, end use, and glass container disposal. Energy consumption for lighting and heating or cooling during processing and production was included within the boundary, while indirect energy consumption, such as energy to manufacture the machines and build the facilities or to rinse glass containers by residents before recycling, was excluded. In addition, this study does not account for containers that were produced inside New Jersey but exported out of New Jersey for use. Furthermore, new glass containers, cullet, and discarded glass containers that are only in transit through New Jersey were not included. The use of glass containers by residents and businesses was estimated to have a negligible effect on the system energy requirement and therefore was not taken into account. Energy consumption for bottling was allocated to the food/beverage processing industry (Koroneos et al. 2005) and energy consumed for landfill operations was allocated to the waste industry. Therefore both of these processes were excluded.

Scenarios

Five different scenarios were considered (table 1): (1) current glass container recycling practice; (2) current glass container recycling practice with an approximate threefold increase in use of cullet for higher beneficial uses (i.e., glass container manufacturing and fiberglass production); (3) dual-stream collection replaced by single-stream collection; (4) current glass container recycling with aggregate as dominant end use; and (5) no curbside glass container recycling (77% to landfills, 23% to waste-to-energy facilities). All scenarios include the same processes until the glass containers reach the consumer.

Modeling Approach and Data Acquisition

Glass Container Flows

Glass container flows and processes associated with glass containers used and discarded in New Jersey in 2008 were identified and quantified (figure 1).

Downstream of Use by Consumers

The quantity of glass containers used and discarded by consumers was estimated based on the sum of the disposed of and the recycled glass container quantities in New Jersey. The quantity of disposed of glass containers was calculated based on the MSW quantity disposed of in New Jersey and out of state (NJDEP 2008) and the assumption that 2.5% of the disposed MSW is glass container packaging (CDM 2005, 2008). The quantity of recycled glass containers was determined based on recycling reports submitted by the municipalities to the New Jersey Department of Environmental Protection (NJDEP). The fate and quantity of the cullet after being processed in MRFs was determined based on a survey that was sent to all 32 MRFs in New Jersey (see the survey in Tsai [2010] and the supporting information available on the Journal's Web site). This flow included cullet from drop-off centers, because in many cases the drop-off centers also delivered their recycled glass containers to the MRFs. The survey results were validated by contacting the facilities that received the cullet after exiting the MRF.

The fate and quantity of cullet delivered to and exiting intermediate cullet processing facilities was determined based on the inventory reports of these facilities. Assuming that all recycled glass containers collected in bars and restaurants were used by in-state glass container manufacturers, this quantity was estimated as the difference between the quantities of cullet from New Jersey sources and from New Jersey MRFs and intermediate cullet processing facilities entering the glass container manufacturing facilities.

Upstream of Use by Consumers

To determine raw material quantities, it was assumed that 1.17 tons of raw materials are required to make 1 ton of new glass containers, while 0.17 tons are released as carbon dioxide during the chemical reaction of the raw materials (Davis 1992; Gaines and Mintz 1994; see table S1 in the supporting information on the Web). The quantities of glass containers produced and used in New Jersey were determined based on information from the in-state glass container manufacturers. As of 2008, only two food and beverage glass container manufacturers were located in New Jersey, both producing flint glass containers only. For imported glass containers, it was estimated that 90% were imported from other states and about 10% from foreign countries (Goldammer 2008; U.S. DOE 2002b).

Energy Analysis

Primary Energy Sources and General Assumptions about Transportation

The energy consumption for each process was determined. The energy required to produce the primary fuels is included in calculating all primary fuel consumption that was used for producing electricity or for direct power generation. The energy consumption for each process was determined based on data collected from the mining industry, the glass container manufacturing industry, MRFs, and cullet processing facilities,

Table 1 Scenarios and key assumptions

Scenarios		*Fuel savings during curbside collection compared to current practice*	*Cullet exiting material recovery facilities*			*Increase in specific energy consumption at intermediate cullet processing facilities*
			To landfills or construction industry as aggregate	*Processed at intermediate cullet processing facilities*	*To other end markets*[a]	
1	Current practice	0%	76%	22%	2%	0%
2	Current practice with increased use of recycled glass containers as feedstock in container or fiberglass production	0%	28%	70%	2%	0%
3	Single-stream curbside collection replacing dual-stream curbside collection	17%[b]	76%	22%	2%	33%[c]
4	Current practice with dominant use of recycled glass containers as aggregate substitute	0%	98%	0%	2%	0%
5	No curbside glass recycling	0%	0%	0%	3%[d]	0%

Notes: All flows of glass containers before being discarded by consumers were the same in all scenarios. Total percentage of cullet exiting material recovery facilities equals 100% for scenarios 1, 2, 3, and 4.
[a]Including cullet exported out of state and cullet transported directly to glass container manufacturers for use as feedstock.
[b]Based on interviews with both recycling coordinators and private waste haulers in New Jersey (range 10% to 25%).
[c]To handle the higher contaminant levels in the cullet in scenario 3, it is assumed that the specific energy consumption for processing cullet at the intermediate cullet processing facilities increases by one-third compared to the energy consumption in scenario 1, based on information from one intermediate cullet processing facility.
[d]Glass collected from drop-off centers only. The slightly higher percentage was due to the assumed higher quality of glass containers collected from drop-off centers where additional processing at intermediate cullet processing facilities was not needed.

as well as from the literature if actual data were not available. Primary fuel sources for the electricity consumed in New Jersey are based on the New Jersey electricity grid: coal, 25%; nuclear, 47%; natural gas, 26%; and others, 2% (EIA 2008). This distribution of fuel sources assumes that 27% of New Jersey's electrical energy is produced in Pennsylvania and 73% in New Jersey. For electricity consumption in other states of the United States, the average U.S. electricity grid was used: coal, 49%; nuclear, 19%; natural gas, 22%; hydro and others, 10% (Franklin Associates 2004). The mining industry consumed coal, natural gas, and electricity, while the glass container industry used mainly natural gas for manufacturing (Gaines and Mintz 1994). All transportation fuel was assumed to be in the form of diesel (Gaines and Mintz 1994).

Truck types, average masses per load, and road and train transportation distances are listed in table S2 in the supporting information on the Web. An empty back-haul was assumed for all transportation processes, which is a conservative assumption.

Downstream of Use by Consumers

The integrated solid waste management decision supporting tool (ISWM-DST) (Harrison et al. 2001; Solano et al. 2002a, 2002b) was used to calculate fuel consumption during collection of recycled and to-be-disposed-of glass containers. Input parameters into the ISWM-DST are disposed of and recycled glass container quantities in urban, semiurban, and rural counties separated between single family, multifamily, and commercial locations (see table S3 in the supporting information on the Web). If the collection system of disposed of glass containers included a transfer station, the fuel consumption during transport was calculated based

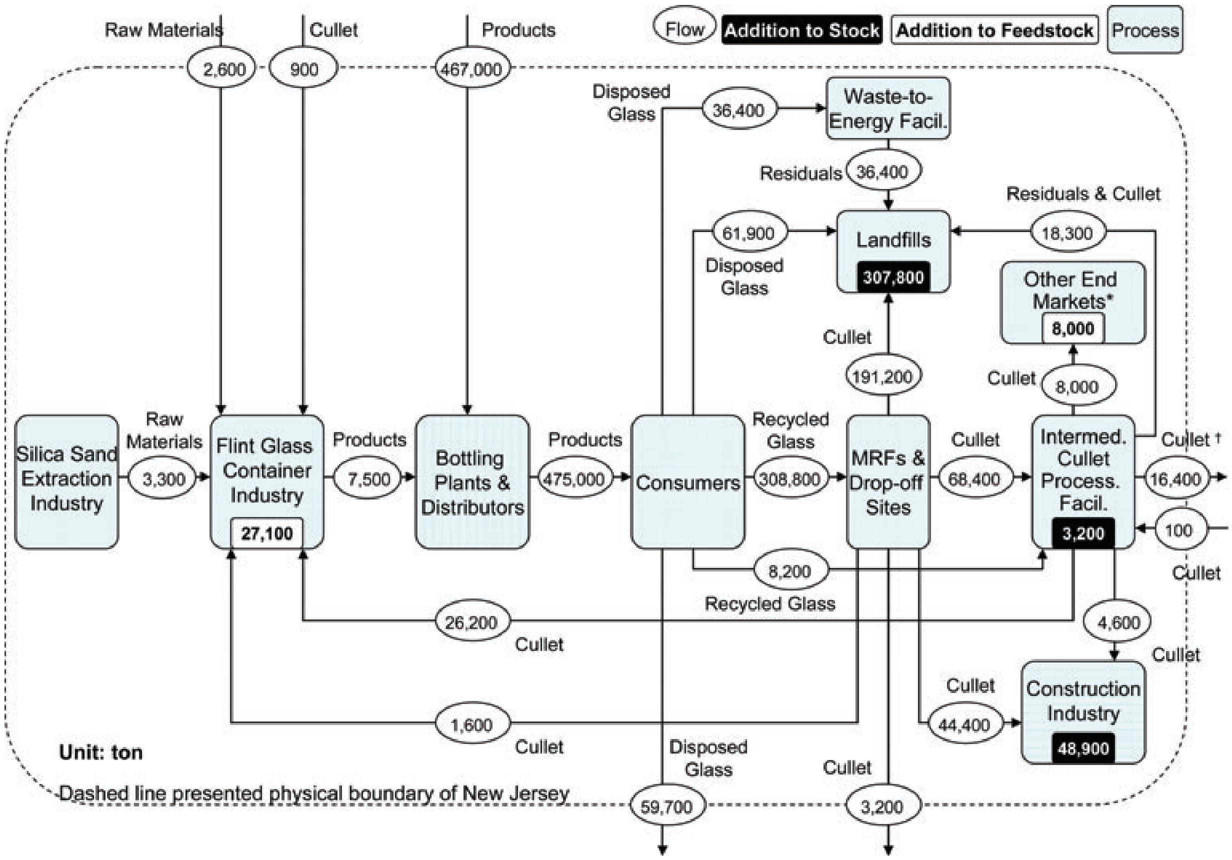

Figure 1 Material flow analysis of glass packaging containers used and discarded in New Jersey in 2008.
Note: Material flows and processes that occurred outside the New Jersey border were not specified in the figure for simplicity. The glass container industry in New Jersey sells only about 5% (7,500 tons) of the total production (300,000 tons) within the state. *Other end markets include the fiberglass and sandblasting industries. †Cullet was sent to out-of-state container (86%) and fiberglass (14%) industries. MRFs = material recovery facilities; Intermed. Cullet Process. Facil. = intermediate cullet processing facilities.

on quantities and transport distances obtained from the NJDEP (see table S2 in the supporting information on the Web).

A loss of energy to heat the glass containers was assumed if glass containers were disposed of in waste-to-energy facilities (i.e., the specific heat capacity of glass is 0.84 kilojoules per kilogram-Kelvin [kJ/kg-K] equaling 0.2 British thermal units per pound-degree Fahrenheit [Btu/lb-°F]) and 65% conversion efficiency for converting generated heat to steam [Brunner 1984; Tipler 1999]). The average transport distance of the ash from all five waste-to-energy facilities was estimated to be 9.5 miles (NJDEP 2008).

An average transport distance from MRFs to different end uses was determined based on the previously mentioned survey. The average distance for transporting processed cullet from intermediate cullet processing facilities to various end uses was based on data obtained from the intermediate cullet processing facilities.

To estimate energy consumption at MRFs and intermediate cullet processing facilities—including equipment operation, rolling stock such as front-end loaders, and heating and lighting (Nishtala 1997)—data were obtained from selected MRFs and cullet processing facilities in New Jersey (see table S4 in the supporting information on the Web). When no data were available, a national average was used (Nishtala and Solano-Mora 1999).

An energy credit was given if the cullet was used in container manufacturing (5,230 kBtu/ton for in-state manufacturers; 4,612 kBtu/ton for out-of-state manufacturers) (Beerkens et al. 2004; U.S. DOE 2002b; Worrell et al. 2008), fiberglass production (7,841 kBtu/ton) (Ecoinvent 2009; NAIMA 1996; Papke 1993), or as construction aggregate (340 kBtu/ton) (U.S. DOE 2002a; Morris 1996). The energy credit was determined based on energy savings from substituting virgin raw materials and accounting for extraction and production processes and all transportation involved. Cullet that was allocated for in-state manufacturing of glass containers, which were then sold, used, and discarded in the state, was not accounted for in the energy credit for container manufacturing. This is because the reduced energy consumption associated with the cullet was already taken into account when determining the energy consumption in the in-state glass manufacturing process. No energy credit was assumed for the sandblasting industry, because savings are believed to be negligible.

Upstream of Use by Consumers

The fuel type and consumption for raw material extraction and manufacturing of glass containers by in-state glass container manufacturers and by an average out-of-state U.S. glass container manufacturer were determined based on various sources, including U.S. Department of Energy (DOE) reports (Gaines and Mintz 1994; U.S. DOE 2002a, 2005), National Renewable Energy Laboratory data (NREL 2009), and industry information (table S4 in the supporting information on the Web). Transportation distances of raw materials to glass container manufacturers were based on data from the in-state glass manufacturing industry for New Jersey and on U.S. national averages (see table S1 in the supporting information on the Web).

The energy source consumed by U.S. glass container manufacturers was assumed to be 77% natural gas and the rest electricity from the local electricity grid (U.S. DOE 2002b, 2006). On average, the cullet content in new glass containers in New Jersey is 33%, according to the in-state glass container industry, and 30% in the United States (Worrell et al. 2008). The energy savings when using cullet as feedstock were calculated based on the assumption of 3.0% energy reduction if the cullet share increased by 10% by mass (Beerkens et al. 2004; Dolley 2006; Gaines and Mintz 1994; Worrell et al. 2008). BUWAL 250 (1996) data were used for the energy consumption for imported foreign glass container products, including energy consumption for raw material extraction and glass container production. Energy savings for manufacturing fiberglass are similar to those of glass container manufacturing, with energy savings of 3.3% for every 10% of recycled cullet (Papke 1993). A typical cullet content of 30% (NAIMA 1996) was assumed for fiberglass production.

Fuel consumption for transportation from manufacturing facilities to wholesale and retail locations was based on the WAste Reduction Model (WARM) (U.S. EPA 2004), at 1.016 MBtu/ton. Energy consumption for transportation of imported glass containers from abroad was estimated based on rail transport for glass containers from Central or South America and ocean freight for glass containers from Europe.

Sensitivity and Uncertainty Analysis

A sensitivity analysis was performed for all point estimates used in the model and an uncertainty analysis for the five most uncertain point estimates. In the sensitivity analysis, a sensitivity ratio (SR) was determined, which calculates, for each input variable (e.g., distance or quantity), the ratio of percentage change in the system energy requirement to the percentage change in the input (U.S. EPA 2001). To calculate the ratio, each input variable in isolation was doubled and the system energy requirement recalculated. The higher the SR, the more the input variable affects the system energy requirement (see table S5 in the supporting information on the Web).

Table 2 Selected uncertainty parameters and their ranges

Uncertainty parameters	*Units*	*Range*
Percentage of foreign imported glass containers	%	8–12
Cullet content in glass containers in the U.S.	%	28–32[a]
Energy reduction in (domestic) glass manufacturing process by using cullet to replace virgin raw materials	%	27–33[b]
European Union cradle-to-gate energy consumption for glass containers	Btu/ton	9.6×10^6–1.3×10^7[c]
Domestic wholesale and retail distribution distance	Miles	632–1,174

Notes: [a]Worrell et al. (2008).
[b]Beerkens et al. (2004); Dolley (2006); Worrell et al. (2008).
[c]95%–130% of the baseline value.
[d]70%–130% of the baseline value.
1 Btu (British thermal unit) = 1055.06 joules.
1 short ton = 0.9072 metric tons.
1 mile = 1.6093 kilometer.

The uncertainty analysis was determined for the five most uncertain parameters, which were selected based on both data quality and the sensitivity analysis (table 2). The selected uncertain parameters were assumed to be independent of each other and of the triangular distribution, with ranges based on experience and expert judgment. The uncertainty of the system energy requirement among scenarios was propagated by using Monte Carlo simulation. The system energy requirements calculated in the Monte Carlo simulation are presented as cumulative distribution functions (CDFs).

Results

Material Flow Analysis of Glass Containers Used and Discarded in New Jersey

Current System (Scenario 1)

Only about 1.5% (7,500 tons) of the glass packaging containers discarded by consumers in New Jersey in 2008 (475,000 tons) were manufactured in the state (figure 1). The majority of the glass containers were produced in other states (88.5%) or in foreign countries (10%). Most of the glass containers produced in New Jersey were exported out of the boundary (New Jersey) and are therefore not included in the model.

Of the glass containers used and discarded by consumers in New Jersey, 67% (317,000 tons) were recycled. This amount includes glass containers collected from bars and restaurants (8,200 tons) and from residents, institutions, and businesses (308,800 tons) (figure 1). Glass containers from bars and restaurants were directly sent to intermediate cullet processing facilities. Most of the recycled glass containers sent to MRFs were collected commingled in curbside dual-stream recycling programs (278,700 tons) and in curbside single-stream recycling programs (30,400 tons), while a small fraction was collected at drop-off centers (7,900 tons).

Glass containers discarded by consumers as MSW were disposed of directly or as waste-to-energy facility residuals (ash) in landfills located both in state (61,900 tons + 36,400 tons) and out of state (59,700 tons).

End uses of the recycled glass containers after processing in MRFs and intermediate cullet processing facilities are discussed below.

End Uses of Recycled Container Glass Based on Survey and Interviews

Nineteen of the 32 MRFs returned the survey about the end uses of their processed glass cullet. Glass containers from drop-off sites are delivered to MRFs and therefore are included in the survey. Excluding the glass containers separated in bars and restaurants and delivered directly to intermediate processing facilities, the reported quantity (266,900 tons) covered more than 86% of the recycled glass containers. Assuming that the distribution of end uses was similar for the remaining cullet, only 23% of the recycled container glass exiting MRFs (308,800 tons) was sent to intermediate cullet processing facilities (68,400 tons) and container glass manufacturers (1,600 tons). The use of cullet as aggregate accounted for 14% (44,400 tons) in the construction industry and 62% (191,200 tons) in landfills. End use in landfills included use as daily landfill cover, drainage layers, or temporary road construction material. About 1% was exported (3,200 tons) to a private recycler in Pennsylvania with an unknown end use (table 3).

Table 3 Fate of recycled glass containers exiting material recovery facilities (survey results)

	Reported mass (tons)	*Mass used in material recovery facilities (tons)*[a]	*Comments*
Intermediate cullet processing facility	50,400	68,400	Glass cullet processing for use as container or fiberglass feedstock
Glass container manufacturer	1,400	1,600	Food/beverage glass container manufacturing
Quarry or aggregate processing facilities	40,000	44,400	Road construction
Landfills	172,200	191,200	Landfill cover, drainage layer, temporary road construction
Export	2,900	3,200	Glass container manufacturing in Pennsylvania
Total	266,900	308,800	

Notes: [a]86% of cullet was reported. The same end-use distribution was assumed for the not reported cullet.
1 short ton = 0.9072 metric tons.

Despite the intention to produce an end product for higher beneficial uses of cullet in intermediate cullet processing facilities, only 60% of the cullet processed at intermediate cullet processing facilities was actually used for higher beneficial uses. About one-third (35%) of the cullet processed at intermediate cullet processing facilities was sent to landfills (18,300 tons), the construction industry (4,600 tons), and the sandblasting industry (1,100 tons; part of other end markets).

Overall, as much as 82% (258,500 tons) of the recycled glass containers in New Jersey in 2008 were used as aggregate in landfills (191,200 tons + 18,300 tons) and the construction industry (4,600 tons + 44,400 tons). Only 16% (51,100 tons = 1,600 tons + 26,200 tons + 16,400 tons + 8,000 tons∗0.86) were used as feedstock in glass container or fiberglass production, with the remaining 2% for other uses (see figure 1).

Other Scenarios (Scenarios 2 through 5)

All flows of glass containers before being discarded by consumers were the same in all scenarios. In table 4 the full breakdown of flows can be found. For scenario 2, the approximate threefold increase of cullet leaving MRFs and sent to intermediate cullet processing facilities (216,200 tons) resulted in a diversion of most of the cullet from use as aggregate in the construction industry and landfills (98,800 tons) to use as container and fiberglass feedstock (87,400 tons) when compared to scenario 1. For scenario 3, the decreased recovery efficiency assumed at intermediate cullet processing facilities resulted in an increase in cullet use as aggregate in landfills and the construction industry by 13,400 tons and reduction in the use of cullet as container and fiberglass feedstock by 13,000 tons when compared to scenario 1.

Scenario 4, which simulated an increased end use of cullet as aggregate, resulted in an 18% increase (45,500 tons) in aggregate use in the construction industry and landfills when compared to scenario 1. Scenario 5, which eliminated curbside recycling, resulted in an almost threefold increase (298,000 tons) in glass container disposal via MSW when compared to all other scenarios.

Energy Analysis

Specific Energy Consumption for Current System (Scenario 1)

The specific energy consumption (i.e., energy consumption per ton of glass containers used and discarded by consumers in New Jersey) for the overall system was 17,300 kBtu/ton (figure 2). This result is comparable to findings by Gaines and Mintz (1994), who reported a specific energy consumption of 15,900 kBtu to supply 1 ton of glass containers consumed in

Table 4 Discarded glass container flows in five scenarios (tons)

	Scenarios (see Table 1)				
Flows	*1*	*2*	*3*	*4*	*5*
Recycled glass containers entering and exiting MRFs					
Collected glass containers entering MRFs	308,800	308,800	308,800	308,800	7,800*
Cullet exported from MRFs to other states	*3,200*	*3,200*	*3,200*	*3,200*	*0*
Cullet transported from MRFs to intermediate cullet processing facilities	*68,400*	*216,200*[†]	*68,400*	*0*	*0*
Cullet transported from MRFs to construction industry	*44,400*	*44,400*	*44,400*	*44,400*	*0*
Cullet transported from MRFs to flint glass container industry	*1,600*	*1,600*	*1,600*	*1,600*	*7,800**
Cullet transported from MRFs to landfills (for aggregate use)	*191,200*	*43,400*	*191,200*	*259,600*	*0*
Flows entering and exiting intermediate cullet processing facilities					
Collected glass containers transported directly to intermediate cullet processing facilities (from bars and restaurants)	8,200	8,200	8,200	8,200	8,200
Cullet transported to flint glass container industry	26,100[a]	64,100[a]	20,400[a′]	8,200	8,200
Cullet transported to other end markets§	8,000[b]	24,800[b]	5,500[b′]	0	0
Cullet exported to other states[#]	16,400[c]	51,400[c]	11,200[c′]	0	0
Cullet transported to construction industry	4,600[d]	14,500[d]	3,200[d′]	0	0
Cullet transported to landfills	18,300[e]	57,400[e]	33,100[e′]	0	0
Unprocessed cullet (stock) stored in intermediate cullet processing facilities	3,200[f]	10,100[f]	3,200[f]	0	0
Glass containers disposed of as municipal solid waste	158,000	158,000	158,000	158,000	456,000
Changes in cullet end-use compared to scenario 1[△]					
Changes in aggregate use	—	−98,800	+13,400	+45,500	−258,500
Changes in container and fiberglass use	—	+87,400	−13,000	−41,200	−35,000

Notes: Sum of the values in italics equals the mass of recycled glass containers entering material recovery facilities (MRFs).
*Assuming recycled glass containers collection through drop-off sites remained and was sent to glass container industry after processing at MRFs.
[†]70% of 308,800 tons.
§86% of the cullet sent to other end markets was used in in-state fiberglass industry.
[#]86% and 14% of the exported cullet was used as feedstock in the container and fiberglass industries.
[△]Negative signs refer to a decrease.
[a]26.1% of the input flow from MRFs to intermediate cullet processing facilities, plus 8,200 tons from bars and restaurants to intermediate cullet processing facilities.
[b]11.6%, [c]24.0%, [d]6.8%, [e]26.8%, and [f]4.7%, respectively, of the input flow from MRFs to intermediate cullet processing facilities. The percentages were calculated based on inventory reports from intermediate cullet processing facilities.
[a′,b′,c′,d′] One-third decrease from[a,b,c,d] in scenario 1 based on professional judgment; [e′]Input flow from MRFs to intermediate cullet processing facilities minus all other end uses and unprocessed cullet.
1 short ton = 0.9072 metric tons.

the United States without including energy consumption for wholesale and retail distribution.

Because a large portion (98.5%) of glass containers that are discarded by consumers in New Jersey are manufactured in other states or foreign countries, the highest specific energy consumption (14,866 kBtu/ton) was consumed outside the boundary of New Jersey and is embodied in the containers. This specific energy consumption, which includes the energy consumption for glass container manufacturing and raw material processing and transportation, accounted for 86% of the overall specific energy consumption. To break down the highest specific energy consumption, glass container manufacturing in other states accounted for 12,118 kBtu/ton, while the associated virgin raw material extraction (1,086 kBtu/ton), transportation (276 kBtu/ton), and cullet collection, transportation, and processing (376 kBtu/ton) together accounted for 1,738 kBtu/ton (table S4 in the supporting information on the Web). Less than 7% of the highest specific energy consumption was from specific energy consumption embodied in foreign imported products (1,011 kBtu/ton).

Specific energy consumption for glass product distribution (i.e., product transportation from the manufacturing plants to the consumers) accounted for 1,016 kBtu/ton. This includes glass containers produced both in state (1.5% of the total discarded containers) and out of state. After glass containers were used and discarded by consumers, the highest specific energy consumption was associated with the recycled glass container collection and totaled 790 kBtu/ton (770 kBtu/ton to MRFs and drop-off sites; 20 kBtu/ton to intermediate cullet processing facilities). Specific energy consumption for the remaining downstream flows after the recycling collection was relatively small compared to that of the recycled glass container collection and upstream flows. Overall, the specific energy consumption associated with collection, transportation, and processing of recycled glass containers represented approximately 6% (1,033 kBtu/ton)—and via MSW represented only approximately 1%

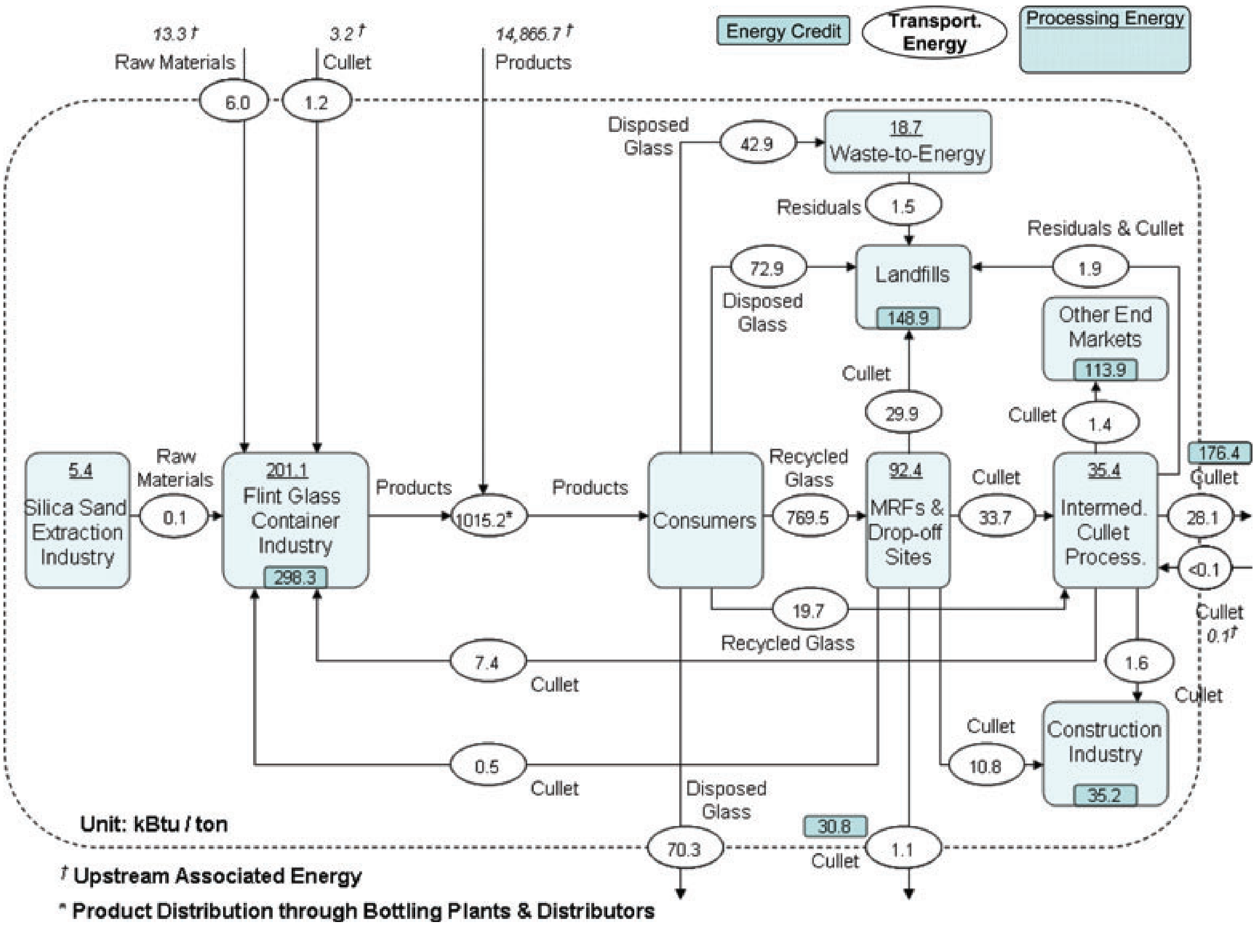

Figure 2 Specific energy consumption of glass containers used and discarded in New Jersey in 2008. kBtu = kilo-British thermal units.

(206 kBtu/ton)—of the overall specific energy consumption (see figure 2 and table S4 in the supporting information on the Web).

Specific energy credits for in-state and out-of-state cullet use as container and fiberglass feedstock (298.3 kBtu/ton + 113.9 kBtu/ton + 176.4 kBtu/ton + 30.8 kBtu/ton) and as aggregate substitute (148.9 kBtu/ton + 35.2 kBtu/ton) totaled 773 kBtu/ton. This offset the overall specific energy consumption by approximately 5%.

System Energy Requirement for Other Scenarios

The system energy requirement for glass packaging containers discarded in New Jersey in 2008 (475,000 tons) was 7.81 TBtu/year in scenario 1. This accounted for a total energy consumption of 8.18 TBtu/year, and a total energy credit of 0.38 TBtu/year (figure 3).

Scenario 2 (increased use as container feedstock) resulted in the lowest system energy requirement (7.46 TBtu/year), while scenario 4 (with aggregate as the sole end use) resulted in the highest system energy requirement (7.97 TBtu/year). Although the most energy was consumed in scenario 2, this scenario also had the highest energy credits, which offset its energy consumption by 10%. This indicates the importance of increased uses as container feedstock in achieving a lower system energy requirement.

The system energy requirements among scenarios 1, 3, and 5 appeared similar, ranging from 7.81 to 7.83 TBtu/year. With no curbside collection, scenario 5 avoided energy consumption associated with recycled glass collection, transportation, and processing, but provided lower energy credits. Therefore elimination of curbside collection did not result in a lower system energy requirement when compared with scenarios 1 and 3.

Sensitivity Analysis and Data Uncertainty

The sensitivity analysis showed that the five most sensitive parameters were the same for all scenarios (table 2). Three of the parameters were related to the manufacturing process, while one was related to the wholesale and retail distribution distance and one was related to the percentage of imported products. The dominant manufacturing-related parameters were due to the large energy consumption of the glass container manufacturing process when compared to other processes. The most sensitive parameter was cradle-to-gate energy for glass container production in foreign countries, mostly in the European Union (see table S5 in the supporting information on the Web). A 100%

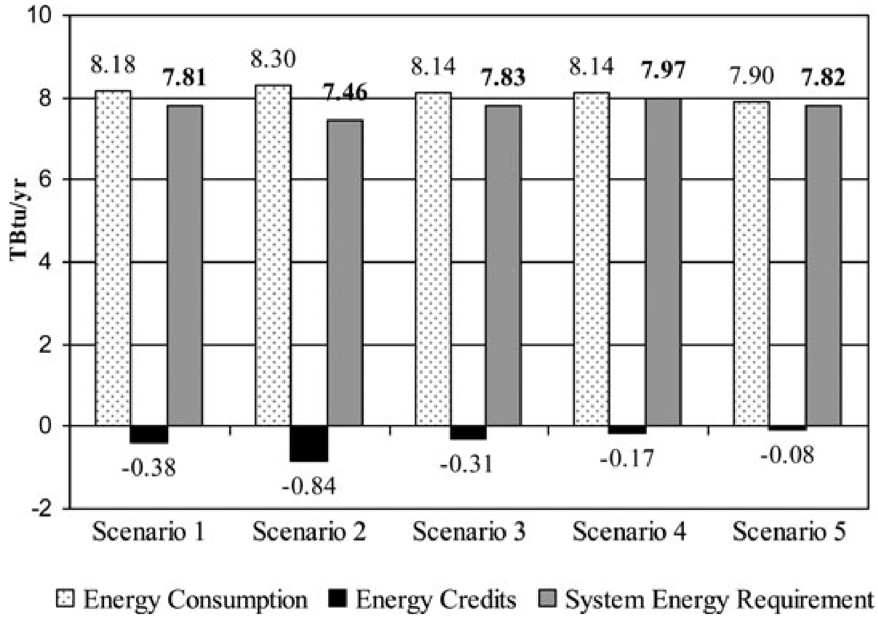

Figure 3 System energy requirements for various scenarios. Scenario 1: current system; scenario 2: increased use as container feedstock; scenario 3: single-stream recycling; scenario 4: aggregate as sole end use; scenario 5: elimination of curbside collection. TBtu/yr = tera-British thermal units per year.

increase in this parameter resulted in a change of system energy requirement of 6%. Although such a change in this parameter is unlikely considering that the technology used for glass container manufacturing is similar in the United States and the European Union, further investigation is required to determine if the parameter is important to the accuracy of the model.

Based on the uncertainty analysis, there was an 80% probability for scenario 2 (increased use in container production) to have a lower system energy requirement when compared with all other scenarios (figure 4). This indicated that increased beneficial uses can achieve a lower system energy requirement. The CDFs in scenarios 1, 3, 4, and 5 are very close together and mostly overlapping. Therefore the probabilities are low for all these scenarios to have different system energy requirements under conditions of uncertainty. There is a probability of 18% for scenario 1 (current practice) to have a lower system energy requirement than scenario 4 (dominant aggregate use).

Discussion

End Use of Cullet as Aggregate versus as Feedstock in Glass Container Manufacturing

The lower system energy requirement in scenario 2 compared to scenario 4 indicated the benefit of increased cullet use (approximately 44% of the recycled glass containers) as container or fiberglass feedstock compared to cullet use as construction aggregate. This confirmed the UK and Canadian case studies (Butler and Hooper 2005; Morris 1996). The lower system energy requirement in scenario 2 is mainly a result of the higher energy credit. The energy credit of 1 ton of cullet used as feedstock for container production (5,230 Btu/ton for in state; 4,612 Btu/ton for other states) is about 15 times higher than the energy credit of 1 ton of cullet used as aggregate (340 kBtu/ton for in state).

Not all discarded and used glass packaging containers in New Jersey can be used as glass container feedstock. As experienced in the United Kingdom (Butler and Hooper 2005), the United States suffers from the color imbalance of recycled glass containers, mainly resulting from the import surplus of green glass containers from foreign countries and the lack of a U.S. green glass container manufacturing industry (Roy 1997). However, based on the estimated color ratio of amber:green:flint cullet of 25:25:50 (CWC 1996), more than the current 8.8% of the recycled glass containers (see figure 1) could be used as feedstock for in-state flint glass container production. The obstacle for the increased use of cullet in glass container production is the quality of the cullet. This is confirmed by in-state flint glass container manufacturers, who reported imports of high-quality cullet from states with bottle bills (e.g., Connecticut and New York) (CRI 2009).

To assess transportation of the cullet used as feedstock in the amber and green glass container industries, which are currently not present in New Jersey, a break-even long-haul distance was determined. To calculate this long-haul distance, the energy credit (4,612 kBtu/ton) gained from the cullet use as container feedstock has subtracted from it the energy consumption involved in additional transportation to and processing at the intermediate cullet processing facilities, which is otherwise avoided if cullet is used as aggregate. The energy credit (340 kBtu/ton) gained from cullet use as aggregate also has subtracted from it the transportation fuel consumption from MRFs

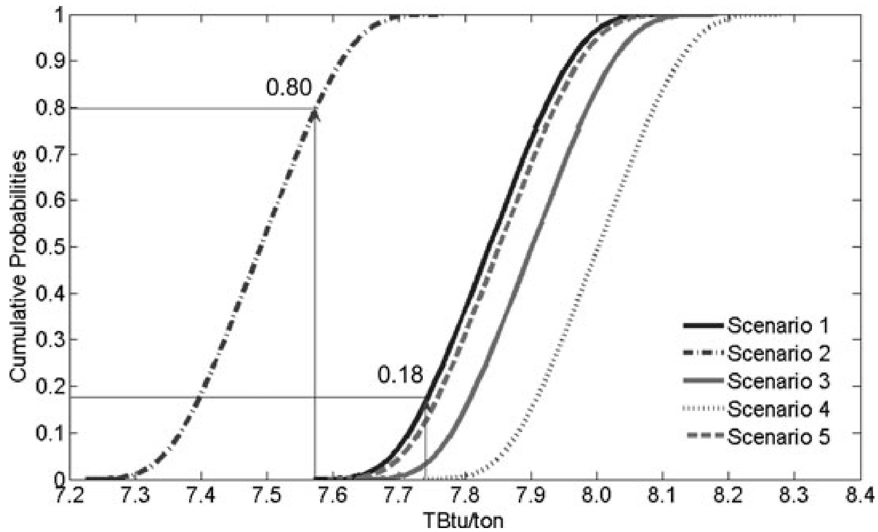

Figure 4 Cumulative distribution functions (CDFs) for system energy requirements under conditions of uncertainty. Scenario 1: current system; scenario 2: increased use as container feedstock; scenario 3: single-stream recycling; scenario 4: aggregate as sole end use; scenario 5: elimination of curbside collection. TBtu = tera-British thermal units.

to the construction industry or landfills. The energy difference between the two adjusted energy credits for the container feedstock and the aggregate substitute is then used to determine the long-haul transportation fuel consumption for the cullet. Given the estimated fuel economy of 6 miles/gallon, the assumed truckload capacity of 22 tons, and an empty back-haul, the break-even distance can be calculated using the following equation:[3]

$$\begin{aligned}[t] &[(\mathrm{EC_{cont}} - \mathrm{T}_i - \mathrm{P}) - (\mathrm{EC_{aggr}} - \mathrm{T}_c)]/[(\mathrm{F_{diesel}}/(\mathrm{E_f} * \mathrm{tpd})]/2 \\ &= [(4,612,000 - 232,276 - 240,157) \\ &\quad -(340,000 - 82,567)]/(158,000/6/22)/2 \\ &= 1,622 \text{ (miles, one-way)}, \end{aligned} \tag{1}$$

where EC_{cont} = energy credit of cullet as container feedstock, Btu/ton; EC_{aggr} = energy credit of cullet as aggregate substitute, Btu/ton; T_{i} = fuel consumption for transportation of 1 ton of cullet from MRFs to in-state intermediate cullet processing facilities (value based on the survey results from the MRFs), Btu/ton; T_{c} = fuel consumption for transportation of 1 ton of cullet from MRFs to in-state construction industry or landfills (value based on the survey results from the MRFs), Btu/ton; P = energy consumption for processing 1 ton of cullet at intermediate cullet processing facilities (value based on the report provided by facilities), Btu/ton; F_{diesel} = primary fuel consumption per gallon of diesel consumed (= 158,000 Btu/gal) (Franklin Associates, 2004); E_{f} = fuel economy (= 6 miles/gallon); and tpd = truck capacity per load (= 22 tons).

The calculated long-haul distance would allow amber, green, and additional flint cullet collected in New Jersey to be used by glass container or fiberglass manufacturers from the East Coast to the Midwest and Canada, where more than three-dozen glass container manufacturing facilities are located (GPI 2010). The break-even distance can be even higher if a partially loaded back-haul is assumed instead of the calculated worst-case scenario of an empty back-haul. In terms of energy consumption, this result confirmed suggestions by Butler and Hooper (2005) that long-haul of recycled glass cullet used as container feedstock is more beneficial compared to local use as aggregate. While energy consumption is usually used as a major environmental indicator, other environmental, economic, and possibly social factors need to be taken into account when assessing this finding.

This case study was conducted in New Jersey, however, the findings may be applicable to other states, considering that the most sensitive parameters in the model (see table 2) are not New Jersey–specific factors.

Single-Stream Recycling

Increased glass breakage rates and elevated contaminant levels are widely reported with the switch from dual-stream to single-stream curbside collection (CRI 2009; Eureka Recycling 2002; Jamelske and Kipperberg 2006; Morawski 2009; Smith-Teutsch 2010). It is also suspected that the elevated breakage rate adds to the increased contaminant levels (CRI 2009; Tim Goodman & Associates 2006). If cullet is intended for higher beneficial uses in container or fiberglass production, preventing recycled glass containers from breaking during collection is therefore important to obtain more cullet that meets the stringent specifications set by industry (CWC 1996, 1997). Various suggestions have been discussed to reduce the breakage rate during single-stream collection, such as implementation of padding in the collection vehicles (Barker Lemar 2010). However, no study was found to indicate whether the suggestions are effective in reducing the breakage rate.

Further processing of the recyclables might also result in higher-quality cullet, although the capital and operating costs are likely to increase. However, given the higher energy credits that can be achieved with increased higher-benefit uses, it may be important to determine if improvements in separation/sorting technology in recycling facilities can produce a comparable amount of quality cullet from single-stream collected glass containers compared to dual-stream collected glass containers. The increased energy consumption of the improved technology is not expected to outweigh the benefits based on the sensitivity analysis in this study (see table S5 in the supporting information on the Web).

Conclusions

The MFA in this study discloses the interrelationships between complicated flows and processes in the glass recycling system on the state level and beyond. Compared to life cycle assessment (LCA), which in most cases relies on a database of national averages, MFA on a state level increased the transparency of the system studied. In 2008 approximately only 11% of the glass containers consumed in New Jersey were used in glass container or fiberglass production.

The energy analysis built upon the MFA confirmed that the energy-intensive processes in container glass manufacturing account for the major energy consumption over the whole life cycle of the glass container recycling system. To achieve a lower system energy requirement, results from this study confirm UK and Canadian case studies that the use of cullet as container feedstock outweighs the benefit of the use of cullet as construction aggregate, even over longer transportation distances.

To increase the use of cullet as container feedstock, further assessment is needed to determine if single-stream recycling could achieve comparable glass cullet quality when compared to dual-stream recycling, assuming further processing at cullet processing facilities is implemented. Technologies are most likely available, but they will probably add to the overall operating costs. Alternatively, practices such as additional collection from bars and restaurants could be explored.

Currently the recycling regulations in New Jersey require the state to increase the recycling rate, assuming the mass of recyclables is the sole indicator for environmental impacts. However, due to the large difference in energy savings for different end uses of recycled glass containers, it may be beneficial to base future policies and regulations on MFA and LCA.

Finally, given the continuous efforts toward saving energy in manufacturing processes in the container glass industry, periodic updates for data related to manufacturing-related processes are recommended for future simulations.

Acknowledgments

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Notes

1. The data in this study are reported in U.S. customary units to make it easier for the reader to review the original references. Conversion factors to metric units are provided. 1 short ton = 0.9072 metric ton.
2. 1 British thermal unit (Btu) = 1055.06 joules. Throughout the rest of the paper, kBtu refers to kilo-Btu, MBtu to million Btu, and TBtu to tera-Btu.
3. 1 mile = 1.6093 km, 1 gal = 3.78 L.

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About the Authors

Ching-Ling Tsai, at the time of writing, was a Ph.D. candidate at the Department of Environmental Sciences, Rutgers University, New Brunswick, New Jersey, USA. **Uta Krogmann** is an associate professor at the Department of Environmental Sciences at Rutgers University.

Supporting Information

Additional supporting information may be found in the online version of this article.

Supporting Information S1: This supporting information provides a table listing correlation coefficients for selected mass and energy flows, and a figure showing an example comparison of simulation results with linear mass and energy flow functions.

Please note: Wiley-Blackwell is not responsible for the content or functionality of any supporting information supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.