ANL/ESD-18
NREL/TP-430-5703

Energy Implications of Glass-Container Recycling

A Joint Effort

Energy Systems Division
Argonne National Laboratory
Operated by the University of Chicago
for the U.S. Department of Energy
under Contract W-31-109-Eng-38
Authors: L. L. Gaines
M. M. Mintz

National Renewable
Energy Laboratory
Operated by Midwest Research Institute
for the U.S. Department of Energy
under Contract DE-AC02-83-CH10093
Technical Monitor: Philip B. Shepherd

Argonne National Laboratory and the National Renewable Energy Laboratory
are part of the national laboratory system to the **U.S. Department of Energy.**

ANL/ESD-18
NREL/TP-430-5703 • UC Category: 249 • DE94000288

Energy Implications of Glass-Container Recycling

L.L. Gaines & M.M. Mintz
Argonne National Laboratory
Argonne, Illinois

Technical Monitor: Philip B. Shepherd

A Joint Effort

Energy Systems Division
Argonne National Laboratory
Operated by the University of Chicago
for the U.S. Department of Energy
under Contract W-31-109-Eng-38

National Renewable
Energy Laboratory
Operated by Midwest Research Institute
for the U.S. Department of Energy
under Contract DE-AC02-83-CH10093

This report was prepared under Task #WM41.1010
and Subcontract #DA-1-11157-1

March, 1994

NOTICE

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A05

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

Printed on recycled paper

Contents

Contents (Cont.)

Figures

Tables

Tables (Cont.)

Acknowledgments

The authors would like to thank the many people who helped and supported us during the preparation of this report. We would like to thank Fran Mazenko of Owens-Brockway and Ronald Ozdarski of Maryland Environmental Service for the information and insight they provided; Calvin Tigcheleer of Resource Management, Richard Van Der Molen of Browning-Ferris Industries, Edward McMann of Advance Cullet, Craig Phillips of Clearing Recycling and Waste Service, and Eric Keeley and Keith Trychta of DuPage County Department of Environmental Concerns for data on shipment loads and travel distances of transportation equipment; and the reviewers from the Glass Packaging Institute for their helpful comments. We would also like to thank the people who managed and sponsored the work for their guidance: Frank Stodolsky at Argonne, Philip Shepherd and Bimleshwar Gupta at NREL, and Simon Friedrich at DOE. Finally, the authors gratefully acknowledge the efforts of Leslie Crosser for document processing and of our editor, Ellen Hathaway.

Energy Implications of Glass-Container Recycling

by

L.L. Gaines and M.M. Mintz

Abstract

This report addresses the question of whether glass-container recycling actually saves energy. Glass-container production in 1991 was 10^7 tons, with cullet making up about 30% of the input to manufacture. Two-thirds of the cullet is postconsumer waste; the remainder is in-house scrap (rejects). Most of the glass recycled is made into new containers. Total primary energy consumption includes direct process-energy use by the industry (adjusted to account for the efficiency of fuel production) plus fuel and raw-material transportation and production energies; the grand total for 1991 is estimated to be about 168×10^{12} Btu. Melting is by far the most energy-intensive step in the production of glass, because large quantities of material must be heated to high temperatures (2,400-2,900°F). Less energy is required to melt cullet than to melt and react the batch materials. The primary energy consumption totals are 17.0×10^6 Btu/ton of bottles with no postconsumer recycling, 14.8×10^6 Btu/ton with maximum recycling, and 15.9×10^6 Btu/ton for the current mix of recycling. The total primary energy use decreases as the percent of glass recycled rises, but the maximum energy saved is only about 13%. If distance to the landfill is kept fixed and that to the recovery facility multiplied by about eight, to 100 mi, a break-even point is reached, and recycling saves no energy. Previous work has shown that to save energy when using glass bottles, reuse is the clear choice. Recycling of glass does not save much energy or valuable raw material and does not reduce air or water pollution significantly. The most important impacts are the small reduction of waste sent to the landfill and increased production rates at glass plants.

Summary

Introduction

Recycling is popularly perceived as a benefit to the environment and a way to conserve materials and energy. This work was undertaken to address the simple question: Does recycling actually save energy? The answer depends on location, both because of the energy required to transport materials and because the fuels used for production and power generation differ by region. The answer also depends on the definition of energy. The total quantity of primary energy expended for supply of a product includes considerably more than the direct process energy consumed at the manufacturing plant. One form of energy may be more important to conserve than another; there are reasons to hold down consumption of fossil fuels, perhaps at the expense of increased use of other resources. The decision to recycle may involve trade-offs among resources, as in the case of recycling white paper, where oil and gas are used to save trees and landfills. Other factors, such as financial costs and process emissions, must be considered as well.

This report describes the situation for glass recycling and presents the key decision factors. It will be seen that recycling glass does not save much energy (compared to reuse) or valuable raw material and does not reduce air or water pollution significantly. The most important impacts are the small reduction of waste sent to the landfill and the increased production rates enabled at glass plants.

Current Statistics

The glass industry cites 1991 production at 10×10^6 tons, with cullet (crushed glass) making up about 30% of the input to glass-container manufacture. Purchases of cullet were 2.1×10^6 tons in 1991; the remainder of the cullet used in the production process was in-house scrap (rejects). Most of the glass recycled is made into new containers, with the rest being made into "glassphalt" (road-surface material made with cullet replacing the aggregate), fiberglass, and glass beads for reflective highway paint.

The container-glass industry purchased 125×10^{12} Btu in 1985: 78% was in the form of natural gas, 19% in the form of electricity, and the remaining 3% in the form of distillate oil. When the efficiency of electricity generation is taken into account, these figures imply primary energy consumption of 173×10^{12} Btu.* The actual energy consumption implied by these purchases must take into account the efficiency of fuel production; when this is done, the total consumption is approximately 190×10^{12} Btu. Accounting for transportation and raw-material production energies in the same way gives a grand-total primary energy consumption of 203×10^{12} Btu for 1985. The grand total for 1991 is estimated to be about 168×10^{12} Btu, with the reduction due to lower production and increased recycling.

Glass-Container Production Process

The basic steps for production of glass containers are the same whether virgin raw materials or cullet is used. Raw materials are brought to the plant, prepared, melted at high temperature, and formed into containers. The main differences between the manufacture of new and recycled containers are the supply and preparation pathways for the materials and the additional

---

* Babcock, E., et al., 1988, *The U.S. Glass Industry: An Energy Perspective*, Energetics, Inc., prepared for Pacific Northwest Laboratory, Sept.

energy required in the melting process for the endothermic chemical reactions of virgin raw materials to form glass.

Melting is by far the most energy-intensive step in the production of glass, because large quantities of material must be heated to high temperatures (2,400-2,900°F). It is also the one process step where cullet content influences energy consumption. Less energy is required to melt cullet than to melt and react the batch materials; lower energy use reduces combustion gas emissions at the plant. In addition, less dust is produced, and less CO_2 is generated from the batch chemical reactions. The temperature of the melt is lower, and operation at lower temperature increases furnace life and therefore decreases production costs. However, some batch materials are generally required along with cullet to adjust product composition (the amount needed depends on the quality of the postconsumer cullet received) and to aid in the removal of bubbles during the refining stage.

Discarded glass containers are picked up by truck, either separately or mixed with other wastes, and transported to a material recovery facility (MRF) or a landfill. From the MRF, the material goes back to the glass melter, often by way of a beneficiation facility. Emissions from transportation are significant and may negate the benefits to air quality from cullet use.

Energy Analysis

The major energy inputs for glass-container production from virgin raw materials are natural gas and electricity at the glass plant (gas for melting and annealing, electricity for forming) and coal and natural gas for raw-material mining and processing. The energy consumed in melting glass varies widely and depends on many factors. The total energy consumed in processing glass containers with no postconsumer recycling is approximately 9.4×10^6 Btu plus 484 kWh per ton of containers delivered (per net ton). Converting the electricity to primary energy consumption at 10,500 Btu/kWh yields a total primary usage of 14.5×10^6 Btu. (Note that most previous studies report energy use per ton of glass melted [per gross ton], a practice that neglects pack losses, which are the in-house production losses due to defective product.) Transportation and fuel production/conversion energies must be added to give total energy use.

For the case of maximum recycling of glass containers, even assuming 100% return of bottles, there is still a small requirement for batch materials necessitated by the loss of material in the MRF. The major energy inputs for this case are still natural gas and electricity at the glass plant, but gas use is reduced by about 1.2×10^6 Btu per net ton. Additional energy savings are realized by reducing the energy to produce raw materials; these savings are only partly offset by the electricity usage in material recovery and beneficiation. Energy use will also be affected by material losses at the MRF. Total process energy for the case of maximum recycling is about 6.6×10^6 Btu plus 551 kWh per ton of containers, or 12.4×10^6 Btu of primary energy. About 16% of the processing-fuel savings will be offset by additional transportation energy in the recycling loop.

The contribution of transportation to production energy is 0.39 × 10^6 Btu/ton of glass containers for maximum new materials, 0.73 × 10^6 Btu/ton for maximum recycling, and 0.49 × 10^6 Btu/ton for the mix of new and recycled materials currently used. All consumption is in the form of diesel fuel (much of it made from imported petroleum). Collection accounts for 15% of transportation energy use, assuming that cullet moves 200 mi from MRF to beneficiation plant and another 200 mi to a container plant.

To calculate the total energy expended to supply one ton of containers to the consumer, process and transportation energies must be added, and conversion efficiencies for electricity generation and fuel production (including fuel used to generate electricity) factored into the total. The final totals are 17.0 × 10^6 Btu per net ton for minimum recycling, 14.8 × 10^6 Btu per net ton for maximum recycling, and 15.9 × 10^6 Btu per net ton for the current mix. The total primary energy use decreases as the percent of glass recycled rises, but the maximum saving is only about 13%. However, if cullet quality declines as the quantity recycled increases, the 13% saving could be negated by a higher reject rate. Previous work has shown that to save energy when using glass bottles, reuse is the clear choice. Even taking into account the heavier weight of reusable bottles, the energy per use drops by a factor of ten or more.*

When considering the sensitivity of energy savings to transportation distance, the intuitive and correct result is that transportation of materials over long distances can negate any energy savings achieved by recycling. The only question is how far the material can be transported before a break-even point is reached. The energy intensity of the vehicles used in recycling is higher than that for garbage or packer trucks. Therefore, the run length to the landfill can be increased more than that to the MRF for the same energy change. If the distance to the landfill is kept fixed and that to the MRF multiplied by about eight, to 100 mi, a break-even point is reached, and recycling saves no energy.

Sensitivity of energy savings from recycling to losses as high as 30% (from the 10% baseline) was examined. Savings were found to be reduced from 2.2 × 10^6 to 1.6 × 10^6 Btu per net ton of containers, or about 1.3% reduction in savings per percent loss. This result points to the need to minimize material losses.

Conclusions

Recycling of glass containers saves some energy but not a significant quantity compared to reuse. The energy saved is about 13% of the energy required to make glass containers from virgin raw materials. This estimate includes energy required for the entire product life cycle, starting with raw materials in the ground and ending with either final waste disposition in a landfill or recycled material collection, processing, and return to the primary manufacturing process. The actual

---

* Gaines, L.L., 1981, *Energy and Material Use in the Production and Recycling of Consumer-Goods Packaging*, ANL/CNSV-TM-58, Argonne National Laboratory, Argonne, Ill., prepared for U.S. Department of Energy, Office of Industrial Programs, Feb.

savings depend on local factors, including population density; locations of landfills, recovery facilities, and glass plants; and process efficiencies at the specific facilities available. The savings increase if wastes must be transported long distances to a landfill or if the containers are made in an inefficient furnace. They decrease if there is no local MRF or glass plant, or if material losses in the recycling loop are high.

The options for disposition of used glass containers can be compared on the basis of the important decision factors, including energy saved, landfill space required, and emissions. Table S.1 gives a qualitative comparison for several options. In order of energy saved, the options for disposition of glass containers are reuse, recycling to the same product, recycling to a lower value product, and landfill. No real trade-off exists; the options with minimum energy use generally have the lowest other impacts as well. The energy savings are small, and the balance can be altered by local or regional conditions. In the East, where landfills are distant and MRFs and glass plants are close, energy is saved by recycling glass containers. In the West, however, landfills may be close, but MRFs or glass plants may be distant, because of the low population density. In that case, recycling of glass may not save energy. However, energy use will not be the only decision criterion. Local and national decision makers may choose to make trade-offs involving energy use, landfill and labor costs, and environmental impacts.

TABLE S.1 Comparison of Glass-Container Disposition Options

Alternative	Energy Impact	Environmental Impact	Material Sent to Landfill	Comments
Reuse	Saves most of production energy	Avoids production emissions; possible impacts from water treatment	None	Refillable bottles currently have a low market share in the United States
Recycle to containers	Small reduction in production energy	Small reduction in emissions[a]	Cullet processing losses	Bottles now made from 20% old bottles; color separation required
Recycle to fiberglass	Small reduction in production energy	Small reduction in emissions[a]	Cullet processing losses	Inefficient furnaces used
Recycle to reflective beads	Small reduction in production energy	Small reduction in emissions[a]	Cullet processing losses	Can use clean, mixed cullet
Recycle to glassphalt	Saves no energy	Full production emissions	Cullet processing losses	Can use clean, mixed cullet
Landfill	Saves no energy	Full production emissions	Maximum	Economic cost, no return

[a] Dust and SO_2 reduced, but NO_x increased.

1 Introduction

Recycling is popularly perceived as a benefit to the environment and a way to conserve limited materials, energy, and landfill space. This work was undertaken to address the simple question: Does recycling actually save energy? The answer is considerably less simple. Recycling may not always be the optimal use of resources. It depends on the material and the different recycling options available. For aluminum, recycling is clearly an energy saver,[1] but for glass, the answer is less obvious. The answer depends on location, both because of the energy required to transport materials and because the fuels used for production and power generation differ by region. It also might depend on such details as the production plant schedule, which determines whether a process uses electricity from base-load nuclear power plants or natural-gas-fueled peaking units.

The answer also depends on what is meant by energy. The total quantity of primary energy expended for supply of a product includes considerably more than the direct process energy consumed at the manufacturing plant. One form of energy may be more important to conserve than another; there are reasons to hold down consumption of fossil fuels, perhaps at the expense of increased use of other resources. The decision to recycle may involve trade-offs among resources, as in the case of recycling white paper, where oil and gas are used to save trees and landfills. Other factors, such as financial costs and process emissions, must be considered as well. This report investigates the energy implications of glass recycling and presents the key decision factors for recycling postconsumer glass containers.

Glass containers were chosen for study for several reasons. They are a large-volume product without the variety of compositions that complicate plastic recycling, and the technology for recycling is straightforward. The options are simple: containers that are not reused are either recycled or thrown away; they are not combustible, and therefore no energy can be recovered from them in waste-to-energy (WTE) plants. In fact, glass is generally removed from WTE feed because it forms a slag in the furnace.

In this analysis, we compare the energy balance for recycling glass with that for a system where consumer wastes are sent to landfills. The issues concerning recycling of glass are different from those for other wastes, because glass is not combustible and its recycling process is almost identical to its production process. It will be seen that recycling glass does not save much energy (compared to reuse) or valuable raw material and does not reduce air or water pollution significantly. The most important environmental impact is in reduction of waste sent to the landfill, and even this impact is small. Glass makes up a relatively small fraction of waste (6.5% by weight) and is inert. In addition, it is denser than most other products in municipal solid waste

---

[1] The benefits are often overstated because fabrication energy is neglected.

(MSW) and therefore only makes up 2.2% of MSW by volume, as can be seen in Table 1.1. Of this material, less than 75% is containers. There is an economic benefit to glass manufacturers from recycling because cullet use increases production rates and decreases costs.

This analysis is based on the premise that consumers are to be provided with one ton of glass containers. The glass can be produced from virgin raw materials or cullet (crushed glass). After use, the bottles can either be discarded and sent to a landfill (perhaps via a materials recovery facility [MRF] or WTE plant, where they are removed as waste), or they can be recycled into new bottles. The options of bottle reuse and recycling to other products are discussed briefly, but they are not included in the detailed analysis. The results of the analysis are the physical impacts on the rest of the world — the inputs and outputs of the system supplying containers to consumers. The primary input of interest is energy, with special attention paid to the form in which it is supplied; raw materials are also examined. Major concern has been expressed that transportation could represent a significant energy input, especially if materials are shipped long distances, so the energy for transportation has been included in this study. The waste products, especially air pollutants and solids that are sent to a landfill, are also considered, but in less detail than energy use. Previous reports concentrated on limited aspects of glass-container production and recycling; a comparison of this work with previous work is included as Appendix A.

TABLE 1.1 Volume of Materials Discarded in Municipal Solid Waste in 1990

MSW Component	1990 Discards (10^6 tons)	Weight (% of MSW total)	Volume (% of MSW total)	Ratio of Volume % to Weight %
Paper and paperboard	52.4	32.3	31.9	1.0
Plastics	15.9	9.8	21.1	2.2
Yard trimmings	30.8	19.0	9.8	0.5
Ferrous metals	10.4	6.4	8.9	1.4
Rubber and leather	4.4	2.7	6.1	2.2
Textiles	5.3	3.3	6.4	1.9
Wood	11.9	7.3	6.8	0.9
Food wastes	13.2	8.1	3.2	0.4
Other	5.8	3.5	1.4	0.4
Aluminum	1.6	1.0	2.2	2.1
Glass	10.6	6.5	2.2	0.3
Total	162.3	100	100	1.0

Source: EPA (1992).

2 Current Statistics

The glass-container industry is included in the Standard Industrial Classification (SIC) Manual (OMB 1987) under category SIC 32: stone, clay, and glass products. The largest energy user in the category is hydraulic cement. The glass industry includes manufacture of containers (SIC 3221), pressed and blown glass (SIC 3229), flat glass (SIC 3211), and fiberglass (insulation in SIC 3296 and fibers in SIC 3229). Container manufacture is the largest glass sector, accounting for approximately 40% of the 1990 energy consumption[2] and almost 35% of the value of shipments. The value of shipments for glass containers was almost $5 billion in 1990 (U.S. Department of Commerce 1992a). The cost of purchased energy was $414 million (about half for electricity), or 8% of the value of shipments. Material costs were 46%, payroll was 22%, and capital expenditures were 5% of the value of shipments (U.S. Department of Commerce 1992b).

Table 2.1 shows the distribution of glass-container production for various uses in 1991. In that year, 40 billion glass containers were produced in the United States; most of them were beverage bottles, but some were jars for various foods. This number works out to about 150 per person per year, or one each day per household. The largest component was beer bottles, both in number and tonnage. About 64% of U.S. production was flint (clear), 23% amber, and 13% green (Glass Packaging Institute 1992b). Imports equal about 4% of production, and exports about 2%; therefore, they do not affect the analysis significantly. Most glass containers are used for packaging of products that are consumed rapidly and pass from useful life to waste at a rate approximately equal to their production rate. The glass waste stream is therefore dominated by containers. In fact, 90% of the 13.2×10^6 tons of glass discarded in 1990 was containers (EPA 1992). The remaining 1.3×10^6 tons was glass as a component of durable goods, including appliances, furniture, and consumer electronics. This material is a mixture of glass compositions and would be extremely difficult to separate and recycle.

The U.S. Environmental Protection Agency (EPA) reports that the mass of glass waste more than doubled from 1960 to 1980 but has since declined. The absolute quantities recovered have increased, so that the percent recovered has increased dramatically, from 1.6% in 1960 to 22% in 1990. Figure 2.1 shows this increase, as well as a range of projections for the year 2000, with up to 40% recovery as a possibility. The glass container industry cites 1991 production at 10×10^6 tons, with cullet making up about 30% of the input. According to the Glass Packaging Institute, recycled content currently averages 30% nationally (3×10^6 tons),[3] and the industry is committed to increasing that rate "as much as possible, as soon as possible" (Glass Packaging Institute 1992a). Purchases of cullet were 2.1×10^6 tons in 1991, which is consistent with the

---

[2] Estimated on the basis of the costs of purchased fuels and electric energy (U.S. Department of Commerce 1992b).

[3] Including in-house waste.

TABLE 2.1 Shipments of Glass Containers by Type of Container for 1991

Product Code	Product Description	Number (10^3 gross)	Weight (10^6 lb)
221_ __	All types of containers	277,657	21,092
Narrow-Neck Containers		202,974	15,422
2210 11	Food	23,477	1,752
2210 13	Medicinal and health supplies	8,872[a]	—
2210 15	Chemical, household, and industrial	1,198[a]	—
2210 17	Toiletries and cosmetics	3,944[a]	—
2210 19	Beverage, refillable	57,141	3,655
2210 50	Beverage, nonrefillable		
2210 23	Beer, refillable	84,304	5,991
2210 60	Beer, nonrefillable		
2210 27	Liquor	10,565	1,481
2210 29	Wine	13,473	2,016
Wide-Mouth Containers		74,683	5,670
2210 31	Food and dairy products, including fruit jars, jelly glasses, and packers' tumblers	74,683	5,670
2210 32	Medicinal and health	[a]	—
2210 33	Chemical, household, and industrial	[a]	—
2210 34	Toiletries and cosmetics	[a]	—

[a] Data for these wide-mouth containers are included with the same categories of narrow-neck containers.

Source: U.S. Department of Commerce (1992c).

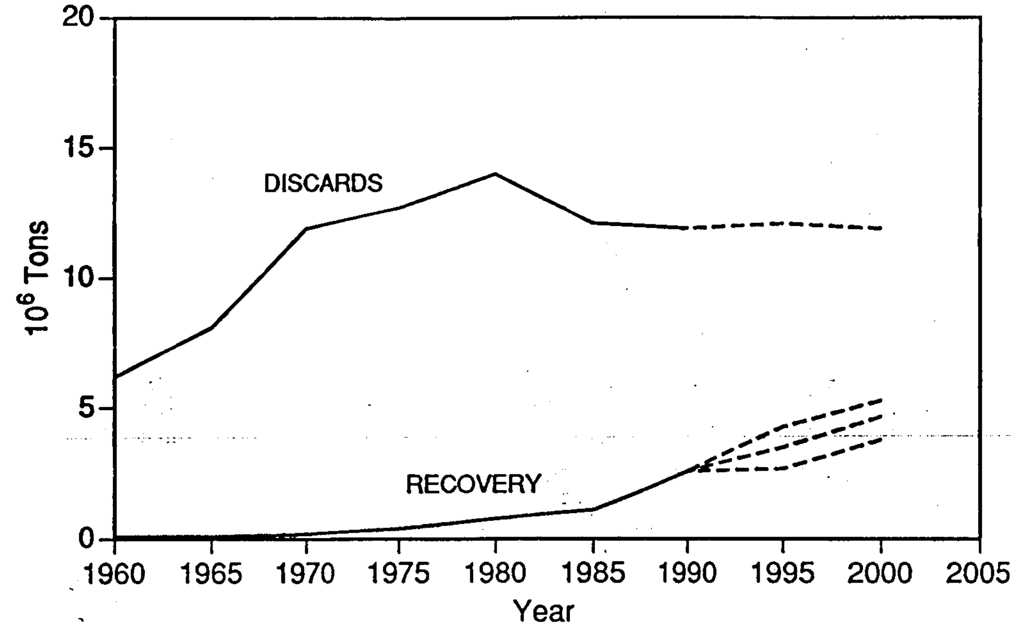


FIGURE 2.1 Glass Packaging Discards and Recovery (Source: EPA 1992)

postconsumer recycling rate reported by the EPA; the remaining 9% is in-house scrap (rejects). Most of the glass recycled is made into new containers, with the rest made into "glassphalt" (road-surface material with cullet replacing the aggregate[4]), fiberglass, and glass beads for reflective highway paint.

The container-glass industry purchased 125×10^{12} Btu in 1985: 78% in the form of natural gas, 19% in the form of electricity, and the remaining 3% in the form of distillate oil.[5] When the efficiency of electricity generation is taken into account, these figures imply primary energy consumption of 173×10^{12} Btu (Babcock et al. 1988). The actual energy consumption implied by these purchases must take into account the efficiency of fuel production; when this is done, the total consumption is approximately 190×10^{12} Btu. Note that these figures exclude raw-material production energy and transportation energy, which are estimated in this report.

---

[4] Note that the cullet replaces a low-value material. This form of recycling cannot be claimed to save energy. However, it represents an improvement over landfill when there is insufficient market for the cullet. The case of glassphalt is in contrast to the case of asphalt rubber, where discarded tires replace the asphalt itself, an energy-intensive petroleum product (Gaines and Wolsky 1979).

[5] New data from the Annual Survey of Manufactures (U.S. Department of Commerce 1992b) show 1990 electricity purchases down to 4.2×10^9 kWh, as compared with 1985 purchases of 7.0×10^9 kWh cited by Babcock et al. (1988). This decrease may be due to increased electricity costs or shifts in the regional distribution. Current census data report electricity purchases in kilowatt-hours and dollars, but fuels in dollars only. If the reported \$232 million is assumed to include purchased fuels at \$3 per 10^6 Btu, the fuel and electric energy purchases in 1990 totaled 92×10^{12} Btu, somewhat lower than 1985 purchases.

Accounting for transportation and raw-material production energies in the same way gives a grand-total primary energy consumption of 203 × 10^{12} Btu for 1985. The grand total for 1991 is estimated to be about 168 × 10^{12} Btu, with the reduction due to lower production and increased recycling.

To determine the overall primary fuel mix would require a regionally weighted analysis, which is beyond the scope of this study. Using the national average fuel mix for electricity generation, 64% of the primary energy consumption for 1985 glass-container manufacture was in the form of natural gas and 20% was coal. For the heavily coal-dependent east central region, 60% of the primary energy use was in the form of gas (this was the energy used in the gas-melting process), but almost 34% was in the form of coal. For the heavily nuclear Commonwealth Edison service area (Illinois), 32% of the primary energy use was nuclear (see Table 2.2).

TABLE 2.2 Estimated Primary Fuel Use Implied by 1985 Glass-Plant Energy Purchases

				East Central Region Energy Consumption		Commonwealth Edison Area Energy Consumption		National Average Consumption		
Fuel	Conversion Efficiency[a,b]	Fuel Production Efficiency[b,c]	Primary Efficiency	Percentage Electricity[a]	Percentage Primary Energy	Percentage Electricity[a]	Percentage Primary Energy	Percentage Electricity[a]	Percentage Primary Energy	Primary Energy (10^6 Btu)
Coal	0.329	0.98	0.322	87	33.7	19	7.2	53	20.2	39.2
Gas	0.325	0.87	0.283	1	59.3	1	58.2	13	63.6	123.0
Oil	0.318	0.78	0.248	3	3.7	1	2.7	9	6.6	12.8
Nuclear	0.32	0.95	0.304	8	3.3	79	31.9	17	6.9	13.3
Other	0.32 (est.[d])	0.95 (est.)	0.30 (est.)	0	0	0	0	7	2.7	5.2
Total	—	—	—	—	—	—	—	—	—	193.5

[a] Source: Electric Power Research Institute (1992).

[b] Conversion efficiency and fuel production efficiency do not vary rapidly.

[c] Source: DeLuchi (1991).

[d] est. = estimated.

3 Glass-Container Production Process

The basic steps are the same for production of glass containers from virgin raw materials or from cullet, as shown in Figure 3.1. Raw materials are brought to the plant, prepared, melted at high temperature (2,400–2,900°F), and formed into containers. The main differences are the supply and preparation pathways for the materials and the additional energy required in the melting process for the endothermic chemical reactions of virgin raw materials to form glass.

3.1 Raw Materials

New glass is made from sand (silica), limestone ($CaCO_3$), soda ash (Na_2CO_3), feldspar (aluminum silicates with potassium, sodium, calcium, or barium), and small quantities of other additives. Glass can be made from 100% new materials, but cullet is generally added to aid melting and produce other benefits (see Section 3.2.2). Because carbon dioxide (CO_2) is generated by the chemical reactions that form the glass, 1.15 tons of raw materials are required per ton of new glass. These raw materials are all mined, processed, and transported to the glass plant. Energy requirements for raw-material supply are summarized in Table 3.1.

3.1.1 Sand

Sand makes up the bulk of the raw-material input to glassmaking. If no postconsumer cullet were used, the batch input to produce one ton of glass would contain 1,285 lb of sand. Glassmaking consumed 42% of the industrial sand (as contrasted with construction sand, a different material) used in 1989. The price of the material is low (~$14/ton), so there is little economic benefit to displacing it as a raw material. Industrial sand production is dispersed around the United States, the five leading states being Illinois, Michigan, California, New Jersey, and Texas; thus, long transport distances generally are not needed. Because of its wide geographic dispersion, sand is assumed to travel only 100 mi from mine to glass-container manufacturer.[6] Shipments of sand are assumed to be in 22-ton loads on dump trucks that average 5.2 mi/gal. Actual transport of industrial sand shipments in 1989 was 58% by truck and 34% by rail.

Industrial sand is mined from open quarries, then crushed, screened, and classified. The primary energy consumed in 1987 by SIC 1446 (Sand and Gravel) is estimated to be 0.7×10^6 Btu/ton: one third in electricity and over one half of the rest in the form of natural gas

---

[6] Weighted average distances are for total U.S. production and are computed from a recent study for the New York State Energy Research and Development Authority (Appendix III-B in White et al. 1992). For a plant such as Owens-Brockway located in Streator, Illinois, sand would travel 100 mi (as opposed to 150 mi), and feldspar would travel 600 mi (as opposed to 430 mi).

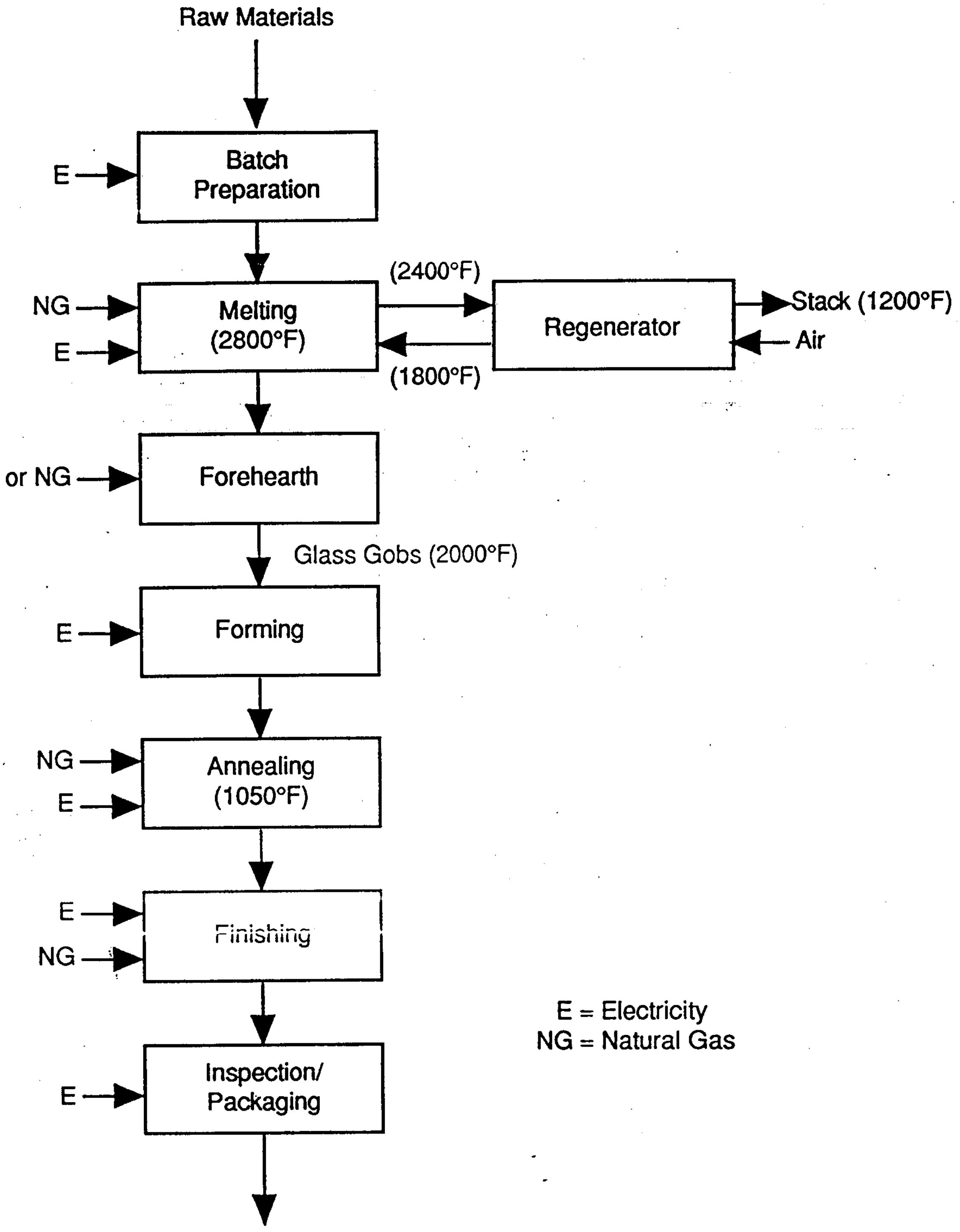


FIGURE 3.1 Container-Glass Production (Source: Garrett-Price 1986)

TABLE 3.1 Energy Inputs from Raw-Material Production and Transport

Material	Production Energy (10^6 Btu/ton material)	Transport Mode	Average Distance (mi)	Transport Energy[a] (10^6 Btu/ton material)	Total Energy (10^6 Btu/ton material)	Weight of Material Needed[b] (tons/ton bottles)	Total Energy (10^6 Btu/ton bottles)
Sand	0.71[c]	Dump truck	100	0.12	0.83	0.64	0.53
Limestone	0.09[d]	Rail	150	0.06	0.15	0.20	0.03
Feldspar	1.37[e]	Rail	430	0.17	1.54	0.10	0.15
Soda ash	4.5–6.0[f]	Rail	1,100	0.44	4.94–6.44	0.22	1.09–1.42

[a] At 1,200 Btu/ton-mi for truck and 400 Btu/ton-mi for rail.

[b] No consumer cullet.

[c] Based on data from U.S. Department of Commerce (1990a).

[d] Based on data from White et al. (1992).

[e] Based on data from White et al. (1992) and U.S. Department of Commerce (1990b).

[f] From U.S. Department of the Interior (1991).

(U.S. Department of Commerce 1990a). The primary environmental concern in sand production is particulates in the air when making fine products, because silica dust can cause silicosis. However, glass sand is coarser than silica flour, and wet and dry methods of dust control can be employed. Water from washing and screening operations requires treatment because of suspended clay. There are also concerns about noise from blasting and heavy trucks.

3.1.2 Limestone

Limestone deposits are also widespread; because of its wide geographic dispersion, limestone is assumed to travel only 150 mi, primarily by rail, from mine to glass-container manufacturer (White et al. 1992). Limestone (SIC 1422) is mined from quarries and then crushed. Its production is the least energy-intensive of the inputs to glassmaking, requiring about 0.09×10^6 Btu/ton (White et al. 1992), and makes a negligible contribution to the total energy. Therefore no new data were obtained. If no postconsumer cullet were used, the batch input for one ton of glass would contain about 395 lb of limestone.

3.1.3 Feldspar

Feldspar is mined in seven states, with North Carolina accounting for 67% of 1989 production (U.S. Department of the Interior 1991). The other states are Connecticut, California, Georgia, Oklahoma, Idaho, and South Dakota, so there is a broad geographical spread, and no location is distant from a supply of feldspar. Most feldspar is shipped less than 1,000 mi, generally in rail hopper cars. This analysis assumes an average travel distance of 430 mi. Glassmaking is the largest user of feldspar, consuming 54% of 1989 production. The cost of the material is $40/ton, and about 200 lb (a value of $4) is used per ton of glass from new materials. Feldspar contains aluminum silicates, along with potassium, sodium, and calcium. It is added to glass batches because the alumina improves the workability of the molten glass and the chemical stability of the containers.

Feldspar is quarried by open-pit procedures, which include drilling, blasting, and breaking. The material is then sent for primary and secondary crushing and is ground to 20–40 mesh. It is sent through two flotation stages to remove mica and iron-bearing minerals (garnet); then it is filtered and dried. Feldspar production (SIC 1459600) makes up 17.4% of the value of shipments in SIC 1459 (clay, ceramic, and refractory materials, n.e.c.) (U.S. Department of Commerce 1990b). Therefore, its energy use can only be estimated from census data. The fuel use for the larger industry group is a mixture of distillate, gas, and fuels to generate electricity; the average primary energy use in the sector is estimated to be 1×10^6 Btu/ton (estimated from data in U.S. Department of Commerce [1990b]). This energy is consistent with the older unit process data cited by White et al. (1992) and makes a very small contribution to the total energy for glass production.

3.1.4 Soda Ash

Production of glass uses natural soda ash, primarily recovered from trona ore. Glassmaking accounted for 51% of 1989 soda ash consumption, with 59% of that, or 30% of the total, going to container manufacture (U.S. Department of the Interior 1991). About 440 lb of soda ash is used for each ton of glass made from new materials to lower the viscosity of the melt. Soda ash, with deposits almost exclusively confined to southwestern Wyoming, is assumed to travel an average distance of 1,100 mi by rail. Some may also be transported short distances by truck to rail depots.

The Wyoming trona deposits are enormous; the Green River deposit alone could supply current world demand for over 600 years. Five companies mine the hard, abrasive ore using underground mining techniques similar to those used for coal. The current mines range from 800 to 1,500 ft below the surface. The most commonly used method is the room and pillar technique, but longwall and shortwall techniques are also used. The ore is undercut, drilled, blasted (using ammonium nitrate and fuel oil [ANFO]), mucked, crushed, and transported to the surface via modern conveyor belt systems. The crushed trona ore is calcined in a rotary kiln at 325–400°F (with CO_2 and H_2O as by-products). The calcined ore is dissolved in water and insoluble impurities like shale are allowed to settle out and are removed by filtration. The solution is concentrated in triple-effect evaporators (or more recently in efficient mechanical vapor-recompression units) until crystals form. Soluble impurities remain in solution; the crystals are separated by centrifugation and calcined again at 300°F to drive off the remaining water. Environmental concerns associated with Wyoming soda ash manufacture include injury to migrating waterfowl from the alkaline solutions in evaporation ponds. There is a rehabilitation program for the birds, and some operations have now changed to underground injection. The rapid growth of the natural soda ash industry has also caused problems because of the influx of workers to undeveloped areas; these problems are being dealt with by the companies.

One California company produces soda ash from a subsurface brine lake 50–350 ft underground. The brine, containing 4.3–4.8% soda ash, is treated with CO_2 to produce sodium bicarbonate, which precipitates and is separated from the rest of the components. The bicarbonate is calcined back to the carbonate, and the process is repeated to produce a denser, more refined product. Several other chemicals are also recovered from the brine.

Soda ash is the costliest and most energy-intensive input to glass manufacture. Its price (f.o.b. Wyoming) was $77/ton in 1989 (U.S. Department of the Interior 1991). Energy use was estimated to be 7.2×10^6 Btu/ton on the basis of 1973 data from the Bureau of Mines (U.S. Department of the Interior 1991). Previous reports relied on this data and earlier results as high as 8.9×10^6 Btu/ton (White et al. 1992). However, more efficient processing units are reported to be in use now, and newer data from the Bureau of Mines show energy consumption reduced to 4.5×10^6 to 6.0×10^6 Btu/ton of soda ash produced, with variation within this range from site to site (U.S. Department of the Interior 1991). This reduction lowers the contribution of raw-material production energy to glassmaking from all new materials by

TABLE 3.2 Summary of the Baseline Process Energy

Process Step	Loss Assumed (%)	Energy Form Used	Quantity of Energy	Data Source
Batch handling	0	Electricity	50 kWh/ton glass	Babcock et al. (1988)
Melting				
All virgin materials	0	Natural gas	5.17×10^6 Btu/ton glass	Derived from White et al. (1992)
100% cullet[a]	0	Natural gas	3.74×10^6 Btu/ton glass	White et al. (1992)
30% cullet	0	Natural gas	4.74×10^6 Btu/ton glass	White et al. (1992)
Bottle forming	0	Electricity	382 kWh/ton glass	Babcock et al. (1988)
Annealing	13.6[b]	Natural gas	1.84×10^6 Btu/ton glass	Babcock et al. (1988)
MRF processing	10	Electricity	40 kWh/ton bottles[c]	Ozdarski (1992)
Cullet beneficiation	1	Electricity	30 kWh/ton glass from MRF	White et al. (1992)

[a] Limiting case; extrapolated from operations at different cullet-use rates.

[b] 88% pack-to-melt ratio, with losses assigned to last process step.

[c] In mixed recyclables.

beneficiation is done on-site by about one third of the operating glass-container plants (Mazenko 1992); the rest of the plants purchase furnace-ready cullet from beneficiators, such as Allwaste, which are often located nearby. The energy for beneficiation is primarily electric; the quantity is of minor significance (~50 kWh/ton glass).

Figure 3.2 shows the locations of all cullet suppliers and glass-container manufacturers in the United States as of 1993. Note that both industries are highly concentrated. Owens-Brockway supplies approximately 40% of all glass containers manufactured in this country. Anchor, Ball-InCon, and Foster-Forbes (a division of American National Can) account for most of the remaining 60%. Owens-Brockway accounts for the bulk of all internal or co-located beneficiation capacity, while Allwaste is the leading independent supplier of glass cullet. Allwaste operates 23 plants throughout the United States and owns the three oldest commercial suppliers (Advance Cullet, Circo, and the Bassichis Company).

3.2.2 Melting

Melting is by far the most energy-intensive step in the production of glass, because large quantities of material must be heated to high temperatures (2,400–2,900°F). It is also the one process step where cullet content influences energy consumption. Several earlier reports describe the melting process in great detail and discuss opportunities for energy conservation. The information in those reports will not be duplicated here; the reader is referred in particular to the reports by Babcock et al. (1988) and Garrett-Price (1986) for extensive information on different furnace types and operating procedures. In this report, we will provide enough background to support the discussion of the question at hand, without requiring the reader to refer to the earlier studies.

Most glass in the United States (approximately 80% according to Babcock et al. [1988], p. 2.9) is made in large regenerative furnaces. This type of furnace therefore forms the basis for the analysis. The batch is melted, chemical reactions (oxidation/reduction) forming glass occur, and the glass is refined to improve properties and reduce bubbles. The furnaces are generally heated by natural gas, which is burned over the surface of the glass. Electric boosting is common and has several reported benefits, including reduction of gas use, reduction of dust, and increased production (Fourment 1982). The electrical energy is supplied by electrodes under the surface of the glass, which is a conductor at high temperatures; the electricity is used more efficiently than the heat from gas combustion, but generally not efficiently enough to offset the losses in generation. Thus, primary energy consumption is not reduced. However, there may be some parts of the furnace, such as the forehearth, where electric heating is so efficient that it is an energy saver even on the basis of primary energy consumption. Furnace efficiency can also be increased by using oxygen-enriched air. The Babcock et al. (1988) and Garrett-Price (1986) reports provide a much more complete survey of energy-conservation opportunities. Improvements in glass-melting efficiency reduce energy use for both virgin and recycled product and are likely to reduce the differential in energy use between the two types of feedstock.

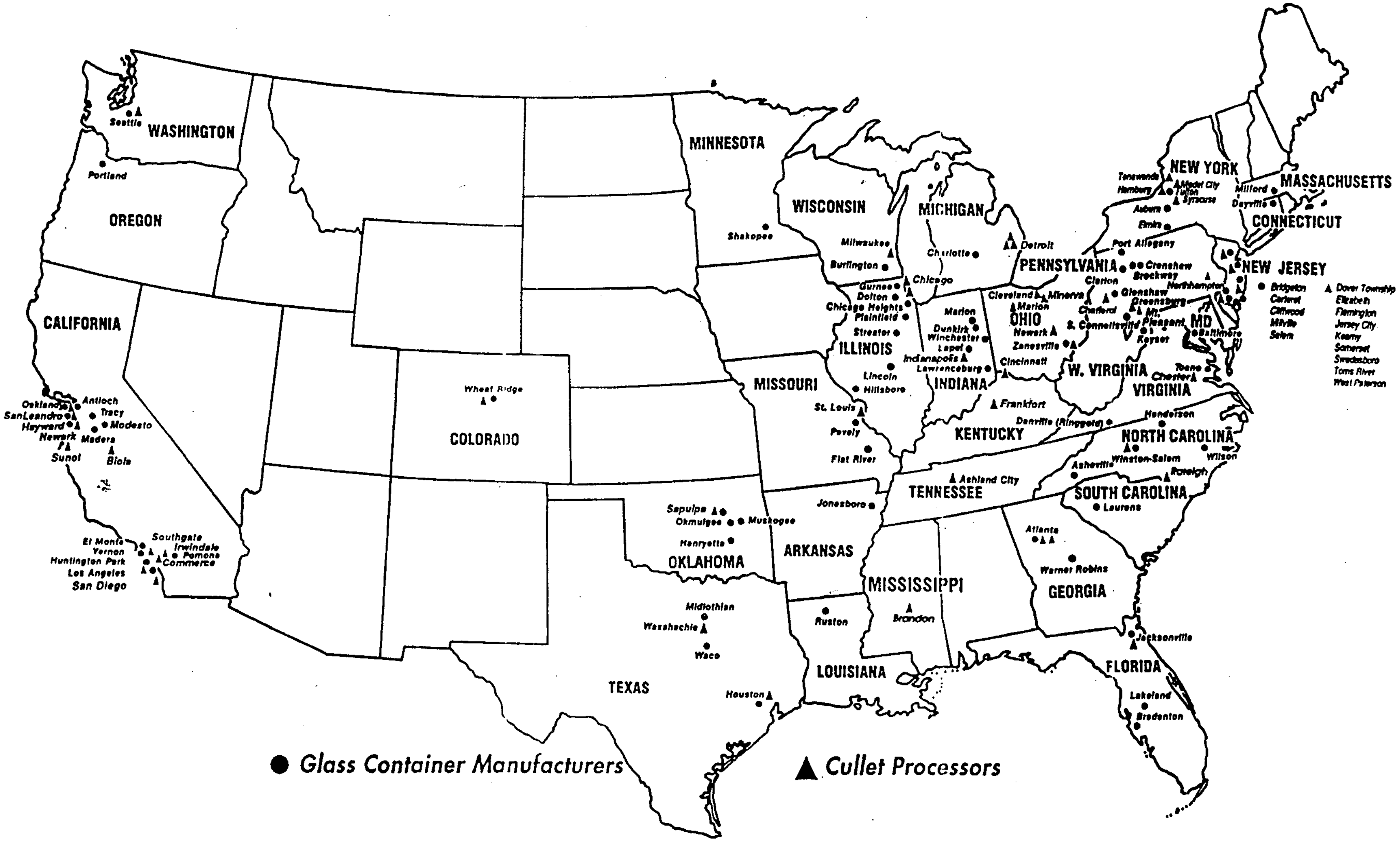


FIGURE 3.2 Location of Domestic Glass-Container Manufacturing Plants and Commercial Cullet Suppliers (reproduced with permission of the Central States Glass Recycling Program)

Increasing the use of cullet in glass furnaces has several advantages. Cullet acts as a flux and aids the melting of the batch. Less energy is required to melt cullet than to melt and react the batch materials, which reduces combustion gas emissions. The temperature of the melt is lower, and operation at lower temperature increases furnace life and therefore decreases production costs. In addition, less dust is produced, and less CO_2 is generated from the batch chemical reactions. However, some batch materials are generally required along with cullet to adjust product composition, depending on the quality of the postconsumer cullet, and to aid in the removal of bubbles during the refining stage. Cullet use is also reported to allow higher production rates (increased pull rate), allowing old furnaces to provide enough glass for newer bottle-making machines. A higher pull rate implies lower unit energy requirements, because the furnace heat losses ("no-load" fuel factor) are spread over more product.

There is a wide range of energy use in melting (see Babcock et al. 1988); we estimate 5.17×10^6 Btu gas/ton of glass melted for all new material[8] and 3.74×10^6 Btu gas/ton for all cullet, based on data in White et al. (1992), which presented new industry data.

3.2.3 Forming

Red-hot gobs of molten glass (at 1,800–2,250°F) are forced through orifices into molds; air is then blown into them to form the bottles (Babcock et al. 1988). Other molding techniques are discussed in the Babcock report, but are not examined here because process changes affect new and recycled glass equally. A typical machine produces 400 bottles per minute. All of the energy for forming is electrical (to generate compressed air; ~382 kWh/ton glass formed). The bottles are coated with tin or titanium oxide for scratch resistance, and then they proceed by conveyer to the lehr, or annealing furnace, where they slowly move through the large gas-fired furnace. They are held at over 1,000°F to anneal them, which relieves stresses that could weaken the product. The residence time is about an hour, and all of the energy is supplied as gas. This process is identical for containers made from new or recycled material. The energy use is about 1.84×10^6 Btu gas/ton processed, regardless of the amount of cullet in the batch.

The bottles then pass through several manual and automated inspections for such defects as stones (nonmelting impurities), nonuniform thickness, undersized opening, and bubbles. The rejects generally are crushed to become part of the in-house cullet pile and are eventually returned to the melting furnace. However, bottles with stones are removed from the stream; the quantity of these is small. After inspection, the bottles may be labeled. Then they are packed into cartons or shrink-wrapped pallets for shipment.[9] There is very little breakage in these operations, and the small quantity of energy used is electrical.

---

[8] Hypothetical limiting case extrapolated from data for higher cullet-use rates.

[9] Mobil's shrink wrap is recycled.

It is desirable to keep the pack-to-melt ratio (percentage of acceptable product) over 90%, because melting the same material repeatedly increases costs and energy use. The quality of the feed is crucial for the pack-to-melt ratio. Poor-quality cullet input lowers this ratio; it is therefore very important to beneficiate postconsumer cullet before charging it to the furnace. In one instance reported, a load of cullet came in on a truck that had previously hauled a material that doesn't melt at glass-furnace temperatures, and the pack for the whole run using this load in the feed was down 3%. This material had to be discarded rather than recycled. Ceramic contaminants cause similar problems. In another instance, a small quantity of green glass contaminated flint (clear) cullet, causing the whole batch to be lost. (The material was presumably recycled as green.) Labels and other remnants on the cullet burn off, but excesses affect the process and can even change the color of the glass.

3.2.4 Shipment to the Consumer

The completed containers leave the glass plant for a series of destinations. Transport from destination to destination is generally by truck. First, the containers are sent to a food or beverage plant (bottler), where they are filled, capped, and labeled (if this wasn't done at the bottle-manufacturing plant). Storage at warehouses is a possible additional step before or after filling. The filled containers are shipped to retail outlets, such as grocery or liquor stores, restaurants, or bars, where they are purchased by final consumers. Consumption of the contents and subsequent creation of the empty containers as waste can either take place immediately at the point of purchase (restaurant or bar) or some time later, generally at a residence. For the last transfer only, the mode is automobile.

The energy consumed at each destination is relatively small. The energy consumed in transport may be significant, and it is all in the form of petroleum distillates. However, this transport energy varies with the content of the container and the assumed use pathway. In addition, this energy use is the same for virgin or recycled containers and, therefore, does not affect this comparative analysis. Thus, no estimate of the energy required for supplying completed containers to final consumers is included in this study.

3.3 Material Recovery Steps

Discarded glass containers are picked up by truck, either separately or mixed with other wastes, and transported to a MRF or landfill. From the MRF, the material goes back to the glass melter, often by way of a beneficiation facility. The energy consumed depends on the destination (i.e., whether the container is to be recycled or not), and there is serious concern that this amount of energy might be considerable. Therefore, the energy for material collection is discussed in detail, along with that for processing steps.

The transportation portion of the energy used to recycle glass containers is consumed by the curbside collection of either mixed waste or mixed recyclables, the transfer of these materials to a MRF, and the distribution of MRF-separated materials to secondary processors.[10] Collection is inherently energy-inefficient — small volumes of recyclables are generated by many physically dispersed consumers. Although commercial, industrial, and multifamily units generate additional volumes of recyclables that should be considered in a comprehensive analysis of this subject, these consumers typically contract with private haulers whose collection practices differ from the MSW systems that serve relatively low-density residential areas (i.e., single-family units and 2–4 unit multifamily structures). Because of these differences and their associated impact on energy efficiency, this analysis was limited to residential collection via conventional MSW systems.

As shown in Figure 3.3, glass containers can take a number of paths through the MSW system. Transportation occurs at each of the links that connect the boxes shown in the figure. Because each of these trips has somewhat different energy efficiencies associated with it, the overall energy efficiencies of the various paths differ substantially. Thus, the following discussion focuses not on the path (which in turn is a function of the type of collection and processing program available to the municipality), but on the *individual links* connecting each of the boxes alphabetically labeled in the figure. Energy intensities of the different links are summarized in Table 3.3. Generally speaking, as recyclables move from consumer to recovery to reprocessing into new products, efficiencies improve, because shipment size or volume rises while the fuel efficiency of the vehicles (for the most part, trucks) remains relatively stable.

3.3.1 Collection and Transport to MRFs or Landfills

Generally, recyclables are either collected at curbside or deposited by consumers at various types of drop-off locations, such as local recycling centers, community service clubs, dealers, and commercial buy-back centers. For completeness, the drop-off path is shown in Figure 3.3. However, because it is beyond the scope of our analysis, shading and dashed lines are used to distinguish it from other possible pathways. Curbside collection of recyclables can be accomplished either in conjunction with the pickup of all MSW or as a separate activity. The following discussion focuses on each in turn.

3.3.1.1 Co-Collection

While co-collection systems (box B in Figure 3.3) range from complete commingling of all waste with later separation at a mixed-waste MRF to transporting essentially source-separated recyclables ("blue bags") in the same truck as MSW, only these two ends of the spectrum are shown in Figure 3.3. The major benefit of a co-collection system is that the municipality or hauler

---

[10] Because average load, length-of-haul, and vehicle efficiencies for the movement of recycled materials from secondary processors to manufacturers are assumed to be comparable to those for virgin material inputs, the transportation analysis becomes less detailed as we progress to final production.

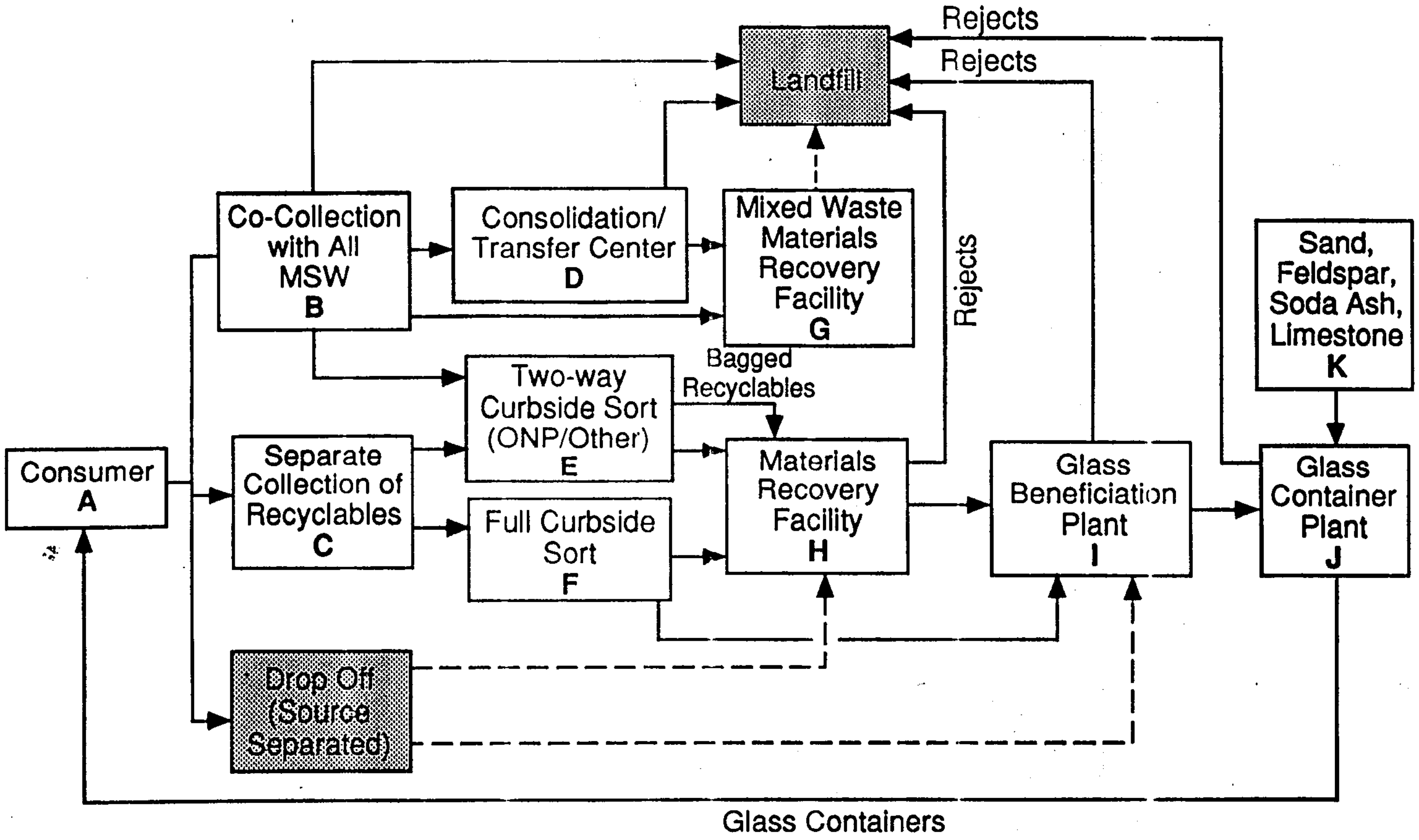


FIGURE 3.3 Pathways of Postconsumer Glass Containers

TABLE 3.3 Transportation Data for the Baseline Recycling Loop

	Transport					
Material	From	To	Distance or Length of Haul (mi)	Mode	Btu/ton-mi	10^6 Btu/ton
Mixed waste	Households	Landfill or transfer station	15	Packer truck	12,500[a]	0.187
Mixed waste	Transfer station	Landfill	20	Transfer truck	3,080[a]	0.062
Recyclables	Households	MRF	14	Recycling truck	18,700[a]	0.262
Waste	MRF	Landfill	25	Transfer truck	3,080[a]	0.077
Cullet	MRF	Beneficiation	200	Dump truck	1,200	0.24
Cullet	Beneficiation	Glass plant	200	Dump truck	1,200	0.24

[a] Includes energy for empty backhaul.

need not acquire dedicated recycling vehicles, which can cost $56,000–$120,000 each, depending on size, features, duty cycle, etc. (Edelman 1992). However, because contamination reduces the marketability of recovered materials, relatively few communities choose this option. Indeed, mixed-waste systems often achieve less than 50% recovery of marketable recyclables, including recovery for such low-value uses as daily landfill cover (Edelman 1992). Although blue-bag systems have achieved rates of 70% or higher,[11] this rate is still substantially less than the 90% or higher recovery achieved by separate systems (Keeley 1992). Participation (or setout rate) is another problem with co-collection systems. By definition, completely commingled co-collection achieves 100% participation. However, with blue-bag systems, households must purchase (albeit nominally priced) bags. Thus, participation is substantially below that typical of separate recycling systems. For example, in Houston (Chicago Tribune 1992) and in Omaha (Sink 1992), participation rates for blue-bag programs average 30% and 50%, respectively, as compared with 70–90% for most separate recycling programs (McCann 1992).[12]

On the surface, co-collection appears to be superior from an overall energy standpoint, because a single vehicle collects both MSW and recyclables. However, if only 38% of recyclables are recovered with co-collection (50% participation × 76% recovery) as compared with 83% for separate systems (90% participation × 92% recovery), this conclusion is not necessarily warranted. Further, because the few communities with co-collection tend to be larger, have a more diverse population, and use larger-capacity trucks (which tend to be more energy efficient on a Btu per ton basis, but less so on a miles per gallon basis), comparisons can be misleading. As shown in Table 3.4, packer trucks typically achieve little more than 2 mi/gal because (1) much of their duty cycle is spent idling followed by quick acceleration and (2) their hydraulic systems (for operating compactor rams and lift arms) consume additional fuel. Miles per gallon are also affected by route characteristics that determine the number of daily runs and, hence, the daily mileage of the vehicles. Route characteristics include housing-unit density (i.e., units/acre), roadway configuration (primarily the frequency of cul-de-sacs), tree cover (which limits overhead loading), parking and traffic along the route, and distance to the MRF and/or landfill.

To simplify this analysis, we assume that a 240-hp packer truck would be the typical co-collection vehicle as well as the basic MSW collection vehicle. We also assume that glass containers account for a proportional share of fuel use (tonnage shares are generally 70% old newsprint [ONP], 10% glass, and 20% other). Note that fuel use is apportioned by weight, but energy intensity (in Table 3.4 and elsewhere) is calculated on the basis of a full load.

---

[11] In Omaha, 90–94% of bags are recovered at the MRF, and 81% of the tonnage sorted at the MRF is recyclable (Sink 1992). In 1991, the resulting recovery rate was 73–76%.

[12] To illustrate the effects of participation rates, approximately 7,500–12,500 tons of glass would be recovered for a community of 500,000 with a blue-bag program, as compared with 17,500–22,500 tons for a comparably sized community with a separate curbside recycling program (Glass Packaging Institute 1992b).

TABLE 3.4 Characteristics of Trucks Used for Curbside Collection of Municipal Solid Waste and Recyclables

	Packer Truck				Recycling Truck (Straight Truck)			
Parameter	Mixed MSW A[a]	Mixed MSW B[a]	Mixed MSW C[a]	Co-collected Recyclables[b]	Curb Sort	Mixed Recyclables D[a]	Mixed Recyclables E[a]	Mixed Recyclables F[a]
Fuel	diesel	diesel	diesel	diesel	diesel	diesel	diesel	diesel
Engine size (hp)	237	240	240	300	180	180	180	160
Typical load (gross tonnage)	10	10	9.5	12	1.3	3	2.5	2.7
Fuel consumption rate (gal/d)	26.8	36	28	38	18	17	18	24
Daily mileage (mi)	60	80	60	80	93	80	70	93
No. of daily trips	2	2	1.5	2.5	3	3	3	1.5
Daily gross tonnage[c]	20	20	14.25	30	3.9	9	7.5	4.05
Miles per gallon	2.24	2.22	2.14	2.11	5.17	4.71	3.89	3.88
10^6 Btu per gross ton	186	250	273	176	640	262	333	822
Btu per ton-mile	3,098	3,121	4,542	2,196	6,883	3,275	4,755	8,838
Total capacity (yd^3)	25	25	25	31	18	20	31	20
Load density (lb/yd^3)	800	800	760	774	144	300	161	270
Speed (mi/h)	6	8	6	8	9.3	8	7	9.3
Emission Rate (g/mi)[d]								
NO_x	<—— approx. 28–87 ——>							
CO	<—— approx. 4–54 ——>							
HC	<—— approx. 2.4–8.5 ——>							

[a] Letters refer to various Chicago suburbs.

[b] Blue-bag system in Omaha (Sink 1992).

[c] Total tonnage of glass containers typically accounts for 10%.

[d] Depends on engine, driving cycle (primarily vehicle speed), and accumulated mileage (Guensler et al. 1991; Wang 1992).

Sources: Tigcheleer (1992); Nanky (1992); Phillips (1992); and Van Der Molen (1992).

Thus, on the basis of the assumptions shown in Table 3.4, a generic blue-bag program is estimated to have a collection-energy intensity of 315,000 Btu/ton (3,940 Btu/ton-mi) as compared with 250,000 Btu/ton (3,121 Btu/ton-mi) for mixed waste under comparable route conditions. All of the difference is due to our assumption that compaction will be 80% of current gross loading under a blue-bag program. If equivalent compaction is assumed, there should be no difference in the energy intensity of recyclable materials. However, for both co-collection alternatives, nonrecyclables could travel an additional distance if loads are dumped at a consolidation/transfer center (shown as box D in Figure 3.3),[13] then loaded onto transfer trucks for shipment from the MRF to a landfill or WTE plant. If one assumes that a 5.2-mi/gal transfer truck hauls a 13.1-ton load a distance of 40 mi (20 mi each way, with an empty return), the energy intensity for the nonrecyclable fraction (some 97.5% of the gross tonnage collected in Omaha [Sink 1992]) of a blue-bag program with full compaction rises by 81,000 to 331,000 Btu/ton (4,139 Btu/ton-mi).[14]

3.3.1.2 Separate Collection

Separate collection programs generally use bins or "toters" into which consumers have deposited ONP and mixed recyclables. Contents are then sorted at curbside in conjunction with loading onto a separate collection vehicle. Curbside sorting is labor- and equipment-intensive. In suburban settings, collection rates can vary from 78–85 homes per hour with a two-way sort (ONP vs. mixed recyclables) to only 45 homes per hour with a full sort of ONP, plastics, and glass (Edelman 1992). Thus, the trend is to two-way sorting at curbside with later separation of commingled recyclables at a MRF. For dedicated recycling trucks, the time savings achieved with two-way sorting (both at curbside and on unloading at the MRF) often permits adding another daily trip; also the elimination of separate bins on the truck may increase load capacity. These two factors translate into major savings in capital and labor costs, but little real energy savings. (See Appendix A for a detailed discussion and illustration.)

The key to reducing collection-energy intensity lies in maximizing gross daily tonnage. In practice, an optimal combination of daily runs and loads is more significant than curb sort vs. mixed collection. This can be seen in Table 3.4, where the most energy-intensive system moves only 4 tons of recyclables per vehicle per day, as compared with 9 tons for the least energy-intensive system.[15] The impact on energy intensity is dramatic — the 9-ton system uses less than

---

[13] Note that consolidation/transfer centers are generally co-located with MRFs.

[14] Truck shipments of MSW are assumed to be via transfer trucks (also called platform trucks with devices). According to the 1987 Truck Inventory and Use Survey, average fuel efficiency and loads in 1987 were 5.2 mi/gal (harmonic-mean) and 13.1 tons, respectively (U.S. Department of Commerce 1989).

[15] Although that particular hauler does curb sort, similar efficiencies were reported for mixed-collection systems (see Appendix B).

half the energy per ton-mile compared with the 4-ton system. The same principle applies to packer trucks, where energy intensities of trucks moving only 14.25 tons of recyclables per vehicle per day are 45% greater than those for trucks moving 20 tons per vehicle per day.

Although packer trucks are far heavier (hence, less fuel efficient) than the straight trucks used for curbside recycling, high-tonnage packers can have energy intensities on the order of 2,200 Btu/ton-mi, as compared with 3,300 or even 8,800 Btu/ton-mi for recycling trucks, because of material densities. Although glass typically accounts for roughly 8% of the weight of most recyclable loads, it accounts for only 2% of the volume (Glass Packaging Institute, undated). By contrast, plastics and aluminum tend to fill the vehicle long before its tonnage capacity is reached. As a result, some haulers have added small, stationary compactors to their recycling trucks, and vehicle manufacturers such as LaBrie and EnviroPack have begun producing vehicles equipped with plastics compactors (Van Der Molen 1992). Other haulers use packer trucks on some of their recycling routes to permit higher loadings, as well as to avoid the cost of dedicated equipment (Edelman 1992).[16]

3.3.2 Material Recovery Facility

The variety of designs in use for MRFs in the United States result in different quality products with different energy consumptions. As recycling rates increase, new facilities will be built, which will represent the majority of operating MRFs. Therefore, process flows and energy use for an exemplary new facility, located in Montgomery County, Maryland, are described in this report. This plant is reported to process 100 tons/d of commingled waste and produce 1,350 tons/mo (about 60 tons/d of operation) of glass product. The average scrap rate is about 10% of the total output (excluding paper) (Ozdarski 1992). However, the reject rate may be different for different materials, and the effect of reduced glass recovery will be examined in the sensitivity analysis (Section 4.3.2). The process description given below is excerpted from a brochure distributed by the recycling center. A block flow chart for the process is shown in Figure 3.4.

> Tipping floor: Recycling trucks dump the mixed glass, plastic, and metal containers on the tipping floor. Bucket loaders push the material into the pit for the infeed conveyor belt.
>
> Mixed Recyclables Infeed Line: A conveyor belt moves the mixed recyclables into the sorting area. A computer regulates the speed of the conveyor to maintain a steady flow of materials.

---

[16] Although packer trucks permit greater flexibility, they can cost well over $120,000 each, as compared with $50,000–$60,000 for a recycling truck. Thus, flexibility has a price.

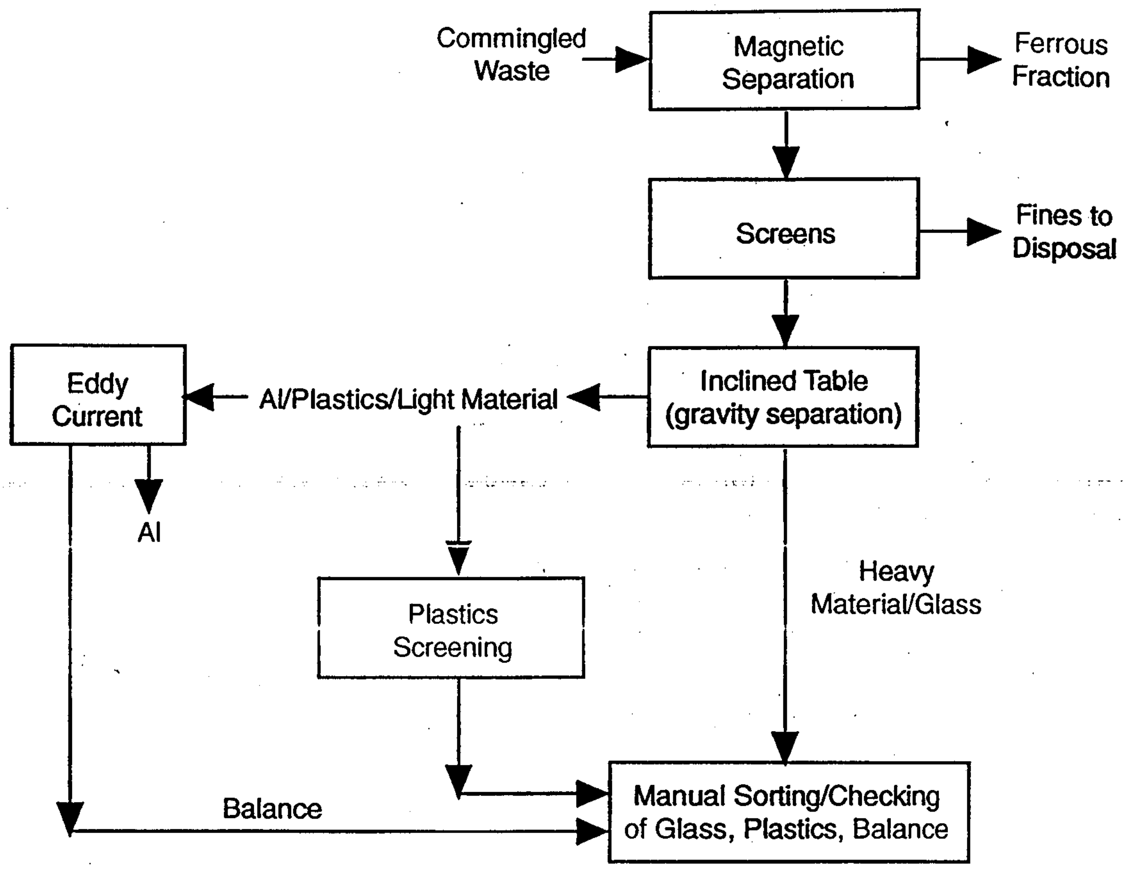


FIGURE 3.4 Process Flow Chart for the Montgomery County, Md., MRF

Presort Platform: Recycling center employees remove any nonrecyclable materials (contaminants) that were mistakenly included with the recyclables. They also remove aluminum foil products and place them in a separate bin for baling.

Electromagnet and Ferrous Baler: As the mixed recyclables continue on the processing line, a powerful magnet pulls out steel, tin, and bimetal cans, which contain iron, and sends them to a baler for compacting into 1,200-lb bales for shipment to steel mills.

Screening Machine: This machine automatically screens out broken glass and other small particles of material. The pieces of broken glass are too small to be sorted by color. Instead, they are cleaned and processed together to produce a mixed-color glass aggregate that has been used to make champagne bottles, glass-based asphalt, and fiberglass products.

Inclined Sorting Table: Glass bottles, aluminum cans, and plastic bottles pass over an inclined sorting machine. Rotating chain curtains automatically divert the lightweight aluminum and plastic to each side of the table,[17] while the heavier glass falls through the chains and brushes.

Glass Sorting Platform: Recycling center employees separate green, brown, and clear glass, dropping them into separate bins. Workers remove ceramic, mirror, or window glass because glass recycling plants will refuse shipments containing these items.

Glass Storage: Glass is conveyed to a glass processor where it is crushed and stored in 20-ton tanks until taken to market. (Source: Montgomery County Recycling Center, undated)

Note that hand separation of glass bottles results in a much more usable product and therefore a higher recovery rate: a trade-off of labor for energy. If glass is broken before the colors are separated, the resulting product is of very low value for container manufacture. Mixed-color glass may be salable for glassphalt, glass beads for reflective paint, or possibly fiberglass, but there is no market for it in containers. One MRF is reported to be unable to market almost half of its recovered material because of poor separation.

3.3.3 Transport from MRF to Beneficiation Facility

Table 3.5 presents assumptions used to calculate the energy efficiency for glass shipments from MRFs to secondary processors. The data for the trucks correspond to shipments on the following links in Figure 3.3: MRF-to-landfill (or WTE plant, shown as "rejects" in Figure 3.3) and MRF-to-glass beneficiation plant. Truckloads of rejects (or waste) assume the use of a captive fleet of vehicles with no return haul.

As shown in Figure 3.3, glass that has been separated into flint (clear), amber (brown), green, and mixed colors is transported from the MRF (box H) to a glass beneficiation plant (box I), where the different types are screened to remove contaminants and crushed to densify the glass for shipment and subsequent remelting into new containers. Some beneficiation plants are co-located with container-manufacture operations.

As shown in Figure 3.2, most commercial cullet suppliers are located either east of the Mississippi or in the states of California, Texas, or Oklahoma. Due to its density and low value, glass from MRFs outside these areas is more likely to be landfilled or used in secondary products than shipped to distant beneficiation plants. Although some waste glass (i.e., glass prior to

---

[17] These materials then undergo further separations, which are indicated on the figure but are not described here.

TABLE 3.5 Characteristics of Transportation Mode Used for Distribution of Recyclables and Nonrecyclables from the MRF

Parameter	Transfer Truck	Dump Truck	Rail
Fuel	Diesel	Diesel	Diesel
Engine size (hp)	300	350	3,000
Typical load (gross tonnage)	13.1	23	80
Fuel consumption rate (gal/d)	15.4	40	—
Daily mileage (mi)	80	200	—
No. of daily trips	2	1	—
Daily gross tonnage	26.2	23	—
Miles per gallon	5.2	5	—
10^6 Btu per gross ton	81	241	0
Btu per ton-mi	1,018	1,206	418
Average length of haul (mi)	40	200	500
Speed (mi/h)	11.4	25	—
Emission rate (g/mi)[a]			
NO_x	<– approx. 16–30 –>		—
CO	<– approx. 9–59 —>		—
HC	<– approx. 2–7 ——>		—

[a] Depends on engine, driving cycle (primarily vehicle speed), and accumulated mileage (Guensler et al. 1991; Wang 1992).

Sources: Guensler et al. (1991); Wang (1992); and *Railroad Facts* (1991).

beneficiation) and glass cullet move by either barge or rail, the bulk of all shipments are by over-the-road trucks. One cullet supplier reports mode shares of over 70% truck, 25% rail, and less than 5% barge. Another reports a 100% truck share. Although cullet suppliers often operate their own truck fleets, common carriers generally handle the longer hauls, often as return hauls.[18] Given the mix of short one-way hauls vs. long hauls with loaded returns, a reasonable average shipment distance appears to be on the order of 200 mi (Ozdarski 1992; Mazenko 1992).

3.3.4 Cullet Beneficiation

A typical beneficiation plant in Illinois gets all its color-separated feed by truck from recyclers, curbside programs, drop-off centers, and MRFs as far away as North Dakota (Mazenko

---

[18] However, by requiring truck drivers to submit a certificate of verification certifying that each truck (or roll-off container) has been cleaned and washed of foreign materials prior to loading and indicating the material that was previously hauled in the truck (or container), some manufacturers are making cullet a less desirable return haul (Mazenko 1992).

1992). Material that has gone through a MRF will generally have the fewest contaminants. The flint cullet processed is used on-site at the Illinois plant, and the green and amber are shipped by rail to plants that produce colored glass. These can be 1,000 mi or more away.

The quality of the input varies, which affects the rate at which material can be processed. The maximum rate for one plant built in 1984 is 25 tons/h, but 14–18 tons/h is a more typical operating rate. Considering the operating schedule, this rate works out to about 200 tons/d average or 72,000 tons/yr. The plant has four large motors to run the conveyor belts and the vacuum system. All of the energy used is electrical, and the operations are similar to those at the MRF described above. The energy use is therefore expected to be comparable. A newer plant would use less energy than a nine-year-old one.

The feed material, with labels still on it, is dumped in huge piles that may contain various plastic bottles, lids, incorrect colors, etc. The area is swept so that little material is lost. The feed material is loaded by a bucket loader into a large hopper. A conveyer belt then carries it through a strong electromagnet to remove ferrous metals. At this step, a small amount of glass can be lost if any part of the bottle is still attached to the cap. Once the ferrous metals are removed, the material is screened to remove large pieces, which are broken up and returned to the system; this stream is periodically purged and discarded.

The screened material passes through an air separator, where light materials (labels, plastics) are blown off, and then to a nonferrous metal detector. The detector works like a trapdoor, and as much as 5 lb of glass can be removed with each nonferrous item. This removal may represent 5% of the glass stream. Therefore, during slow periods, the nonferrous stream (which has been accumulated) is sent slowly back through the plant to recover more of the glass: the final quantity of glass lost depends on how busy the plant is, but it is small (perhaps 1%). About 3% of the feed is nonglass waste that is removed. No equipment for removal of ceramic contaminants is included; such equipment is under development (DeSaro 1992). The product cullet is dropped into storage areas, where it is stored in large piles for use in bottle making. It is important to have some reserve, because melting operations cannot be changed rapidly to accommodate different input mixes of cullet and batch.

3.3.5 Transport from Beneficiation Facility to Glass Plant

As shown in Figure 3.2, most cullet suppliers are clustered in relative proximity to glass-container manufacturing plants. However, because not all manufacturers produce all colors of glass (most of the green glass used in this country comes from Canada and Europe), and because manufacturers may broker for several plants, cullet can be shipped over 1,000 mi.[19] Table 3.6 presents pertinent energy data for truck, rail, and barge shipments of cullet[20] (McMahon 1992; Hecht 1992). Note that the apparent energy efficiency of trucks is solely a function of the shorter average length of haul. On the basis of energy per ton-mile, barge and rail are three times more energy efficient. As mentioned above, however, the bulk of all tonnage moves by truck.

As shown in Figure 3.3, rejects or waste leave each of the reprocessing stages. Most of these rejects are (a) nonrecyclables exiting a mixed-waste MRF and (b) contaminants separated from glass at either a MRF or a beneficiation plant. Nonrecyclables are assumed to exit a mixed-waste MRF on transfer trucks (see Table 3.3 for shipment characteristics); contaminants and reject bulk are assumed to be hauled in 6-ton truckloads to a local landfill or WTE plant.[21]

TABLE 3.6 Characteristics of Transportation Mode Used for Distribution of Cullet from the Processor

Parameter	Dump Truck	Rail	Barge
Fuel	Diesel	Diesel	Diesel
Engine size (hp)	300	3,000	5,600
Typical load (gross tonnage)	23	100	1,500
Fuel consumption rate (gal/d)	39	—	—
Daily mileage (mi)	200	—	—
No. of daily trips	1	—	—
Daily gross tonnage	23	—	—
Miles per gallon	5.1	—	—
10^6 Btu per gross ton	236	522	691
Btu per ton-mi	1,182	418	395
Average length of haul (mi)	200	1,250	1,750
Emission rate (g/mi)[a]			
NO_x	18	—	—
CO	6	—	—
HC	2.2	—	—

[a] Depends on engine, driving cycle (primarily vehicle speed), and accumulated mileage (Guensler et al. 1991). Assumes an average speed of 50 mi/h.

---

[19] Another factor affecting shipping distances is the limited market for green glass. As of May 1992, Owens-Brockway was paying only $5/ton for green glass as compared with $50/ton and $25/ton for flint and amber, respectively (Mazenko 1992).

[20] Truck shipments of glass cullet are assumed to be via dump trucks, which in 1987 had a weighted fuel efficiency of 5.2 mi/gal, averaged over all loads and hauls (U.S. Department of Commerce 1989).

[21] Average load of rejects exiting the DuPage County Intermediate Processing Facility in December 1991 (Trychta 1992).

4 Energy Analysis

Figures 4.1–4.3 are material and process flow charts for the life cycle of one ton of glass containers supplied to the consumer for three cases: the two limiting cases, maximum use of new materials and maximum recycling, and an intermediate case that represents average current practice in the United States. These flow charts show energy and material inputs and outputs, starting from raw materials in the ground and ending with final disposition of any wastes. Direct inputs to the processes are shown, along with transportation energy along each link. Energy consumed to produce and supply electricity and fuels is not included on the flow chart, but these values will be estimated to calculate the total amount of energy required. Energy to produce process equipment is not included, because this contribution is negligible. Process energy is discussed in Section 4.1 and transportation energy in Section 4.2. The total primary-energy consumption is discussed, and a sensitivity analysis is performed to identify key factors (both in Section 4.3).

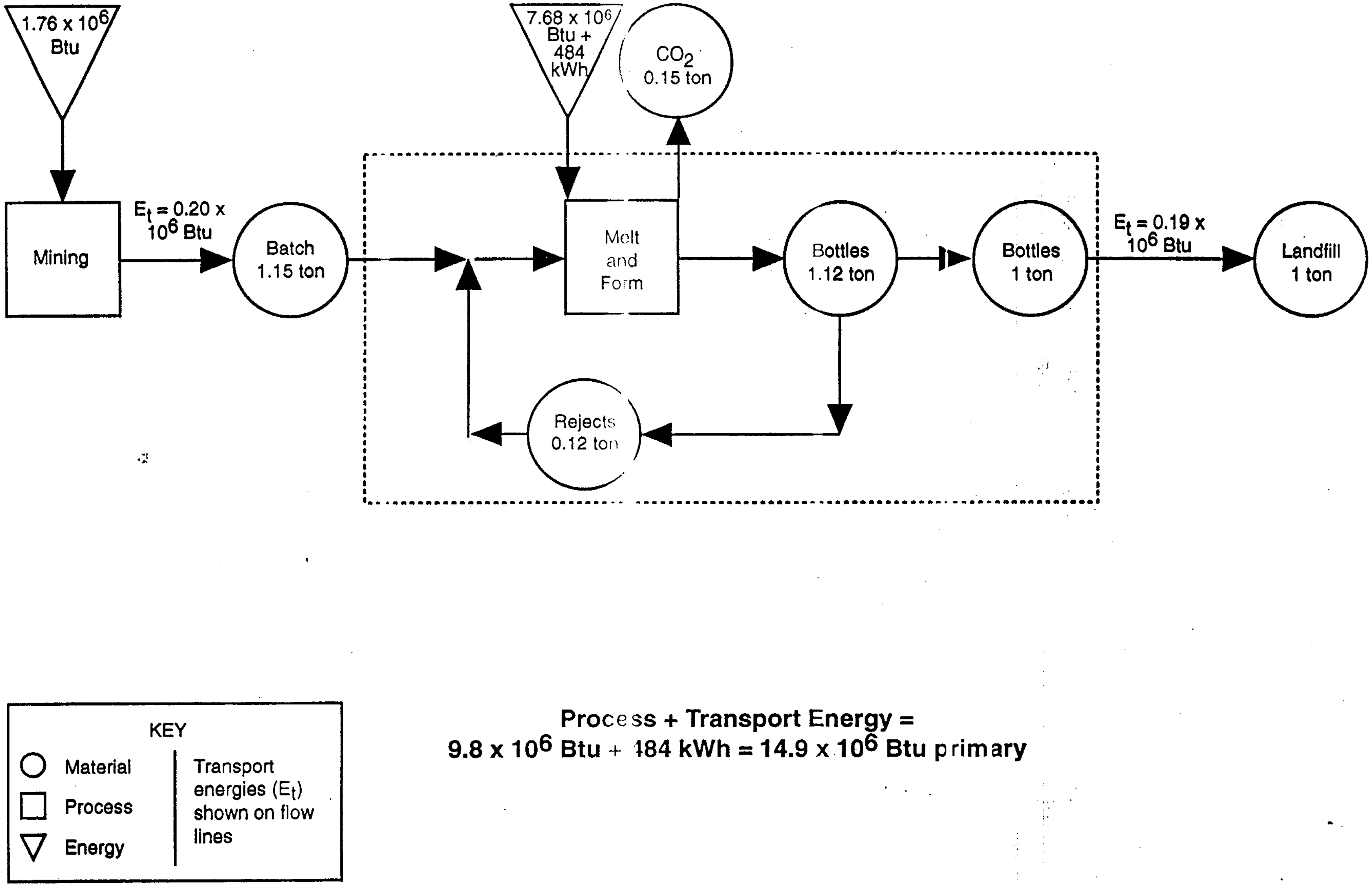
4.1 Process Energy

Figure 4.1 shows the simplest option to analyze for glass-container manufacture. For this option, containers are made from virgin raw materials, used once by consumers, and sent to landfills. Note that there is a recycling loop within the manufacturing plant: rejected bottles are returned to the process. Such internal recycling is standard practice, makes good economic sense, and is therefore included even for this case where no postconsumer recycling occurs. The quantity of material in this loop, which depends on the pack-to-melt ratio achieved at the plant, will be seen to affect the energy use for melting and forming the glass; the greater the number of rejects, the greater the amount of glass that must be processed to supply one ton of bottles to consumers. Note also that more feed material is fed into the process than glass produced because CO_2 is generated by the chemical reactions forming the glass.

The major energy inputs for glass-container production from virgin raw materials are natural gas and electricity at the glass plant (gas for melting and annealing, electricity for forming) and coal and natural gas for raw-material mining and processing. The energy consumed in melting glass varies widely and depends on many factors. We have used an average[22] number, rather than the absolute value, and concentrated on the differences between melting virgin and recycled materials. Therefore, the total for any one plant might be considerably different from the number cited here, but the effect of recycling will be appropriately determined. With this caveat, the total energy consumed in processing is approximately 9.4×10^6 Btu plus 484 kWh *per ton of containers delivered* (per net ton). (Note that most previous studies report energy use per ton of glass melted [per gross ton], a practice that neglects pack losses.) Converting the electricity to

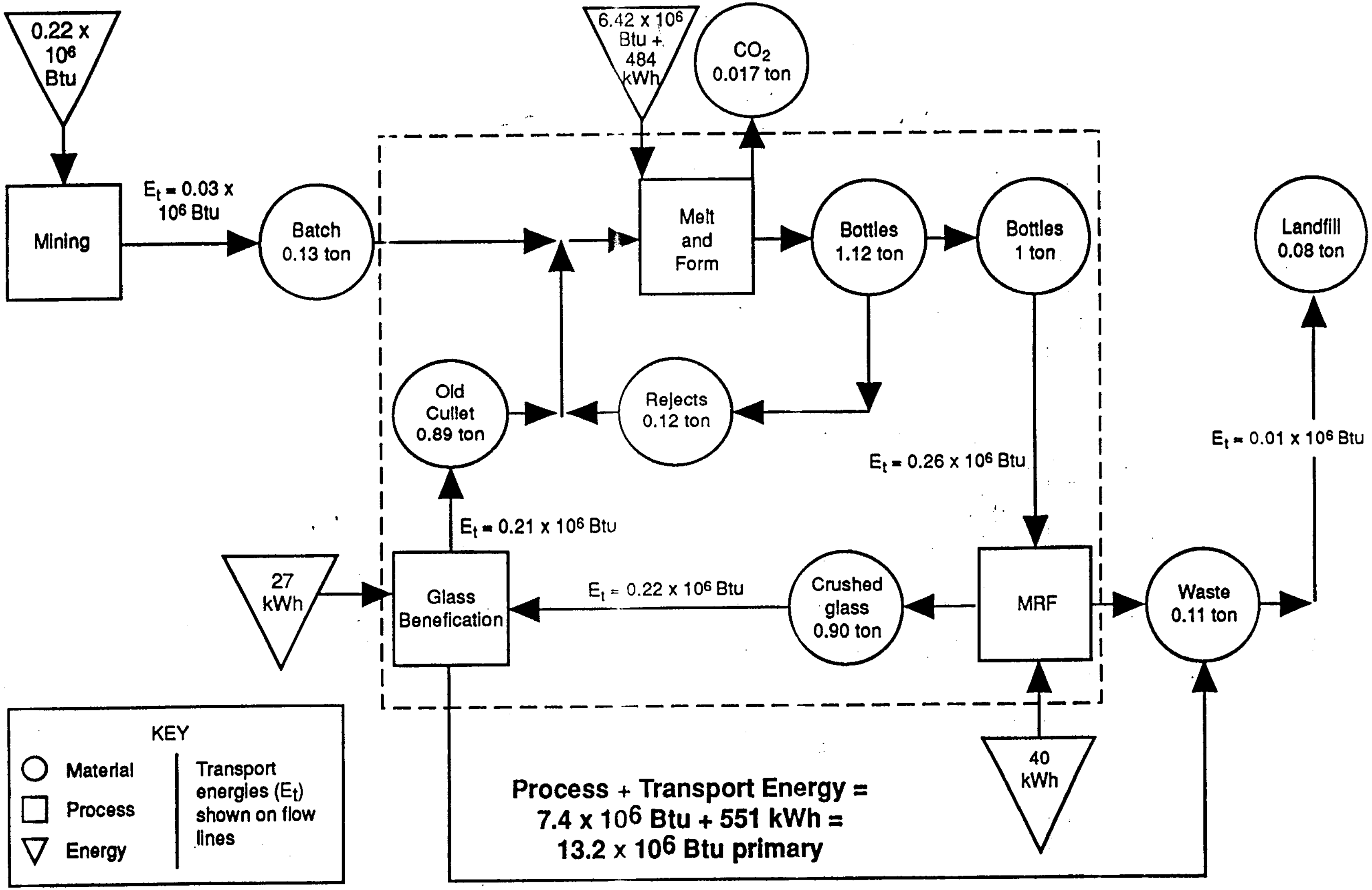
---

[22] We chose an average plant because there is an overcapacity of glass production plants, and few new facilities are likely to be built in the foreseeable future.



Process + Transport Energy =
9.8×10^6 Btu + 484 kWh = 14.9×10^6 Btu primary

FIGURE 4.1 Glass-Container Process Energy and Material Flow Chart for Maximum Use of New Materials (not including extraction and processing energies for fuels)



Process + Transport Energy =
7.4 x 10^6 Btu + 551 kWh =
13.2 x 10^6 Btu primary

FIGURE 4.2 Glass-Container Process Energy and Material Flow Chart for Maximum Glass-Container Recycling (not including extraction and processing energies for fuels)

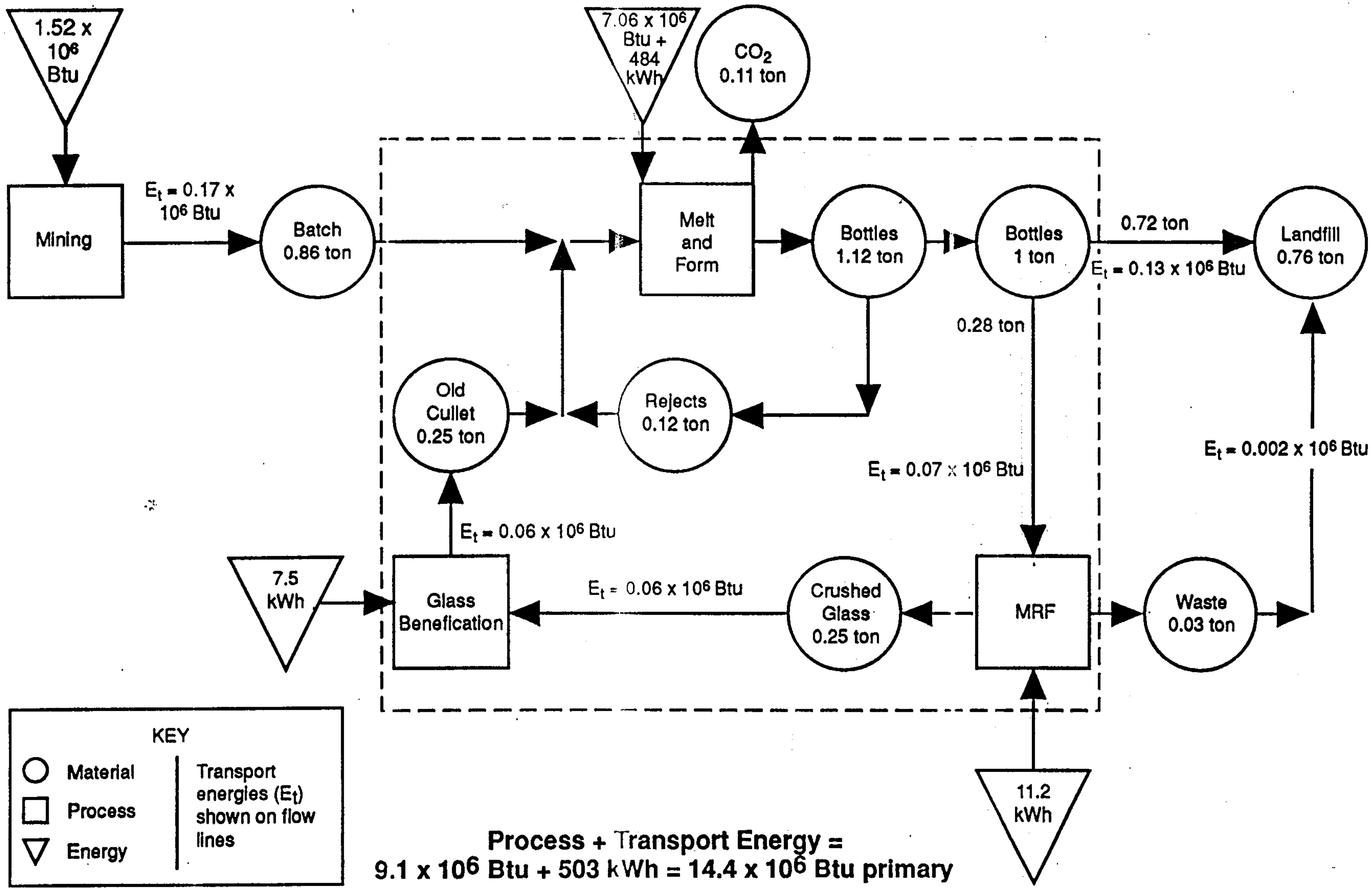


FIGURE 4.3 Glass-Container Process Energy and Material Flow Chart for Current Average U.S. Practice (not including extraction and processing energies for fuels)

primary energy consumption at 10,500 Btu/kWh yields a total primary usage of 14.5×10^6 Btu/net ton. Transportation and fuel production/conversion energies are added below to give total energy use.

Figure 4.2 shows the limiting case of maximum recycling of glass containers. Even assuming 100% return of bottles, there is still a small requirement for batch materials,[23] necessitated by the loss of material in the MRF. The major energy inputs for this case are still natural gas and electricity at the glass plant, but gas use is reduced by about 1.2×10^6 Btu per net ton of containers. Additional energy savings are realized by reducing the energy to produce raw materials; these savings are only partly offset by the electricity usage in material recovery and beneficiation. Note that energy use will be affected by material losses at the MRF; sensitivity to this rate will be examined below. Total process energy for the case of maximum recycling is about 6.6×10^6 Btu plus 551 kWh per ton of containers, or 12.4×10^6 Btu/net ton of primary energy. About 16% of the processing-fuel savings will be offset by additional transportation energy in the recycling loop; sensitivity to transportation distance will also be examined below.

Figure 4.3 shows the current average material flows for supply of one ton of glass containers. For this case, one-third of the material input is cullet. This chart is a linear combination of the previous two and therefore shows intermediate values for energy use. The process energy for this case is about 8.6×10^6 Btu plus 503 kWh per ton of containers, or 13.9×10^6 Btu/net ton of primary energy.

4.2 Transportation Energy Analysis

The contribution of transportation to production energy is 0.39×10^6 Btu/ton of glass containers for maximum new materials, 0.73×10^6 Btu/ton for maximum recycling, and 0.49×10^6 Btu/ton for the current mix. Note that all consumption is in the form of diesel fuel (much of it made from imported petroleum). Collection accounts for 15% of transportation energy use, assuming that cullet moves 200 mi from MRF to beneficiation plant and another 200 mi to a container plant. If these latter distances were considerably shorter (see below), the collection share of energy consumption would rise substantially.

There is considerable potential for improving collection efficiency, thereby reducing the collection share. As previously discussed, increasing average loads is the major strategy that haulers are using to increase efficiencies. However, their flexibility to do so is often limited by contractual obligations with the municipality (e.g., collection times and frequencies, vehicle sizes and replacement schedules, the types of recyclables collected); by physical constraints associated with locating MRFs; by the types of vehicles available in the marketplace; etc. Because of their size, the largest haulers are much less constrained by vehicle availability. Through licensing agreements, they have access to technology that appears to substantially increase average loads by

---

[23] Individual manufacturers would be able to purchase additional cullet to achieve 100% recycled input, but the industry as a whole could not. Other plants would then need to use more virgin materials.

using multiple, detachable trailers, each of which is loaded at curbside until full and then dropped off for a transporter vehicle. Because the transporter can bring two or three trailers on each of its trips to the MRF, average loads (hence efficiencies) can be dramatically increased. As mentioned above, the use of small stationary compactors can also increase loadings; however, such increased loads must be balanced against possible losses in sort efficiencies at the MRF.

4.3 Total Primary Energy Use and Sensitivity to Key Factors

The baseline energy use for glass-container manufacture and recycling was estimated on the basis of typical industry practice and our best estimates of average transportation distance. A sensitivity analysis was performed to see how varying several key factors affected the energy savings expected from recycling one ton of containers. The results of the sensitivity analysis allow estimation of how savings from recycling can be expected to change as plants are modernized and how savings vary now as a function of facility location and local conditions.

4.3.1 Total Energy Use

To calculate the total energy expended to supply one ton of containers to the consumer, process and transportation energies must be added, and conversion efficiencies for electricity generation and fuel production (including fuel used to generate electricity) must be factored into the total. Table 2.2 shows the conversion and production efficiencies for electricity production and the total fuel usage for the glass-container industry in 1985. Table 4.1 shows similar conversions applied to the numbers on the three flow charts, leading to total energy usages of 17.0×10^6 Btu/net ton of bottles for minimum recycling, 14.8×10^6 Btu/net ton for maximum recycling, and 15.9×10^6 Btu/net ton for the current case. Primary energy use for 1991 glass-container production is estimated to be 168×10^{12} Btu. The total primary energy use decreases as the percent of glass recycled rises, as can be seen in Figure 4.4, but the maximum saving is only about 13%. However, as the percent of glass recycled rises, cullet quality is likely to decline, leading to a higher reject rate and perhaps even resulting in higher energy use than without recycling. Previous work has shown that to save energy when using glass bottles, reuse is the clear choice. Even taking into account the heavier weight of reusable bottles, the energy per use drops by a factor of ten or more (Gaines 1981).

The mix of fuels used for each of the three cases is also shown in Table 4.1. Most of the energy used (about 60%) is in the form of natural gas, whether glass is recycled or not, so recycling will not affect the fuel mix drastically. More gas is used for glass production from virgin materials than from recycled materials because of both the higher melting energy and the raw-material production energy required for virgin materials. The primary fuel mix can also be changed by increasing the quantity of electric boosting. This increase will affect glass production from new and recycled materials similarly, and further discussion of this option is beyond the scope of this study.

TABLE 4.1 Total Primary Energy Consumption for Glass-Container Production, Transport, and Final Disposition, Including Fuel Production

Energy Form	Production Efficiency[a]	Percentage of Fuel for Electricity[b] (%)	Energy Consumed (10^6 Btu)			Percentage of Total Consumption[c] (%)		
			Minimum Recycle	Maximum Recycle	Current Average	Minimum Recycle	Maximum Recycle	Current Average
Oil	0.78	11	1.4	1.7	1.4	7.5	10.7	8.7
Gas	0.87	14	10.5	8.3	9.5	61.9	56.7	59.7
Coal	0.98	51	3.6	3.3	3.5	21.1	22.2	21.9
Nuclear	0.95	17	1.0	1.1	1.0	5.9	7.2	6.3
Other	0.95	7	0.5	0.4	0.5	3.6	3.1	3.6
Total	—	100	17.0	14.8	15.9	100	100	100

[a] DeLuchi (1991).

[b] Based on U.S. average generation mix and conversion efficiency (Electric Power Research Institute 1992).

[c] Totals may not add to 100% due to rounding.

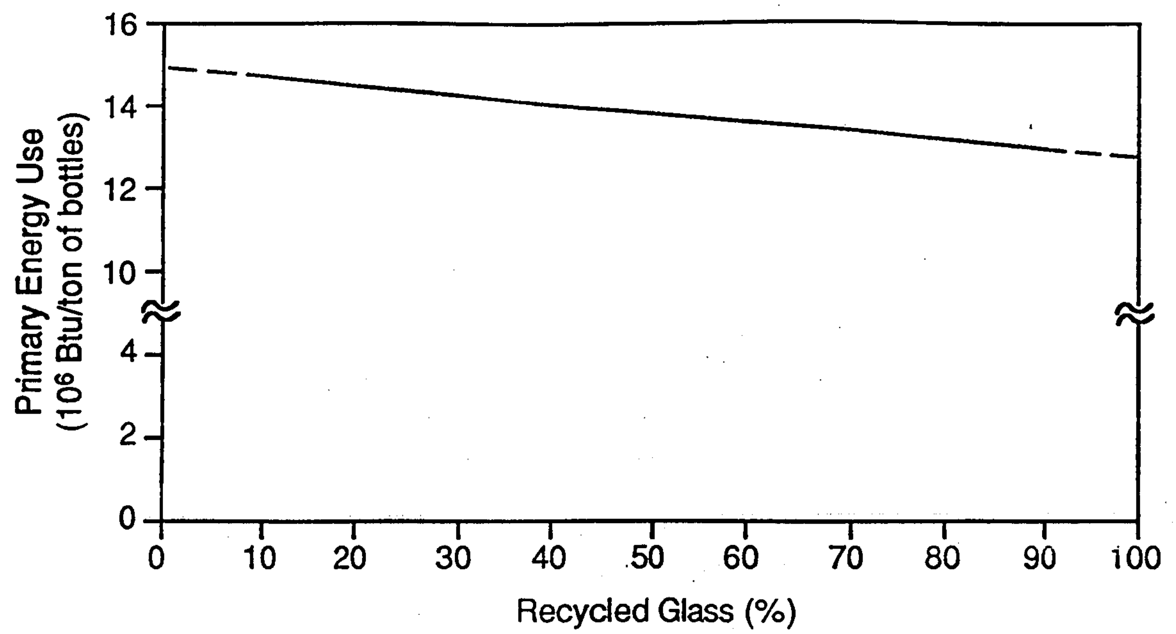


FIGURE 4.4 Energy Use as a Function of Percent Bottles Recycled

4.3.2 Sensitivity Analysis

The energy use in glass manufacture varies widely from plant to plant. However, the energy to be saved from recycling varies considerably less, and the sensitivity of energy use to certain key factors is much easier to determine. Some of these factors are the rate of material loss in recycling, the reject rate or pack-to-melt ratio, and the transportation distance. The savings are also affected by changes in industry practice, such as process improvements and other conservation measures, and by recycling to other products.

4.3.2.1 Sensitivity to Material Losses

Material loss rates vary from facility to facility and are also a function of the feedstock quality, which can vary with time and supplier. Material losses in processing are essentially equivalent to lower recovery rates from the consumer.[24] This section analyzes losses at the MRF, where actual losses may be significant; analysis of losses in beneficiation would yield similar results. Data from the Montgomery County MRF indicated a 10% material loss rate in processing (mixed cullet that must be landfilled) (Ozdarski 1992). This number was used as the baseline for energy calculations. However, this number was an average rate and did not account for possible differences among materials. Another MRF is reported to receive a large quantity of broken glass as part of its feedstock (perhaps because of compacting in transport), and therefore mixed cullet

---

[24] Losses in recycling imply slightly higher energy consumption because of additional transportation and processing energy expended.

makes up a disproportionate fraction of its waste. Up to 30% of the glass input may be lost this way (Trychta 1992).

Therefore, sensitivity of energy savings from recycling to material losses as high as 30% was examined. Savings were found to be reduced from 2.2×10^6 to 1.6×10^6 Btu/ton of containers, or about 1.3% reduction in savings per percent loss. This result indicates the need to minimize material losses.

4.3.2.2 Sensitivity to Pack-to-Melt Ratio

One glass-container production plant typically runs with a pack-to-melt ratio of about 88% (12% reject rate), but this rate depends on the quality of the feedstock, especially if a high fraction of cullet is used. The rate also may depend on the equipment and the maintenance cycle. Pack-to-melt ratios as high as 96% (4% rejects) are not uncommon (Mazenko 1992). Therefore, sensitivity of energy savings to variation in this ratio was estimated. A minimal reduction in savings (about 5%) occurs when the reject rate is reduced from the baseline estimate of 10% to 4%. The overall energy use for melting new and recycled glass are both reduced (by about 0.5×10^6 Btu/ton) by the decrease in reject rate; the energy use for new glass is higher and therefore is reduced more, explaining the small decrease in savings. The overall energy use is sensitive to the pack-to-melt ratio, whether recycled glass is used or not, but the savings are not very sensitive to it.

4.3.2.3 Sensitivity to Transportation Distances

When considering the sensitivity to transportation distance, the intuitive and correct result is that transportation of materials long distances can negate any energy savings achieved by recycling. The only question is how far the material can be transported before a break-even point is reached. The relevant distances are those between the material pickup site and the MRF or landfill, from the MRF to the cullet beneficiation facility, and from the facility to the glass-container plant. Variations in the latter two distances affect the analysis in the same way as distance to the MRF; therefore, this analysis focuses on relative variation in the distance between the pickup site and the MRF or the landfill. Note that the precise quantities being examined are the lengths of haul,[25] even though distances traveled by the collection vehicles along their pickup routes and to the drop-off point are considerably longer. The energy consumption for the entire trip is charged to the collected material.

Typical collection vehicles were found to make two to three runs per day, with a total mileage of 80 mi, whether the drop-off point was a MRF or a landfill. Therefore, a typical route run length was estimated as 30 mi. The energy intensity of the vehicles used in recycling is higher than that for garbage or packer trucks. Therefore, the distance to the landfill can be increased more

---

[25] Average length of haul is assumed to be the distance from the midpoint of the collection route to the MRF.

than that to the MRF for the same energy change. If the distance to the landfill is kept fixed and that to the MRF is multiplied by about eight, to 100 mi, a break-even point is reached, and recycling saves no energy (although it still is likely to save *money* over landfilling). If the distance to the landfill is increased, as is likely in many urban areas (especially in the Northeast), the energy savings from recycling are increased. For every mile of distance to the MRF, the landfill can be about 1.4 mi further away to maintain the same energy saving (energy use for both options rises equivalently). Similarly, another break-even point is reached by increasing the distance to the beneficiation plant or glass plant to about 1,750 mi from the baseline estimate of 200 mi if the mode is still dump truck; however, rail would actually be used for such large distances, and recycling would still be preferred on energy grounds.

4.3.2.4 Sensitivity to Final Product

This report has so far assumed that glass containers will be recycled into new containers, as is the most common current practice. However, containers can be recycled into several other products, and the end use affects the energy savings achieved. Alternative end products include glassphalt, reflective beads for highway paint, and fiberglass. The energy savings that can be credited to recycling into other products are equal to the energy displaced — the energy required to supply that product in the usual way.

Cullet can be included in asphalt paving material as a substitute for sand or gravel aggregate. The glassphalt market is more than large enough to use all mixed cullet. (Asphalt usage is approximately 10^9 tons/yr). However, the energy required to supply these materials is extremely low ($\sim 0.3 \times 10^6$ Btu/ton),[26] and the process energy required to size-reduce the cullet and free it of metals is likely to negate this small saving. Although no energy savings are expected, use of glassphalt avoids the cost of landfill.

Cullet can also be used for reflective beads in highway paint. This use also requires clean material but replaces glass. Reflective glass beads may be a use for which mixed cullet can displace virgin material, achieving savings similar to those for recycling to bottles.

It may also be possible to recycle some cullet into fiberglass, where as insulation, it could compete with recycled paper. Generally, fiberglass is made from borosilicate glass, which contains at least 5% boron oxide. Table 4.2 compares chemical compositions of several types of glasses, including soda-lime and borosilicate. The difference in composition limits the quantity of container cullet that could be used in fiberglass, but the market could still be substantial. Producing fiberglass is more energy-intensive than producing container glass, and so it would

---

[26] Estimate based on data in the 1987 Census of the Mineral Industries report on sand and gravel (U.S. Department of Commerce 1990a).

TABLE 4.2 Composition of Commercial Glass Products

			Fiber		Glass-Ceramic				
Constituent	Clear Float (wt%)	Container (wt%)	E-Glass (wt%)	Insulation (wt%)	Cooking-Ware (wt%)	Cook-Top (wt%)	Boro-Silicate Labware (wt%)	Ion-Exchange (wt%)	Sodium-Silicate (wt%)
SiO_2	72.5-73.4	71.5-73.5	54.0	59.0	70.0	72.0	81.0	62.2	76.0
B_2O_3	—	—	10.0	3.5	—	—	13.0	—	—
Al_2O_3	0.1-1.4	1.3-2.3	14.0	4.5	18.0	19.0	2.0	17.6	—
Li_2O	—	—	—	—	3.0	3.0	—	—	—
Na_2O	12.7-14.0	12.4-15.6	0.5	11.0	—	—	4.0	13.1	24.0
K_2O	0-0.6	0-2.9	0.5	0.5	—	—	—	3.3	—
MgO	3.3-4.9	0-1.0	4.5	5.5	3.0	2.0	3.2	—	—
CaO	8.2-9.9	9.3-11.3	17.0	16.0	—	—	—	—	—
BaO	0-0.6	0-0.5	—	—	—	—	—	—	—
TiO_2	—	—	—	—	5.0	4.0	—	—	—
Fe_2O_3	0.06-0.16	—	—	—	—	—	—	—	—
ZnO	—	—	—	—	1.0	1.0	—	—	—
SO_3	0.17-0.38	0.08-0.22		—	—	—	—	—	—

Source: Garrett-Price (1986).

appear that displacing fiberglass instead of container glass would increase energy savings. However, fiberglass production is more energy-intensive because it cannot use efficient regenerative furnaces due to plugging problems (Babcock et al. 1988). Melting the container cullet in these inefficient furnaces would probably require the same energy as melting the borosilicate glass, and therefore recycling to fiberglass would not increase energy savings. Further, melting difficulties were reported in trials of recycling container-cullet to fiberglass because of contaminants (U.S. Congress 1989).

4.3.2.5 Sensitivity to Energy Conservation Options

There are numerous options for energy conservation in glass-container manufacture. These options reduce energy use for both virgin and recycled products and also reduce the differential between the two. To increase energy savings from recycling would require recycling process improvements, but the MRF and beneficiation processes are not very energy-intensive, so the potential is limited. Some impact could be achieved by improving transportation efficiency, as this is the largest component of recycling energy.

Other opportunities for conservation involve changes in material utilization. One option the glass-container industry has tried recently involves reducing the material used for each bottle. Light-weighting decreases the energy required to make each bottle. However, it may have ramifications that partially negate this benefit. Breakage in processing would increase the reject rate at the plant, and breakage in use or recycling would increase the loss rates there. Coating the bottles with protective plastic covers helps reduce breakage, but the plastic requires energy for its production and is not being recycled at this time. A more detailed study would be required to estimate the energy trade-offs in this case.

Other options for saving energy include material substitution and reuse of glass containers. In previous work, energy per use for various packaging options was compared; reuse offers the largest potential for energy conservation (Gaines 1981) and is acceptable overseas. Refillable bottles still dominate the market in several European countries, with over 90% of retail soft drink and beer sales in the Netherlands in returnable bottles, and about 99% of beverage bottles in Denmark returned. In Japan, most bottles are collected and reused, with beer and sake bottles averaging 20 uses each (U.S. Congress 1989). Reuse involves no technical barriers; it is a consumer preference problem in the United States. However, the infrastructure has largely disappeared and would need to be reestablished.

5 Other Decision Factors

This report has concentrated on energy consumption in the production and recycling of glass containers. However, decisions made by governments or municipal groups concerning the disposition of waste products will not be based entirely on energy considerations. Several other factors are likely to enter into the decision, including airborne effluents, landfill overcrowding, and labor and other costs. Although a detailed examination is beyond the scope of this study, these factors are outlined here to help put the energy analysis in perspective.

5.1 Emissions

The most significant source of emissions in processing of glass containers is the melting furnace. The EPA has compiled data on emissions of particulates, sulfur oxides, nitrogen oxides, organics, and carbon monoxide, with and without control devices (EPA 1985a). These data are shown in Table 5.1. The most serious concern comes from dust and particulates emitted when batch materials are heated. The EPA reports that control of these can be 99–100% efficient with a baghouse or cloth filters. Emissions can also be reduced by pretreating the batch (e.g., pelletizing) or dampening the material. Because these emissions emanate from the batch materials, they can be reduced by increasing the amount of cullet feed. The melting furnace also produces emissions of SO_x (3.7 lb/ton bottles), from decomposition of sulfates in batch materials, and NO_x (6.8 lb/ton bottles), because of the high-temperature combustion. Both are reduced by addition of cullet — the sulfur by reducing batch use and the nitrogen by lowering the furnace temperature.

Combustion of natural gas in the melting furnace causes minimal SO_2 and NO_x emissions but does produce approximately 0.2 tons CO_2/ton glass, with the amount reduced slightly by cullet addition. CO_2 is also produced by the chemical reactions that produce glass from virgin raw materials (0.15 ton CO_2 per ton of new bottles) and by calcination of soda ash; there are no such emissions for cullet feed. Combustion of diesel fuels during transportation of virgin raw materials, recycled materials, and wastes produces airborne emissions in proportion to the quantity of fuel consumed. These emissions are summarized in Table 5.2. The important point to note is that NO_x emissions from truck transport are comparable to those from the glass furnace and may be larger for recycled materials than for virgin materials (because of the assumed long haul distances by dump truck). This equivalence negates the NO_x reductions at the glass plant due to cullet use and may even increase total NO_x emissions. Combustion of fuels to produce the electricity used in glass processing produces well-known emissions, which will not be discussed here. These will be similar for virgin and recycled glass.

There are other possible sources of emissions. During bottle forming, smoke may be produced from contact of the gob with old hydrocarbon lubricants; to solve the problem, the hydrocarbon lubricants have generally been replaced with silicones. Tin tetrachloride is sprayed on

TABLE 5.1 Emissions for Container-Glass Manufacturing[a,b]

Process	Particulates[c] (lb/ton)	Sulfur Oxides (lb/ton)	Nitrogen Oxides (lb/ton)	Organics (lb/ton)	Carbon Monoxide (lb/ton)
Raw-materials handling[d]	Negl[e]	0	0	0	0
Furnace[f]					
Uncontrolled	1.4	3.4	6.2	0.2	0.2
	(0.9-1.9)	(2.0-4.8)	(3.3-9.1)	(0-0.4)	(0-0.5)
With low-energy scrubber[g]	0.7	1.7	6.2	0.2	0.2
With venturi scrubber[h]	0.1	0.2	6.2	0.2	0.2
With baghouse[i] or electrostatic precipitator	Negl	3.4	6.2	0.2	0.2
Forming and finishing[j,k]	Negl	Negl	Negl	8.7	Negl

[a] Emissions are expressed as lb/ton of glass produced.

[b] When literature references report ranges in emission rates, these ranges are shown in parentheses along with the average emission factor. Single emission factors are averages of literature data for which no ranges were reported.

[c] Particulates are submicron in size.

[d] Particulate emissions are negligible because almost all plants utilize some form of control (i.e., baghouses, scrubbers, or centrifugal collectors).

[e] Negl = negligible.

[f] Control efficiencies for the various devices are applied only to the average emissions.

[g] Approximately 52% efficient in reducing particulate and sulfur oxide emissions. Effect on nitrogen oxides is unknown.

[h] Approximately 95% efficient in reducing particulate and sulfur oxide emissions. Effect on nitrogen oxides is unknown.

[i] Approximately 99% efficient in reducing particulate emissions.

[j] Hydrocarbon emissions are from the decorating process. Emissions can be controlled by incineration, absorption, or condensation; however, efficiencies are not known.

[k] Tin chloride, hydrated tin chloride, and hydrogen chloride are also emitted during the surface-treatment process at a rate of less than 0.2 lb/ton (0.1 kg/Mg) each.

Source: EPA (1985a).

TABLE 5.2 Emissions Produced by Transportation of Materials in the Glass-Container Production Process, Including Recycling

	Transport						Emission Rates[b]			Emissions (lb)		
Material	From	To	Length of Haul (incl. empty)	Tons of Glass and Cullet	Mode[a]	Btu	NO_x	CO	HC	NO_x	CO	HC
Sand	Various	Glass plant	100	0.501	Dump truck	60,061	15.6	9.5	3.68	1.718	1.046	0.405
Limestone	Various	Glass plant	150	0.154	Rail	9,232	370	130	94	0.025	0.009	0.006
Feldspar	North Carolina, California	Glass plant	430	0.077	Rail	13,281	370	130	94	0.035	0.012	0.009
Soda ash	Wyoming	Glass plant	1,100	0.167	Rail	73,326	370	130	94	0.196	0.069	0.050
Consumer glass	Households	Landfill	30	0.623	Packer truck	57,978	11.44	8.67	2.53	0.471	0.357	0.104
	Transfer station	Landfill	40	0.208	Transfer truck	8,304	18.98	15.92	5.35	0.347	0.291	0.098
Consumer glass	Households	MRF	30	0.623	Recycling truck	65,459	11.44	8.67	2.53	0.471	0.357	0.104
Waste glass	MRF	Landfill	40	0.031	Transfer truck	1,247	18.98	15.92	5.35	0.052	0.044	0.015
Marketable crushed glass	MRF	Beneficiation	200	0.405	Dump truck	97,253	15.6	9.5	3.68	2.781	1.694	0.656
Mixed crushed glass	MRF	Secondary material manufacture	100	0.218	Dump truck	26,184	15.6	9.5	3.68	0.749	0.456	0.177
Cullet	Beneficiation	Glass plant	200	0.385	Dump truck	92,391	15.6	9.5	3.68	2.642	1.609	0.623
Waste cullet	Beneficiation	Landfill	40	0.020	Dump truck	973	15.6	9.5	3.68	0.028	0.017	0.007
Waste	Glass plant	Landfill	40	0.000	Dump truck	2	15.6	9.5	3.68	0.000	0.000	0.000
Total										8.696	5.312	2.051

[a] Recycling and packer trucks are assumed to operate at 10 mi/h, while transfer and dump trucks run at 15 and 25 mi/h, respectively.

[b] In g/mi for trucks; lb/10^3 gal for rail.

Sources: Rail — EPA (1985b); Trucks — Guensler et al. (1991).

the bottles at 1,050°F before annealing; 95% of this material is wasted as an overspray in the form of tin oxide hydrates. The material is expensive, and it corrodes the roof; this is a possible concern for the Occupational Safety and Health Administration, so manufacturers are reported to be trying new materials (Babcock et al. 1988). These concerns are the same for new or recycled glass. A possible concern specific to recycled glass is blowing fines from cullet beneficiation. No effluents are expected from disposal of glass in landfills because the glass is inert. Effluent water contamination is summarized in Table 5.3.

Reuse avoids most of the environmental concerns and has very low direct energy requirements. However, reuse does produce washing wastes (caustic/soapy water). A complete analysis of alternatives would need to include the energy and environmental impacts of treating this water.

5.2 Landfill and Other Costs

5.2.1 Landfill Costs

The current renaissance of interest in recycling was driven not only by concern over energy, but also by concern over the difficulty and expense of finding places to put the garbage that

TABLE 5.3 Effluent Water Contamination in the Manufacture of Brown Glass

Point of Origin	Contaminant	Quantity of Contamination (g/kg glass)
Raw materials quarrying	Solids	<0.3 × 10^{-3}
	COD[a] values	<4.5 × 10^{-3}
Soda ash production	$CaCO_3$	1.02
	MgOH	0.10
	NaCl	47.94
	$CaCl_2$	107.10
	Solids	13.26
Glassworks	NA[b]	NA

[a] COD = chemical oxygen demand.

[b] NA = not available.

Source: Vogelpohl (1992).

Americans generate. Perhaps the most attention was focused on the problem when the garbage barge could not find a place to leave its load. The drive to recycle was originally motivated by material and energy conservation, but it was reinvigorated when people realized that recycling reduces the volume of material requiring disposal. Most disposal in the United States is in landfills; the cost of disposal depends on the location, with the highest costs incurred in the Northeast, where local landfills are full or nearly so, and waste is often transported long distances. Average tipping fees (and ranges) by region are shown in Table 5.4. Communities make trade-offs in terms of cost; they either dispose of material in very expensive nearby landfills, incinerate it, or pay for transport to distant, cheaper landfills. The last option results in increased energy consumption. In deciding whether to recycle, the value of the recovered material is often less than the avoided tipping fee, as can be seen in Table 5.5, and therefore the landfill cost drives the decision to recycle.

5.2.2 Labor Costs

Using current practice, recycling of glass is labor-intensive. Even a modern, automated MRF, such as the one in Montgomery County, employs people to separate different colors of glass by hand. Without this labor input, the product is a mixed cullet with little or no value. There is a choice to be made as to who performs this labor. If households put out mixed recyclables, the materials can be sorted at curbside (generally by a driver at $15/h) or the material can be placed in multipurpose vehicles and separated at the MRF (typical labor cost of $7/h). The latter choice has the advantages of increasing the number of homes served per hour from 45 to 80 and allowing the drivers a four-day, 10 h/d schedule, which they generally prefer (Edelman 1992). The higher pickup rate decreases the per-ton fuel consumption by the trucks. Therefore, it is no surprise that some local recycling services have moved away from curbside sorting.

TABLE 5.4 1990 Tipping Fees by Region

	Fees ($/ton)		
Region	Average	Minimum	Maximum
Northeast	64.76	12.00	120.00
Mid-Atlantic	40.75	6.00	89.00
South	16.92	5.25	40.00
Midwest	23.15	5.65	50.00
West Central	11.06	8.88	13.50
South Central	12.50	6.75	26.25
West	25.63	14.75	55.00

Source: Aquino (1991).

TABLE 5.5 Benefits of the Recycling Process

Recyclable Material	1990 Generation[a] (10^6 tons)	Maximum Value[b] ($/ton)	Total Value ($\$10^6$)	Avoided Tipping Fee[c] ($\$10^6$)	Benefit from Recycling ($\$10^6$)	Percent by Weight[d]	Percent of Total Value[d]	Percent of Total Benefit[d]
Newsprint, magazines	16.2	20	324	486	810	54	19	31
Aluminum cans	1.6	800	1,280	48	1,328	5	74	50
Glass containers	11.9	10	119	357	476	40	7	18
Plastic soda bottles	0.4	14	6	12	18	1	0	1
Total	30.1		1,729	903	2,632	100	100	100

[a] Source: EPA (1992).

[b] Source: *Recycling Times* (1992).

[c] At $30/ton.

[d] Percents calculated on the basis of the four materials listed only, not the entire waste stream.

However, there is also a trade-off between labor cost and recovered-material quality and quantity, which in turn means energy savings. In general, source-separated material (usually separated by hand) is cleaner and more acceptable for recycling than material that has been commingled. However, a multicompartment bin could be designed for automated curbside pickup. This system would reduce the hired-labor cost in return for greater commitment, at no greater time expense, by the household. It would also improve the quality of the recovered materials, but at the expense of capital equipment (better bins and trucks).

Another trade-off that is made tacitly trades consumer labor for significant quantities of energy. The decision to use throwaway containers in place of reusable ones is very costly in terms of energy (Gaines 1981). However, reuse is labor-intensive to the consumer and capital-intensive to drop-off locations where the bottles must be stored. "Bottle bills" have been introduced in most states but passed in few.

5.2.3 Materials Costs

Raw materials for production of glass are available locally in most areas (with the exception of soda ash shipped from Wyoming). They are not very expensive, so there is no major material cost advantage to recycling glass (although there may be some localities without low-cost sources). Therefore, cullet must be relatively inexpensive for universal use. Reusable bottles require more material per bottle than throwaways. However, because they are used multiple times, the material consumption per use is much lower.

6 Conclusions

Recycling of glass containers saves some energy, but not a significant quantity compared to reuse. The primary energy saved is about 2.2×10^6 Btu/ton, or 13% of the energy required to make glass containers from virgin raw materials. This estimate includes energy required for the entire product life cycle, starting with raw materials in the ground and ending with either final waste disposition in a landfill or recycled material collection, processing, and return to the primary manufacturing process. The actual savings depend on local factors, including population density; locations of landfills, recovery facilities, and glass plants; and process efficiencies at the specific facilities available. The savings increase if wastes must be transported long distances to a landfill or if the containers are made in an inefficient furnace. They decrease if there is no local MRF or glass plant, or if material losses in the recycling loop are high. If the MRF is as much as 100 mi away, savings from recycling are negated.

Recycling saves the energy required for raw-material production and transportation, but it uses additional energy to process and transport the recovered material. These two quantities of energy are approximately equal. Melting cullet uses less energy than melting virgin raw materials and results in a net energy saving. The fuel mix for production of glass containers from virgin raw materials differs slightly from that for recycled containers. Production of soda ash uses low-sulfur Wyoming coal, and glass melting uses natural gas. All of the energy saved is in the form of fossil fuels; there are no renewable energy sources used for glass-container production or recycling. Some additional nuclear energy might be used to generate the electricity used for recycling. The differences in energy use are small as compared with the potential savings from reuse.

The options for disposition of used glass containers can be compared on the basis of several important decision factors, including energy saved, landfill space required, and emissions. Table 6.1 gives a qualitative comparison for several options. Note that waste-to-energy is not included because glass is not combustible.[27] In order of greatest energy saved, the options for disposition of glass containers are reuse, recycling to the same product, recycling to a lower-value product, and landfill. There is no real trade-off among these alternatives; the options with minimum energy use generally are lowest in terms of other impacts as well. However, the energy savings from recycling are small, and the energy balance can be altered by local or regional conditions. In the East, where distant landfills are used and MRFs and glass plants are close, energy is saved by recycling of glass containers. In the West, however, landfills may be close but MRFs or glass plants distant, because of the low population density. In that case, recycling of glass may not save energy. However, energy use will not be the only decision criterion. Local and national decision makers may choose to examine what else is saved or replaced and what the other costs are; then they can make trade-offs involving energy use, landfill and labor costs, and environmental impacts.

---

[27] Not only is glass not combustible, but it is also not biodegradable. It is essentially inert. It will not cause any environmental problems by its presence in landfills, where it will stay forever.

TABLE 6.1 Options for the Disposition of Glass Containers

Alternative	Energy Impact	Environmental Impact	Material Sent to Landfill	Comments
Reuse	Saves most of production energy	Avoids production emissions; possible impacts from water treatment	None	Refillable bottles currently have a low market share in the United States
Recycle to containers	Small reduction in production energy	Small reduction in emissions[a]	Cullet processing losses	Bottles now made from 20% old bottles; color separation required
Recycle to fiberglass	Small reduction in production energy	Small reduction in emissions[a]	Cullet processing losses	Inefficient furnaces used
Recycle to reflective beads	Small reduction in production energy	Small reduction in emissions[a]	Cullet processing losses	Can use clean, mixed cullet
Recycle to glassphalt	Saves no energy	Full production emissions	Cullet processing losses	Can use clean, mixed cullet
Landfill	Saves no energy	Full production emissions	Maximum	Economic cost, no return

[a] Dust and SO_2 reduced, but NO_x increased.

7 References

Aquino, J., 1991, "NSWMA Releases Expanded Tipping Fee Survey," *Waste Age* 22(12):24, Dec.

Babcock, E., et al., 1988, *The U.S. Glass Industry: An Energy Perspective*, Energetics, Inc., prepared for Pacific Northwest Laboratory, Sept.

Battelle Columbus Laboratories, 1975, *Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing*, prepared for U.S. Bureau of Mines.

Chicago Tribune, 1992, "Putting Blue-Bag Recycling to the Test," p. 16, March 31.

DeLuchi, M.A., 1991, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, Volume 1: Main Text*, ANL/ESD/TM-22, Argonne National Laboratory, Argonne, Ill., Nov.

DeSaro, R., 1992, *Automatic Ceramic Separation from Recycled Glass — Results from the Engineering Study Tasks*, Busek Co., Inc., prepared for New York State Energy Research and Development Authority, Jan.

Edelman, L., 1992, personal communication, Waste Management, Inc., April.

Electric Power Research Institute, 1992, unpublished information.

EPA: see U.S. Environmental Protection Agency.

J. Fourment, 1982, "Utilisation de l'Energie Electrique pour la Fusion de Verre," Electrotechnologies in Industry, An International Conference, Montreal, May.

Gaines, L.L., 1981, *Energy and Material Use in the Production and Recycling of Consumer-Goods Packaging*, ANL/CNSV-TM-58, Argonne National Laboratory, Argonne, Ill., prepared for U.S. Department of Energy, Office of Industrial Programs, Feb.

Gaines, L.L., and A.M. Wolsky, 1979, *Discarded Tires: Energy Conservation through Alternative Uses*, ANL/CNSV-5, Argonne National Laboratory, Argonne, Ill., Dec.

Garrett-Price, B.A., et al., 1986, *Potential for Energy Conservation in the Glass Industry*, Pacific Northwest Laboratory, prepared for U.S. Department of Energy, Office of Industrial Programs, June.

Glass Packaging Institute, 1992a, *Glass: Preferred Packaging Guidelines*, draft dated May 12.

Glass Packaging Institute, 1992b, *Glass Container Industry Fact Sheet*, Central States Glass Recycling Program, Indianapolis, Ind., June.

Glass Packaging Institute, undated, citing the New Jersey Department of Environmental Protection, in *Curbside Recycling Works.*

Guensler, R., D. Sperling, and P. Jovanis, 1991, *Uncertainty in the Emission Inventory for Heavy-Duty Diesel-Powered Trucks*, Institute of Transportation Studies, University of California, Davis, Calif., June.

Hecht, R., 1992, personal communication, Allwaste, Inc., May.

Keeley, E., 1992, personal communication, DuPage County Recycling Coordinator's Office, Feb.

Mazenko, F., 1992, personal communications, Owens-Brockway, May and October.

McCann, M., 1992, personal communication, Illinois Recycling Association, April .

McMahon, E., 1992, personal communication, Advance Cullet, May.

Montgomery County Recycling Center, Maryland Environmental Service, undated, *What Happens to Your Recyclables*, Denwood, Md.

Nanky, R., 1992, personal communication, Watts Trucking, May.

Ozdarski, R., 1992, personal communications, Maryland Environmental Service, Montgomery County, Md., May and June.

Office of Management and Budget, Executive Office of the President, 1987, *Standard Industrial Classification Manual*, Washington, D.C.

OMB: see Office of Management and Budget.

Phillips, C., 1992, personal communication, Clearing Recycling & Waste Services, May.

Railroad Facts, 1991 Edition, 1991, Association of American Railroads.

Recycling Times, 1992, "The Market Page," p. 5, Aug. 11.

Renard, M., 1982, *A Review of Comparative Energy Use in Materials Potentially Recoverable from Municipal Solid Waste*, prepared for U.S. Department of Energy, Office of Conservation and Renewable Energy, March.

Sink, R., 1992, personal communication, Omaha Recycling Program, May.

Tigcheleer, C., 1992, personal communication, Resources Management, Inc., April.

Trychta, K., 1992, personal communication, DuPage County Department of Environmental Concerns, May.

U.S. Congress, Office of Technology Assessment, 1989, *Facing America's Trash: What Next for Municipal Solid Waste?*, Washington, D.C.

U.S. Department of Commerce, 1989, *1987 Truck Inventory and Use Survey*, Bureau of the Census, public use tape.

U.S. Department of Commerce, 1990a, *Sand and Gravel, 1987 Census of Mineral Industries*, MIC87-I-14B, Bureau of the Census, Washington, D.C., April.

U.S. Department of Commerce, 1990b, *Clay, Ceramic, and Refractory Materials, 1987 Census of Mineral Industries*, MIC87-I-14C, Bureau of the Census, Washington, D.C., March.

U.S. Department of Commerce, 1990c, *Chemical and Fertilizer Mineral Mining, 1987 Census of Mineral Industries*, MIC87-I-14D, Bureau of the Census, Washington, D.C., May.

U.S. Department of Commerce, 1992a, "Value of Product Shipments," *1990 Annual Survey of Manufactures*, M90(AS)-2, Bureau of the Census, Washington, D.C., Feb.

U.S. Department of Commerce, 1992b, "Statistics for Industry Groups and Industries," *1990 Annual Survey of Manufactures*, M-90(AS)-1, Bureau of the Census, Washington, D.C., March.

U.S. Department of Commerce, 1992c, *Glass Containers, Current Industrial Reports*, M32G(91)-13, Bureau of the Census, Washington, D.C., May.

U.S. Department of the Interior, 1991, *1989 Minerals Yearbook*, U.S. Government Printing Office, Washington, D.C.

U.S. Environmental Protection Agency, 1985a, *Compilation of Air Pollution Emission Factors, Volume I: Stationary Point and Area Sources,* AP-42, 4th ed., Washington, D.C., Sept.

U.S. Environmental Protection Agency, 1985b, *Compilation of Air Pollution Emission Factors, Volume II: Mobile Sources,* AP-42, 4th ed., Washington, D.C., Sept.

U.S. Environmental Protection Agency, 1992, *Characterization of Municipal Solid Waste in the United States: 1992 Update,* EPA/530-R-92-019, Washington, D.C., July.

Van Der Molen, R., 1992, personal communication, Browning-Ferris Industries, May.

Vogelpohl, H., 1992, "Beer Bottles — Ecological Considerations," *Brauwelt International* IV:385-396.

Wang, Q., 1992, personal communication, University of California, Davis, Calif., Nov.

White, A., et al., 1992, *Energy Implications of Integrated Solid Waste Management Systems,* Tellus Institute, prepared for New York State Energy Research and Development Authority, draft final report, March.

Appendix A:

Comparison to Previous Studies

This study undertook a complete, systematic analysis of the entire product life cycle (including waste treatment) using material flows to evaluate the quantity of material to be processed at each step. Previous studies were generally of more limited scope. They did not identify the key factors or perform a sensitivity analysis. Key assumptions and boundaries of the studies were often unstated or unclear. Several studies were purposely limited to the glass-plant processes, where significant energy conservation is possible. Most presented energy consumption per ton of glass melted rather than per ton of containers shipped, and thus underestimated energy use for the consumer product by about [illegible] production energy, thus understating the savings from using cullet. Most neglected the transportation and processing energy for the recycling path. None included the energy required to supply the fuels; this omission is not an error, but it means that energy consumption is reported starting at the point where the society has delivered fuels.

The quantity of primary industry data in the literature is small. Much of the information published is compiled or borrowed from previous reports, sometimes with little or no critical analysis. Even some new studies use data collected long ago. A brief description of several previous studies is presented below.

1. *Energy Implications of Integrated Solid Waste Management Systems*, A. White et al., Tellus Institute, prepared for New York State Energy Research and Development Authority, draft final report (March 1992)

This report compares the energy use and recovery for various collection, processing, and disposal options for 13 products. The energy consumption estimates include transport and a rough estimate for cullet beneficiation, but not for MRF processing (not a serious omission). Transport of wastes to the landfill is not included. The basic idea is good, but the data used are of varying quality. Melting energy appears to be new industry data, but the raw-material energy relies on a 1975 Battelle report, which in turn used 1970 census data. The energy is reported per ton of molten glass.

There were several minor problems with the draft report that will probably be corrected in the final version, which was scheduled to be published in January 1993 (as of the publication date of our report, the Tellus report has not yet been published). For example, some of the notes were unrelated to the topic where they were cited, and the addition in one of the glass tables appeared to be incorrect.

2. *The U.S. Glass Industry: An Energy Perspective*, E. Babcock et al., Energetics, Inc., for Pacific Northwest Laboratory (September 1988); and *Potential for Energy Conservation in the*

Glass Industry, B.A. Garrett-Price et al., Pacific Northwest Laboratory, prepared for DOE Office of Industrial Programs (June 1986)

These two reports are grouped together because the Energetics report is an update of the Pacific Northwest Laboratory report. The two reports are very similar. Both look at the primary glass-production processes only; there is practically no information on the recovery portion of the glass life-cycle loop. They focus on melting technologies because these offer the greatest potential for conservation. There is great detail on state-of-the-art and advanced (year 2010) technologies to save energy in glass manufacture. Much detail is given on furnace design and energy efficiency. The technologies discussed will, of course, save energy regardless of whether or not the material is recycled.

The reports estimate energy use, including conversion losses for electricity generation, but not the production efficiency of the fuels. There is no estimate of material production or transportation energies. Thus, they report the consumption of processed fuels for processing at the glass plant only. They present a wide range of energy use, which is probably realistic, and the average for current practice. It is difficult to evaluate the data because no sources are given.

3. *Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing*, Battelle Columbus Laboratories, prepared for U.S. Bureau of Mines (1975)

We did not consider this early Battelle report because it is so old. However, we mention it because it was used as a source in the Tellus report. The Battelle report was a good, useful reference, but the data in it are over 20 years old. Therefore, the data may not reflect the current industry status because of increased efficiency and a shift in the fuel mix to increased electricity use, essentially eliminating oil. This report presented the overall energy per ton of glass melted, including all of the important inputs. There was no analysis of recycling paths.

4. *A Review of Comparative Energy Use in Materials Potentially Recoverable from Municipal Solid Waste*, M. Renard, prepared for U.S. Department of Energy, Office of Conservation and Renewable Energy (March 1982)

This work is a review of some of the work available in 1982 (it missed the Arthur D. Little series for the EPA and the Argonne studies for DOE, among others). The Renard work is entirely based on this incomplete literature review and uses no manufacturers' process data. The report begins by asking the right questions to compare virgin materials with recycled ones. However, the analysis neglects transport and processing energy for recycled glass. The author recognizes the need to specify the boundaries and basis for the study, but he doesn't do so clearly. We would have liked to see the author's best estimates for glass process energies summarized into a table.

The general discussion describes levels of energy analysis and their relation to thermodynamics, but then makes little use of the information. The numbers he uses form a simple second-order direct energy analysis (except for the missing recycling loop). The report's biggest fault is the lack of critical evaluation and synthesis of the information gathered. The key factors in the analysis are not identified. Instead of attempting to evaluate each source on its own, the sources are compared, and electricity conversion was either assumed or not to make the sources look consistent. There is no reason to believe, as the author seemed to, that industry practices are uniform or that published reports are consistent.

There are several apparent errors in handling the data. The author assumes that the melting process uses the average industry fuel mix in order to estimate savings due to cullet melting. However, melting uses a higher percentage of gas, and so the conversion to primary energy isn't quite right. Some of the data used were per ton of glass melted and some per ton of glass shipped; these data do not appear to have been reconciled. In addition, to obtain overall savings, he divided by the percent of process energy that melting represents instead of multiplying by it. All things considered, the analysis in this report is far from complete.

5. *Facing America's Trash: What Next for Municipal Solid Waste?*, U.S. Congress, Office of Technology Assessment (19[illegible])

This report presents an overview, with no analysis, for a number of materials. There is a competent summary of the situation regarding glass production and recycling, including economic factors. However, the report relies on numbers from the Renard report, which are presented with little explanation, and this is a serious flaw. There is little detail on the processes or where and how the energy is used.

6. *Energy and Material Use in the Production and Recycling of Consumer-Goods Packaging*, L. Gaines, Argonne National Laboratory, prepared for U.S. Department of Energy, Office of Industrial Programs (February 1981)

This report presents a quick comparison of energy use among several packaging options. It assumes that transportation and processing in the recycling loop are not major energy inputs (this is a correct first approximation for most materials). The report points out the key factors and demonstrates the types of trade-offs that recycling poses. Energy-consumption estimates for production of several of the virgin materials and for recycling of PET plastic are based on previous detailed Argonne studies of energy and material use in energy-intensive industries.

Appendix B:

Comparison of Energy Use for Separate and Mixed Collection

It has been claimed that curbside sorting increases transportation energy intensity. This cannot be verified. Because the same number of homes must be served, it is immaterial whether one or more vehicles serve the collection route, provided that the number of miles traveled remains constant. For example, with curbside sorting, three vehicles can collect nine tons of recyclables per day from 1000 homes; with mixed collection, two vehicles can collect the same quantity of recyclables (and then some) in two trips.

Curbside Recycling

A vehicle servicing 45 homes per hour, picking up 18 pounds per setout, could collect 810 lb/h. Assuming an average load of 3 tons, the vehicle would fill in 7.4 hours and 333 homes would be served. Thus, three vehicles are needed to serve 1,000 homes. Assuming 20 mi as an average distance to/from the garage facility, 25 mi as an average distance to/from the MRF, and frontage of 80 ft (counting cross streets, other land uses, etc.), 150 mi would be traveled by these three vehicles.

Mixed Collection

A vehicle servicing 78 homes per hour, picking up 18 pounds per setout, could collect 1,400 lb/h. Assuming an average load of 2.5 tons (3 tons is probably not feasible for two runs in a 10-hour day), the vehicle would fill in 3.6 hours. By adding a second run, 560 homes could be served. Thus, two vehicles are needed to serve 1,100 homes. Assuming 20 mi as an average distance to/from the garage facility, 25 mi as an average distance to/from the MRF, and frontage of 80 feet (counting cross streets, other land uses, etc.), 195 mi would be traversed by these two vehicles. If one were to reduce this by the extra 10% homes served, the comparison becomes 150 vs. 175 mi/d. Assuming additional idling for the curb-sort alternative, consumption could easily be comparable.

In fact, figures obtained from Browning-Ferris Industries, which operates both curb-sort and mixed-collection routes show no difference in the daily mileage or fuel use for the two alternatives (Van Der Molen 1992).

DISTRIBUTION FOR ANL/ESD-18

Internal

ANL Technical Publications Services
N. Clodi (6)
E. Hathaway
D. Weeks
L. L. Gaines (60)

External

U.S. Department of Energy Office of Scientific and Technical Information (12)
Manager, U.S. Department of Energy Chicago Field Office
ANL-E Libraries (2)
ANL-W Library

Document Control Page	1. NREL Report No. NREL/TP-430-5703	2. NTIS Accession No. DE94000288	3. Recipient's Accession No.

4. Title and Subtitle

Energy Implications of Glass-Container Recycling

5. Publication Date
February 1994

6.

7. Author(s)
L.L. Gaines and M.M. Mintz
Energy Systems Division, Argonne National Laboratory

8. Performing Organization Rept. No.

NREL/TP-430-5703
ANL/ESD-18

9. Performing Organization Name and Address

Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

10. Project/Task/Work Unit No.
WM411010

11. Contract (C) or Grant (G) No.
(C)DA-1-11157-1

(G)

12. Sponsoring Organization Name and Address

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Note
NREL technical monitor: Philip B. Shepherd, (303) 231-7000, x7829

16. Abstract (Limit: 200 words)

This report addresses the question of whether glass-container recycling actually saves energy. Previous work has shown that to save energy when using glass bottles, reuse is the clear choice. Recycling glass does not save much energy or valuable raw material and does not reduce air or water pollution significantly. The most important impacts are the small reduction of waste sent to the landfill and increased production rates at glass plants.

17. Document Analysis
a. Descriptors
landfills, glass, glass recycling, postconsumer waste, energy consumption

b. Identifiers/Open-Ended Terms

c. UC Categories
249

18. Availability Statement
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

19. No. of Pages
80

20. Price
A05

Form No. 0069E (6-30-87)