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ENERGY AND MATERIALS USE IN THE PRODUCTION AND RECYCLING OF CONSUMER-GOODS PACKAGING

by

L.L. Gaines

Energy and Environmental Systems Division
Special Projects Group

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PREFACE

This report has been prepared for the U.S. Dept. of Energy for distribution to interested persons concerned about the consumption of scarce resources for packaging. It compares the energy requirements for the production and recycling of several types of packaging materials used for consumer goods. The data are derived primarily from a series of detailed reports on the energy and materials flows in energy-intensive industries prepared by Argonne National Laboratory for the Alternative Materials Utilization Branch of the Office of Industrial Programs in the U.S. Dept. of Energy's Conservation and Solar Energy Division. Additional data were obtained from several other technical reports on materials production and use. In order to keep the document brief and easily understood, the results are presented without the details of the process analyses from which they are derived.

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ABSTRACT

The energy consumed annually in the United States to produce paper, glass, steel, aluminum, and plastic for consumer-goods packaging is 2.4 quad.* This report compares these types of packaging, not only with respect to total energy use but also with respect to types of energy used for production. Energy saved through recycling and combustion for energy recovery also is considered. A maximum of 1.5 quad could be saved if this packaging material were recycled, and about 0.6 quad could be recovered if it were burned as part of municipal solid waste. Paper and plastic compete in several markets, including bags and milk containers: in almost all cases, the plastic container requires less energy to produce and recycle. However, the major energy input to paper manufacture is wood, rather than oil and natural gas. Glass bottles require less energy to produce than aluminum or steel cans. On the other hand, aluminum cans take less energy to recycle than bottles, and recycled aluminum cans are the least energy intensive of the single-serving beverage containers, except for refillable glass bottles that are reused several times. For family-sized beverage bottles, a plastic bottle uses less energy to make and to recycle than a glass bottle. In addition, plastic bottles are combustible. However, glass bottles could be made with no oil or natural gas input, and they can be reused.

1 INTRODUCTION

Large quantities of packaging materials are produced in the United States only to be discarded as soon as the contents of the packages are consumed. This report discusses the energy required to produce the more common types of packaging and considers possible reductions in energy use through material substitution, reuse, recycling, and energy recovery through combustion of municipal solid waste.

The packaging materials selected for this study are paper, glass, steel, aluminum, and plastic. The energy consumed in producing these raw materials for package manufacture is 2.4 quad annually; energy requirements are discussed in detail in Sec. 2. The methodology employed adds energy

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*1 quad = 1 quadrillion Btu.

for fuel and feedstock at each production step, from raw material extraction through fabrication, to give the total energy requirements per pound of packaging material made from virgin materials. A similar analysis is carried out for recycled material. To keep the report brief and easily understood, only the results of earlier detailed process analyses are presented.

Competition among these materials for specific container markets is discussed in Sec. 3. Paper and plastic compete in the bag, milk container, meat tray, and cup markets. Aluminum, steel, and glass are widely used for the production of single-serving beverage containers, while glass and plastic compete for the family-sized soft-drink bottle market. Energy use is compared for virgin, recycled, and reused containers. The feasibility of recycling these containers and the possibility of recovering some of their embodied energy through combustion of municipal solid waste instead of, or subsequent to, recycling also are discussed briefly. Section 4 is a summary of the results.

2 MATERIALS USED TO PACKAGE CONSUMER GOODS

The predominant packaging materials are paper, glass, steel, aluminum, and plastics (polyethylene, polystyrene, polyvinyl chloride, and polyester). These materials account for 75% of all packaging materials used in the United States. Table 1 gives annual production figures and energy use data for these materials. The annual volume of packaging is about 600 lb/person/yr, most of which becomes part of municipal solid waste. Energy used for the production of these five materials for packaging applications totals 2.4 quad annually, or 3% of the national energy budget. More than 0.6 quad (70% from paper) could be recovered by burning these packaging wastes as part of a program of energy recovery through combustion of municipal solid waste. However, a maximum of 1.5 quad could be saved if these packaging materials were recycled. (See Table 1 for a breakdown of savings by material.) If recycling of the specific container types discussed in this report (soft-drink cans and bottles, paper and plastic bags, and milk bottles) could be achieved, 0.5 quad would be saved. Recycle of aluminum cans alone would save almost 0.2 quad.

Section 2 includes a discussion of the energy required to produce one pound of each predominant packaging material. In the absence of detailed information about the energy required for container fabrication, the reader can use the per pound energy requirements to approximate the energy intensiveness of competing packages of known weights.

2.1 PAPER

Over 50 billion lb of paper products are used annually in the United States for packaging (about 230 lb/person). These products can be classified into the types listed in Table 2. About 75% of the energy input to these paper products is the heat of combustion of wood, which serves as a material input and as a source of by-product fuel. The rest of the energy is purchased: about 30% of this energy is electricity,* and most of the remainder is oil and natural gas. Coal could be substituted directly for the oil and natural gas used in paper manufacture and could be used to generate the required electricity.

Paper can be recycled at a purchased-energy cost of about 11,500 Btu/lb. Although this is a savings (based on total energy input) of approximately 20,000 Btu/lb, it does represent an increase of about 4000 Btu/lb in fuel purchased. Thus, a policy to minimize total energy consumed or to conserve wood resources would call for paper recycling, while a policy to minimize oil and natural gas consumption would require all new paper.** In the second alternative, paper waste could be burned to recover 8500 Btu/lb. If all paper packaging wastes were burned, about 0.4 quad would be

*A 10,500 Btu/kWh conversion factor was used to reflect 33% efficiency in electricity generation.

**This does not hold for newsprint.

Table 1 Packaging Materials Energy Use

Material	Form	Annual Production (million lb)	Packaging Percentage	Energy Used to Produce Packaging Material (trillion Btu)	H_c[a] (trillion Btu)	E_r[b] (trillion Btu)
Paper	Rolls or liner stock	120,000	43	1,260	439	760
Glass	Containers	30,000[c]	100	261	0	65
Steel	Sheet	210,000	6[d]	287	0	88
Aluminum	Sheet	13,000	18[e]	281	0	236
Low-density polyethylene	Pellets	7,800	62	186	97	181
High-density polyethylene	Pellets	5,000	45	82	45	80
Polystyrene	Pellets	4,000	36	49	26	47
Linear low-density polyethylene	Granules	1,000	80	26	16	25
Polyester (PET)	Pellets	4,200	7[f]	14	4	12
Polyvinyl chloride	Pellets	5,100	7	11	3	10
Total[g]		401,000		2,450	630	1,500

[a]Heat of combustion recoverable by burning municipal solid waste.

[b]Energy recoverable with 100% recycling (see Secs. 3.1.4, 3.2.4, and 3.3.4).

[c]Excludes flat glass.

[d]Cans only.

[e]Sheet only (excludes foil).

[f]Bottles only.

[g]Rounded.

Table 2 Paper Packaging Products

Type	Annual Production of Materials to Be Used for Packaging (million lb)	Production Energy (Btu/lb)[a]	Typical Use
Natural kraft paper	8,400	26,200	Grocery bag
Bleached kraft paper	1,900	32,100	Fast-food bag
Natural linerboard	20,400	25,300	Carton
Bleached board	7,600	33,400	Milk container
Corrugating medium	13,200	16,050[b]	Carton

[a]Includes heat of combustion of wood (8500 Btu/lb).

[b]Thirty percent waste materials used as input.

recovered annually. This is equivalent to 33% of the total energy required to manufacture the products burned. Combustion of paper packaging wastes would displace about 32 billion lb of coal annually.

2.2 GLASS

About 30 billion lb of glass containers (bottles and jars) are produced annually in the United States at an energy cost of approximately 8700 Btu/lb. Over 70% of this energy is natural gas. Although coal could be used at greater than its current 18% level, manufacturers of glass containers do not foresee a shift to coal. About 10% of the energy used in glass manufacture is electricity, which could be generated in coal-fired power plants.

Glass can be recycled. However, recycling saves only about 25% of the energy used for manufacturing glass from virgin materials, because used glass must be remelted at nearly the same high temperature as raw materials for new glass (2700°F). Reusing glass, on the other hand, saves almost all of the energy needed to make new glass. The only energy cost that can be attributed to glass reuse is any additional energy to transport a refillable bottle to a bottler rather than to a landfill and any additional energy required to wash and sterilize a refillable bottle compared to a new one. However, refillable bottles require more energy to make, because they are usually about 50% heavier (to minimize breakage) than the equivalent nonrefillable bottle.

2.3 STEEL

About 13 billion lb of steel (6% of U.S. production) are used for making cans. Production of virgin steel sheet requires 22,800 Btu/lb. About 50% of this energy is supplied by coal, another 10% by electricity, and much of the rest by oil and natural gas. More of the electricity could be generated by coal-fired power plants, and coal could be substituted for the oil and natural gas used directly.

Although steel can be recycled, about 50% of the energy consumed to make sheet is required for fabricating (casting and rolling), which must be repeated for the recycled product. Therefore, recycling achieves about a 30% reduction in the energy requirements for steel sheet.

2.4 ALUMINUM

Aluminum sheet for packaging applications consumes 2.3 billion lb or about 18% of U.S. aluminum production. The energy required to make virgin aluminum sheet is about 120,000 Btu/lb. Half of this energy is electricity, and most of the remainder is oil and natural gas. Direct use of coal and coal-based electricity are possible.

About 80% of U.S. aluminum ore (bauxite) requirements is imported. While recycling aluminum diminishes our dependence on an imported raw material, it also reduces energy requirements for sheet production to about 19,100 Btu/lb, most of which is oil and natural gas used for process heat during fabrication.

2.5 PLASTICS

Over 10 billion lb of plastic are used annually for packaging in the United States, almost 80% of which is low-density and high-density polyethylenes and the new linear low-density polyethylene. Polystyrene, polyester, and polyvinyl chloride account for most of the rest. The energy required to produce these materials is shown in Table 3. Note that more than 50% of the total energy input is feedstocks based on oil or natural gas. Substitutes for these materials based on coal or biomass cannot be produced economically using technologies either currently available or under development.

If a clean, separated waste stream is available, plastics can be recycled to displace new oil and natural gas by remelting at an energy cost of about 1000 Btu/lb. Numerous techniques for separating individual plastics from mixtures of plastics and for using mixed plastic wastes directly are under development. However, separation is difficult and no economical separation technique is now available. Combustion of plastic waste recovers an average of slightly more than 50% of the energy required for production. However, combustion displaces only coal and not the oil and natural gas feedstocks used for production.

Table 3 Plastic Packaging Products

Plastic	Annual Production of Packaging Materials (million lb)	Production Energy (Btu/lb)	Feedstock[a] (%)	Electricity (%)	Oil and Natural Gas[b] (%)	H_c[c] (Btu/lb)
Low-density polyethylene	4,840	38,500	73	17	10	20,000
High-density polyethylene	2,250	36,500	75	10	15	20,050
Polystyrene	1,440	34,300	69	4.5	26.5	17,800
Linear low-density polyethylene	800	32,100	86	6	8	20,000
Polyester (PET)	300	48,700	51	10	39	11,400
Polyvinyl chloride	430	25,600	49	26	25	7,700

[a] Sum of heats of combustion of material inputs for all process steps starting with oil and natural gas.

[b] Consumed as fuel.

[c] Heat of combustion (higher heating value).

3 MATERIALS COMPETITION

3.1 PAPER VERSUS PLASTIC FOR CONSUMER-GOODS PACKAGING

Plastics are somewhat more energy intensive per pound than paper, with ratios of energy inputs of 1-1.3, depending on the specific materials involved. However, paper products generally are heavier than equivalent plastic products. The relative weight ratios are 1.4-2.8 for bags, 1.8 for milk cartons, 0.8-1 for cups, and 3.7 for meat trays. To minimize total energy inputs, plastic bags, milk containers, and meat trays should be used but not plastic cups. If oil and natural gas use is to be minimized, paper is preferable for all these applications, because its manufacture consumes only 20% as much oil and natural gas per pound as does plastics manufacture.

If the containers are burned, plastic has less energy foregone* per container than all the paper containers considered, except the 16-oz cold drink cups. If packaging is recycled, the energy advantage of plastic over paper increases, because the energy required to recycle paper is relatively high (about 11,500 Btu/lb). Recycled paper and recycled plastic use about the same quantity of oil and natural gas; both use more of these fuels than virgin paper.

3.1.1 Markets

Paper and plastic compete in the following major markets for consumer-goods packaging:

- Bags (natural or bleached kraft paper versus high-density polyethylene film),
- Milk containers (bleached linerboard versus blow-molded high-density polyethylene),
- Disposable cups (bleached board versus thermoformed impact-grade polystyrene), and
- Meat trays (pressed pulp versus foamed polystyrene).

Manufacture of paper bags accounts for approximately 50% of total annual U.S. kraft consumption, or 4 billion lb of kraft. Plastic bags account for about 4% of high-density polyethylene use, or 200 million lb. Plastic bags are expected to have 35% of the bag market by 1983. Natural (brown) kraft paper generally is used for self-opening stand-up (SOS) grocery bags. Plastic bags have found limited application in grocery markets, i.e., small bags for wet or frozen foods and larger bags with handles for consumers needing to carry one or more bags of groceries a long distance.

Fast-food applications use self-opening stand-up bags made from bleached kraft. Plastic is not used in this market because of the greater cost of a plastic bag stiff enough to stand up. The relative market shares of

*Energy input minus product heat of combustion.

paper and plastic bags in grocery and fast-food applications are summarized in Table 4. However, plastic is rapidly penetrating the merchandise bag market (see Table 5) and is expected to account for 50% of such bags by 1983. These pinch-bottom bags are already used in retail stores to package soft goods and notions. Thin polyethylene bags (0.85 mil) are now competitive in price with bleached kraft and are expected to be nearly competitive with natural kraft by 1988. Even thinner gauges are now possible with the new linear low-density polyethylene bags. Another advantage is that the lower density of this material means that fewer pounds are required to produce bags of a given thickness. Therefore, this material will have a price advantage for future market penetration as well as considerably lower energy requirements.

Plastic is rapidly gaining ground on plastic-coated cartons in the milk container market (see Table 6). Glass is no longer used to any appreciable extent. About 1.6 billion lb of milk carton stock and 460 million lb of high-density polyethylene (9% of total usage) are consumed to make milk cartons, with half gallon and gallon sizes predominating. Most of the plastic is used for the gallon size, for which plastic and board prices are approximately equal.

Disposable cups in a variety of sizes (3-20 oz or more) are used in household, vending, institutional, and fast-food applications. The fast-food market is the most important, now consuming more than 25% of the 95 billion cups used annually. This market is expected to grow at greater than 15% per year. The average American visits a fast-food outlet on nine occasions per month -- five times to eat in and four times to take out. The polystyrene cup is cheaper than paper in the 9-oz size but more expensive in the 16-oz size because of the added material needed (see Table 7). Fast-food chains generally prefer paper because their logos can be imprinted easily. About 1.4 billion lb of paper and plastic are used annually to make disposable cups. Information on relative market shares is unavailable.

Table 4 Self-Opening Stand-up Bag Applications, 1978 and 1983

Market	1978	1983
Grocery		
Kraft volume (billion bags)	37	36
Polyethylene volume (billion bags)	10	15
Total (billion bags)	47	51
Polyethelene share (%)	21	30
Estimated polyethylene volume (million lb)	100	150
Fast-Food		
Kraft volume (billion bags)	17	18.7
Potential for polyethylene to replace kraft (million lb)	300	330

Table 5 Replacement Pattern, Plastic versus Paper Merchandise Bags, 1976, 1978, 1979, and 1983

Market Parameter	1976	1978	1979	1983
Total kraft bag shipments (million lb)	460	416	404	276
Total high-density polyethylene bag shipments (million lb)	20	42	56	124
Bleached kraft bag shipments (billion bags)	1.7	1.6	1.1	0.5
Natural kraft bag shipments (billion bags)	9.6	8.8	8.7	6.3
Total kraft bag shipments (billion bags)	11.2[a]	10.4	9.8	6.8
Total high-density polyethylene bag shipments (billion bags)	0.8	1.8	2.6	6.8
Total merchandise bag shipments (billion bags)	12.0	12.2	12.4	13.5[a]

[a]Columns do not always add because of rounding.

Source: Ref. 1.

Table 6 Market Trends of Milk Containers, 1968, 1978, and 1983 (%)

Market Parameter	1968	1978	1983
Container			
Cartons	74	66	40-42
Bulk pack carton bag	6	5	3
Glass	12.5	2	1
Nonreturnable plastic	7	30	48-50
Returnable plastic	0.5	0.5	2
Size			
Half gallon	53	30	28
Gallon	16	46	50

Source: Ref. 1.

Table 7 Summary of Energy Inputs for Paper and Plastic Packaging

Package	Weight (lb)	Material	Input Energy (Btu/unit) Wood	Purchased	Total	Energy Parameters (Btu/unit) H_c[a]	E_f[b]	E_n[c]	1978 Price (¢)
Bags									
12-lb grocery	0.032	Natural kraft paper	640	240	880	270	610	410	0.82
12-lb fast-food	0.032	Bleached kraft	780	270	1050	270	780	390	0.96
12-lb high-density polyethylene	0.023	High-density polyethylene	0	1010	1010	460	550	190	1.8
17-lb merchandise	0.065	Bleached kraft	1570	540	2110	550	1560	750	1.9
17-lb natural	0.065	Natural kraft	1290	440	1730	550	1180	750	1.6
17-lb high-density polyethylene, 1 mil	0.030	High-density polyethylene	0	1290	1290	600	690	230	2.3
17-lb high-density polyethylene, 0.85 mil	0.023	High-density polyethylene	0	990	990	460	530	160	1.9
Milk containers									
Half gallon	0.152	Bleached board	3430	1330	4760	1430	3330	1720	5.1
	0.084	High-density polyethylene	0	3600	3600	1670	1930	630	6.9
Gallon	0.253	Bleached board	5670	2180	7850	2340	5510	2860	8.2
	0.143	High-density polyethylene	0	5770	5770	2860	2910	690	8.7
Cold cups									
9-oz	0.012	Bleached board	293	160	450	100	350	180	1
	0.012	Polystyrene	0	480	480	210	270	80	0.9
16-oz	0.022	Bleached board	540	240	780	190	590	300	1.5
	0.029	Polystyrene	0	1130	1130	520	610	170	1.7
Meat trays									
6 x 8.5 in.	0.035	Pressed pulp	280	360	640	300	340	430	1.2
	0.0095	Polystyrene	0	330	330	160	170	70	0.9

[a]Heat of combustion of product (higher heating value).

[b]Energy foregone equals energy input minus product heat of combustion.

[c]Energy needed to recycle container, including fabrication.

Foamed polystyrene has rapidly penetrated the meat tray market because it is extremely light and has a low price. More than 80% of all meat and poultry trays in grocery stores and 35% of egg cartons are made of polystyrene. These tray and carton applications annually consume about 120 million lb and 60 million lb of polystyrene, respectively, which accounts for about 5% of total U.S. polystyrene consumption. Pulp for the same uses totals roughly 280 million lb annually.

3.1.2 Material Comparison

Both plastic and paper have advantages that influence the choice of one or the other by merchants or consumers. Paper is often cheaper, especially if a naturally colored package is satisfactory, but relative costs depend mostly on the amounts of materials required for the product. Paper sacks can be made to stand up easily; they are easier to open and don't stick together. In addition, paper cups can be imprinted easily.

Plastic is waterproof and greaseproof, both of which are important features for food-bag applications. Plastic bags can be manufactured in any color and have excellent graphics possibilities. They have better tear and puncture strength and can be made with handles. In addition, delivery times are short, which avoids the need for large bag inventories.

Plastic milk containers are stronger than cartons. They can be blow-molded in the dairy, which keeps them sanitary and reduces freight and inventory costs.

3.1.3 Energy Requirements

The total energy consumed in producing the plastic and paper products discussed in Sec. 3.1 is about 0.2 quad annually. This energy comprises both the fuels purchased and the energy content of the material inputs to the processes. In general, coal can substitute for purchased fuels but not for feedstocks. For plastics manufacture, the feedstocks are oil and natural gas, which account for as much as 75% of the total energy input. For paper, the input is wood, which contributes almost 80% to the total energy input. Until recently, only that part of the wood feedstock that was later consumed as by-product fuel to run the process was included in the energy accounting for paper manufacture. However, since wood as a fuel is now receiving more emphasis, the energy content of wood should be included in the total energy inputs to papermaking.

On this basis, the total energy input per pound of plastic is as much as 28% more than for a pound of paper (see Table 8). However, the ratio of unit weights of paper to plastic packaging varies from less than 1 (16-oz cups) to over 3.5 (meat trays); it is generally high enough so that the total energy input per unit for a plastic product is somewhat less than that for an equivalent paper product (see Table 7). Energy requirements for paper and plastic products are compared in Fig. 1. Since wood is the predominant energy input to paper product manufacture, policymakers may well decide to use this abundant and renewable domestic resource in preference to oil, much of which is imported.

Table 8 Total Energy Inputs for Plastic and Paper

Material	Feedstock (%)	Electricity (%)	Oil and Gas (%)	Total (Btu/lb)
High-density polyethylene	75[a]	10	15	36,500
Polystyrene	69[a]	4.5	26.5	34,300
Paper	79[b]	5.9	11.5	26,200[c] 32,100[d] 33,400[e]

[a]Oil and natural gas.

[b]Wood.

[c]Natural kraft.

[d]Bleached kraft.

[e]Bleached board.

3.1.4 Recycling

Plastic can be recycled (remelted) at the very low energy cost of about 1000 Btu/lb, but mixtures of plastics need to be separated to produce a high-quality product. When a clean stream of a single plastic is available, most of the energy required to make the product is recovered. Although the barriers to recycling of plastics are mainly institutional, there are technical problems with separating a stream of mixed plastics.

Paper recycling requires roughly 11,500 Btu/lb or about 35% of the energy required to make new paper. However, energy for recycling is purchased fuel, mostly in the form of oil and natural gas. This amount of oil and natural gas is twice that needed for the manufacture of new paper. Thus, policies designed to minimize oil and natural gas consumption might require promoting the use of virgin paper instead of recycled paper or plastic substitutes.*

Almost all paper packaging is discarded and finds its way into the municipal solid waste stream. Since recycling municipal solid waste would require separation and cleaning, recycling discarded paper packaging is not expected to become economic. However, both paper and plastic in municipal solid waste have considerable value as fuels (8,500 Btu/lb and 20,000 Btu/lb, respectively). In the absence of recycling, combustion of solid waste for heat recovery would minimize net energy use for these packaging materials.

3.1.5 Collection

The key to a successful recycling system is inexpensive collection of materials containing a small number of well-known components. One promising

*This does not hold for newsprint.

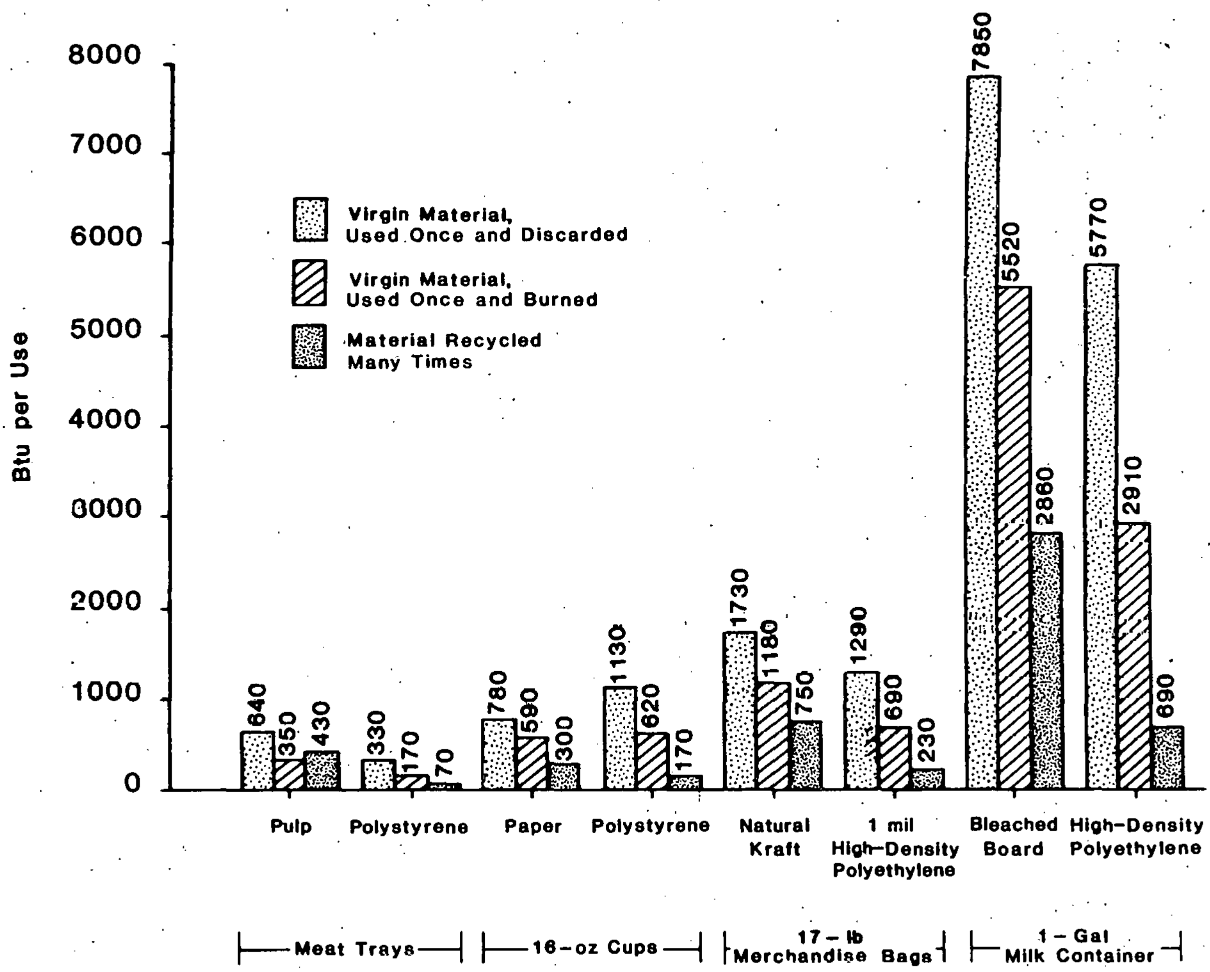

Fig. 1 Energy Consumption per Use for Representative Paper and Plastic Packages

candidate is plastic milk bottles, which could be returned to retail outlets, compacted, and perhaps sent back to their place of origin as a return (back-haul) cargo. Refillable milk bottles (glass, heavy-gauge polyethylene, or polycarbonate) consume the least energy per unit of product delivered. These bottles are economic if they make 20 or more trips, the number depending on the material. However, neither the consumer nor the dairy wants the added bother of dealing with returns.

Supermarket bags could be collected, but they often are used for trash and other purposes. Recycling of merchandise bags is less promising, but they could be collected as part of a separate plastic or paper stream coming from segregated municipal solid waste collection. Paper, plastic, and noncombustibles would have to be kept separate. Given present technology, products separated from mixed municipal solid waste can be recycled only to low-grade uses. Therefore, combustion of municipal solid waste for heat recovery is more promising at this time.

Cups, bags, and other packaging at fast-food outlets (e.g., polystyrene hamburger containers) could probably be separated at the source or collected and then separated before recycling. To increase revenues, it would be more economic to recover more than one material. If energy conservation were judged to be of primary importance and the public still demanded throwaway packaging, a single material (e.g., polystyrene or paper) could be used for all cups, hamburger containers, etc., for a chain of fast-food outlets. The entire waste stream could then be recycled without separation.

3.2 GLASS, ALUMINUM, AND STEEL FOR SINGLE-SERVING BEVERAGE CONTAINERS

For single-serving beverage containers, glass bottles compete with aluminum cans and steel cans with aluminum tops. Although glass bottles require considerably less energy per pound than either of the alternatives, both nonrefillable and refillable bottles are much heavier than cans. If containers are used once and discarded, glass bottles require the least energy per use. Aluminum manufacturers now rely primarily on electricity, steel manufacturers on coal, and glass manufacturers on natural gas. However, all could use coal as their primary fuel. None of these three containers is combustible.

If an aluminum can is recycled twice, it has approximately the same energy requirements per use as an equivalent nonrefillable glass bottle. Recycled nonrefillable glass bottles and aluminum cans have approximately the same energy requirements if they are recycled a large number of times. The relevant ratios, which were calculated using energies for fabricated containers, are summarized in Table 9. Energy requirements for bottles and cans are shown in Fig. 2. The minimum energy per use for single-serving beverage containers is achieved with refillable bottles that are eventually recycled.

3.2.1 Markets

Beer and soft drinks in single-serving containers (usually 12 or 16 oz) are sold in grocery stores, vending machines, and restaurants. The containers are glass bottles (nonrefillable or refillable), aluminum cans, or steel cans with aluminum tops. Plastic bottles are currently used only for containers of one quart and larger, but half-liter plastic bottles are being test-marketed. Plastic cans are not yet available in the United States.

The market shares for the different beer and soft-drink packages are shown in Table 10. The market shares for cans are expected to stay relatively constant at 39% for soft drinks and 62% for beer, with steel cans gaining slightly on aluminum, which now accounts for about 65% of all beverage cans. This shift can probably be attributed to the small price advantage steel cans have over aluminum cans. Although glass bottles are already cheaper than cans, mandatory deposit legislation could provide additional impetus for increasing the share of the soft-drink and beer markets now held by glass bottles.

3.2.2 Package Comparison

Cans have several advantages over bottles: (1) cans stack better and more compactly, (2) cans are lighter, (3) cans do not break, and (4) cans

Table 9 Energy Ratios of Fabricated Single-Serving Beverage Containers[a]

	Glass	Steel	Aluminum
E_{in}/lb[b]	1	7	18
E_n/lb[c]	1	6.5	9
Weight/container	10[d]	2	1
E_f/use[e]			
New product	1	1.4	1.4
Recycling			
1X	0.9	1.2	1.2
10X	0.8	1	0.8

[a]Units are arbitrary.

[b]Energy input per pound of product.

[c]Energy needed to recycle a pound of product (see Secs. 3.1.4, 3.2.4, and 3.3.4).

[d]Nonrefillable.

[e]Energy foregone per use equals energy input minus product heat of combustion, divided by number of uses.

Table 10 Beer and Soft-Drink Packaging, 1978 and 1982

	Aluminum Cans		Steel Cans		Nonrefillable Glass		Refillable Glass		Plastic		Total	
Container	1978	1982	1978	1982	1978	1982	1978	1982	1978	1982	1978	1982
Soft drink												
Volume[a]	25.3	40.0	12.4	17.2	23.0	26.0	35.3	36.7	2.4	12.1	98.4	132.0
Total (%)	25.7	25.2	12.6	14.0	23.4	21.2	35.9	29.8	2.4	9.8	100	100
Beer												
Volume[b]	22.6	23.6	5.7	11.9	15.0	17.7	3.5	4.0	0	0	46.8	56.5
Total (%)	47.2	41.2	14.1	20.8	31.3	31.0	7.4	7.0	0	0	100	100

[a]Billion equivalent 8-oz units.

[b]Billion equivalent 12-oz units.

Source: Ref. 1.

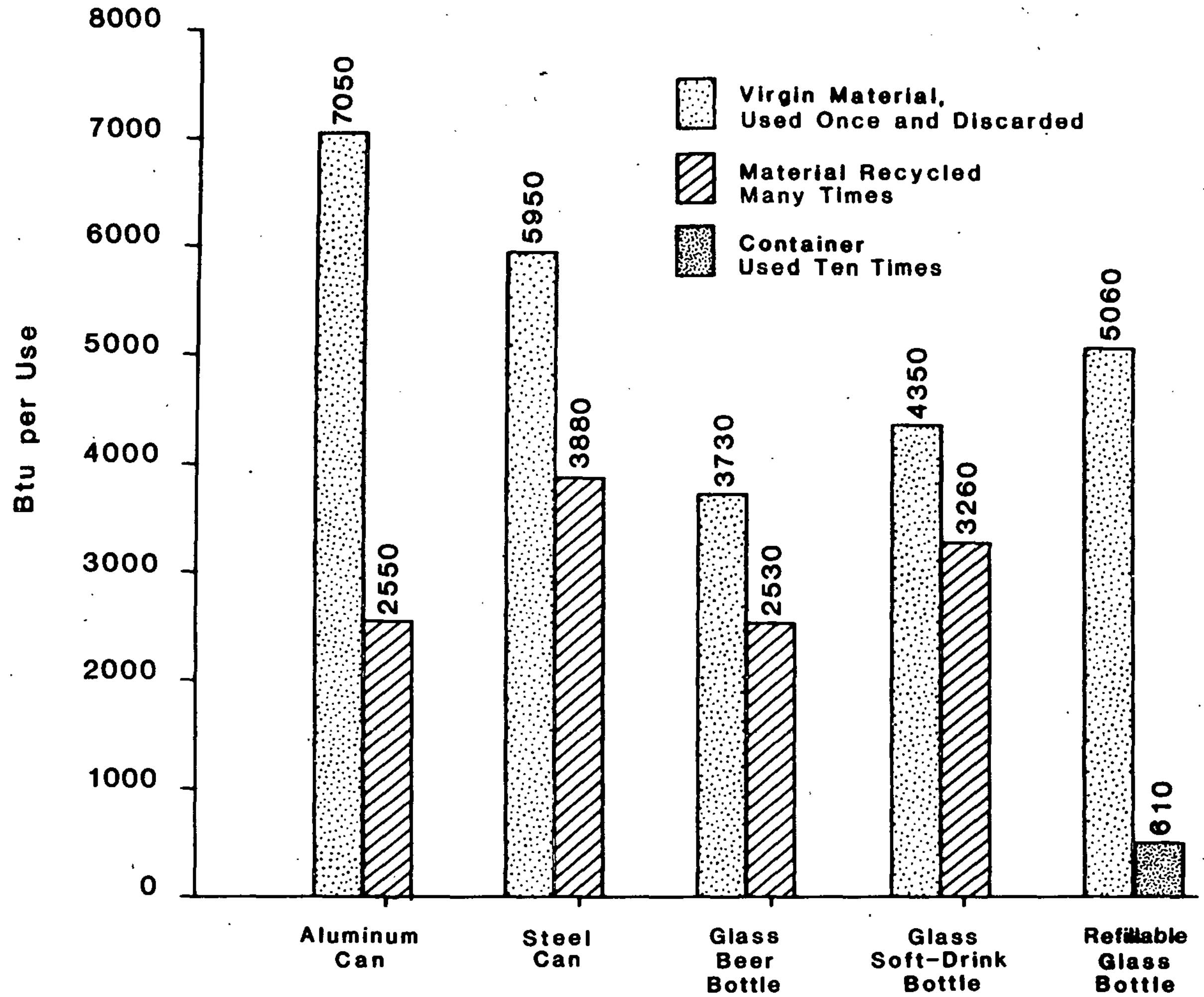

Fig. 2 Energy Consumption per Use for 12-oz Beverage Containers

chill faster. Because of these advantages, cans are cheaper to transport and generally are preferable for consumption at picnics and other outdoor activities.

Bottles are served in many restaurants and bars in preference to cans, because bottles are thought to be more attractive. Another perceived advantage of glass is its transparency, which allows the consumer to view the contents. Finally, many people prefer the taste of beverages in bottles.

3.2.3 Energy Requirements

Manufacture of single-serving beverage containers consumes about 0.4 quad annually. A comparison of the energy required to make glass, aluminum, and steel beverage containers is shown in Table 11. On a per pound basis, aluminum cans are almost 2.5 times as energy intensive as steel cans and 18 times more so than glass bottles. However, aluminum cans are extremely light, weighing about 0.7 oz. They weigh 50% as much as equivalent steel cans and about 10% of equivalent glass bottles. As a result, the per container energy

Table 11 Twelve-Ounce Beverage Container Energy Comparison

Material	New/Recycled	Btu/lb	Btu/Container	Cost (¢)
Aluminum (0.045 lb)	Virgin	158,000	7,050	6.7
	Recycled[a]	57,000	2,550	
Steel (0.092 lb, 13% aluminum)	Virgin	64,800	5,950	6.5
	Recycled[a]	42,300	3,880	
Glass, beer[b,c] (0.388 lb)	Virgin	8,700	3,370	4.2
	Recycled	6,525	2,530	
	Refillable[d]	8,700	5,060 (610)[e]	
Glass, soft drink[b,c] (0.5 lb)	Virgin	8,700	4,350	5.2
	Recycled[f]	6,525	3,260	
	Refillable[d]	8,700	5,060 (610)[e]	

[a]Energy for shredding and separation has been neglected.

[b]Caps are not included.

[c]The energy required for transport has not been included in this analysis, because discarded bottles must be transported to the landfill. Although new bottles must be rinsed, bottles to be refilled must be washed with hot water and caustic at an energy cost of about 100 Btu/bottle.

[d]Assumes the refillable bottle is 50% heavier than lightest nonrefillable.

[e]Approximate energy per use for 10 uses.

[f]Assumes recycling requires 75% of the energy to make new glass.

for virgin aluminum cans (about 7000 Btu) is almost 20% more than steel cans (6000 Btu) and double that of glass bottles (3400 Btu for a beer bottle).

Almost all of the raw material for aluminum manufacture (bauxite) is imported. Aluminum can manufacture relies on electricity (which is expected to become increasingly coal-based) for more than 50% of its energy requirements. Oil and natural gas supply the rest. Steel production uses considerable quantities of coal; coal supplies about 50% of the energy to make ingots, electricity about 11%, and oil and natural gas the rest. The primary energy source for glass manufacture is natural gas (over 70% of energy use). Coal could be used at greater than the present 18% level, but glass manufacturers do not foresee a shift to coal in the future. In summary, all of these materials could use coal as their primary energy source, but only steel uses coal now.

3.2.4 Recycling

The energy comparisons for glass, aluminum, and steel beverage containers look considerably different if recycling is considered. Since used glass must be remelted at nearly the same temperature as the readily available raw materials, recycling saves little energy. Although recycled steel ingots or castings consume considerably less energy than those made from virgin materials, the fabrication operations must be performed again, and these account for more than 50% of the total energy input to new cans. Therefore, only approximately 33% of the energy for steel can manufacture is saved by recycling.

For aluminum, on the other hand, about 66% of the total energy to produce new cans is consumed in making the virgin ingots, and most of this is saved by recycling. A recycled aluminum can requires about 35% of the energy consumed in making a new one. Thirty-five percent of the material in aluminum cans was recycled in 1980, so the average aluminum can requires somewhat less energy than a new steel can.

In summary, a can made entirely from recycled aluminum requires about the same energy to produce as a recycled bottle, but a recycled steel can requires about 50% more. Recycling aluminum cans is more economical than recycling steel cans, because aluminum is worth more per pound and the cost of detinning adds to the total cost of recycling steel cans.

To reduce breakage, a refillable bottle generally is heavier than the equivalent nonrefillable bottle and therefore consumes more energy per container. However, since it is reused many times, the energy per use is by far the lowest of any container option examined. For 10 uses, the energy per use is less than 20% of the energy to produce a recycled aluminum container.*

It should be possible to recycle a large percentage of single-serving beverage containers, either on new container backhaul or at collection centers (e.g., supermarkets). States with mandatory deposit laws have successfully demonstrated effective collection schemes.

3.3 GLASS AND PLASTIC FOR FAMILY-SIZED BEVERAGE BOTTLES

Family-sized soft-drink bottles (one quart and larger) are made from glass and from polyester (PET). The energy required for producing plastic bottles is 6.5 times greater per pound than that for glass bottles, but plastic bottles consume less energy per use than do glass bottles and can be burned to recover about 20% of their embodied energy. Recycled plastic uses less energy per pound than recycled glass, so recycled plastic bottles would have a much lower energy requirement per use than recycled glass. Plastic bottles currently are being recycled into fiberfill and other polyester uses.

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*The energy required for transport has not been included in this analysis, because discarded bottles must be transported to the landfill. Although new bottles must be rinsed, bottles to be refilled must be washed with hot water and caustic at an energy cost of about 100 Btu/bottle.

Refillable glass bottles must be reused three or more times before they can compete with nonrefillable polyester bottles on a total energy basis -- four times if the polyester bottle is burned and six times if it is recycled and then thrown away. However, although glass manufacture relies heavily on natural gas, it could be fueled entirely with coal, while plastics manufacture depends on oil and natural gas. Therefore, if the policy objective is minimizing oil (and/or natural gas) use, glass is clearly the choice.

3.3.1 Markets and Container Comparison

Plastic competes with glass for the family-sized soft-drink bottle market. Consumers often prefer polyester bottles because the bottles are lightweight and shatterproof. Large bottlers like polyester bottles because they can make them on site. Although soft drinks in glass containers have the advantage of longer shelf life and potability, large glass containers of carbonated beverages have been described as "lethal bombs." It is estimated that 2 billion two-liter soft-drink bottles (about 80% of the total two-liter market)[2] were made of polyester in 1980.[3] Table 12 shows that plastic bottles are expected to have an increasingly larger share of the entire soft-drink market, mostly at the expense of glass. Cans are expected to retain their dominance of the market for small containers.

3.3.2 Energy Requirements

On a per pound basis, about 56,700 Btu are needed to make plastic bottles and only 8,700 Btu to make glass bottles. However, a plastic bottle is only 10% as heavy and thus consumes only 62% as much energy in its production as an equivalent glass bottle. Most of the production energy for glass is in the form of natural gas. However, coal could be substituted as a fuel in glass production but could not be substituted economically for the oil and natural gas feedstocks needed to produce plastics.

Table 12 Beverage Container Markets, 1978 and 1982

	Cans		Glass: Nonrefillable		Glass: Refillable		Plastic	
	1978	1982	1978	1982	1978	1982	1978	1982
Volume[a]	37.7	48.2	23.0	26.0	35.3	36.7	2.4	12.1[b]
Percentage of annual total	38.3	39.2	23.4	21.2	35.9	29.8	2.4	9.8

[a]Billion equivalent 8-oz units.

[b]Since 2 billion two-liter plastic bottles were produced in 1980, this figure may be underestimated.

Source: Ref. 1.

3.3.3 Combustion of Plastic Bottles

If discarded plastic bottles are burned, about 12,700 Btu/lb are recovered. In this case, the net energy of the plastic bottles is 44,000 Btu/lb or 50% as much energy per bottle as that required by a glass bottle.

3.3.4 Recycling

Glass bottles can be recycled for about 75% of the energy required to make new glass bottles. Even though a recycled glass bottle requires more energy than a new plastic bottle (see Table 13), coal could be used in glass recycling, whereas most of the energy for plastics manufacture is in the form of oil and natural gas feedstocks.

The possibilities for recycling plastic soft-drink bottles are complicated, because these bottles are made primarily of polyester but generally have high-density polyethylene base cups. Either or both could be recycled or burned. Possible paths for recycling these bottles and the energy use for each step are shown schematically in Fig. 3. In present demonstrations, the polyester is being recycled and the high-density polyethylene discarded because of the low volumes being handled. A two-liter bottle made with recycled polyester with a new base cup would require 52% as much energy to

Table 13 Comparison of Glass and Plastic Soft-Drink Bottles

	Cost (¢)			Energy (Btu/bottle)		
Bottle	1978	1983	Weight (oz)	Input for Production	Recovered by Combustion	Needed to Recycle
Nonrefillable glass						
32 oz	12.7	18	20	10,900	0	8,200
Two liter	19.1	27	32.5	17,700	0	13,300
Refillable glass						
32 oz	18	27	28	15,200	0	11,400
Two liter	28	40	48	26,100	0	19,600
Plastic (polyester)						
32 oz	12.7	16	1.9	6,740[b]	1,500	2,480[a,b]
Two liter	18.5	24	3.1	10,800[b]	2,650	3,740[a,b]

[a]This figure is slightly underestimated, because it excludes blow-molding of the final bottle.

[b]Energy required to recycle the bottle and base cup (includes energy for transport and energy embodied in material added to replace that lost during processing).

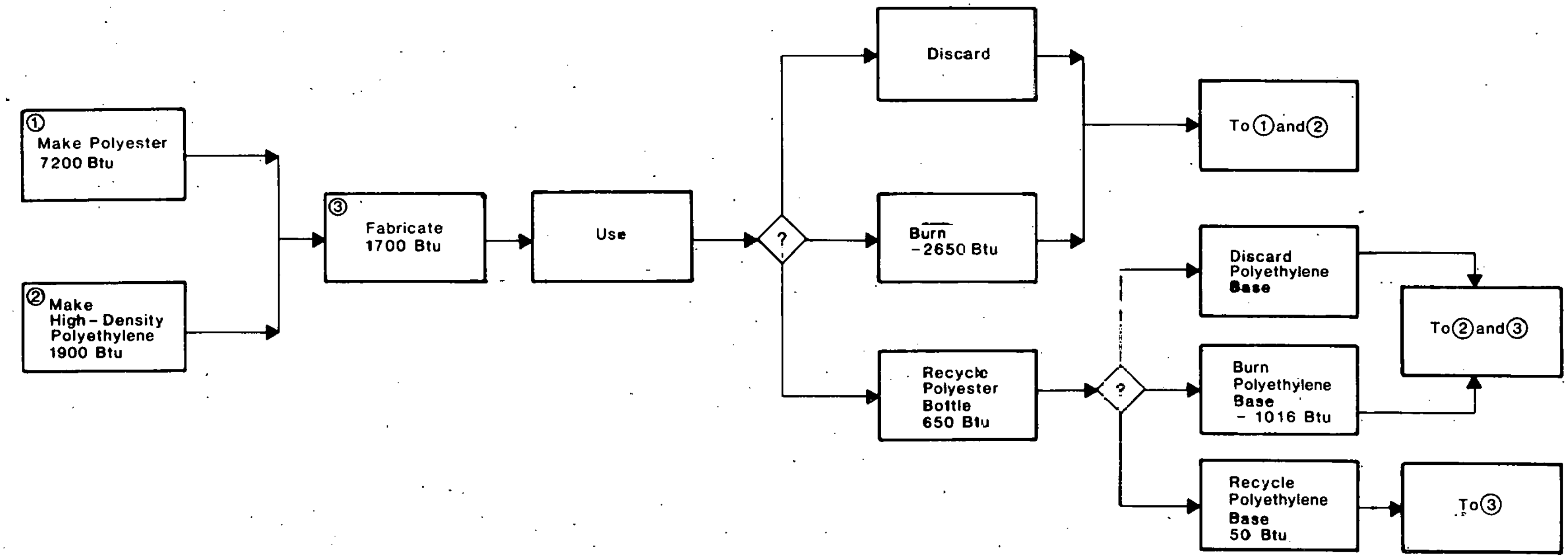

Fig. 3 Energy Flow fcr the Life Cycle of a Two-Liter Plastic Bottle

make as a new bottle* (43% if the discarded base cup is burned and only 35% if it is recycled). The recycled bottle (or other product) can then be burned, which reduces the net energy required for the second use to about 28% of that for a new bottle.

3.3.5 Reuse

The Food and Drug Administration prohibits reusing plastic bottles for food applications. Refillable glass bottles generally are about 50% heavier than the equivalent nonrefillable bottle and require 50% more energy to make. The marginal energy cost for reuse is low, because nonrefillable bottles require transportation to a landfill and new bottles also need washing. Therefore, the marginal per trip energy cost of a refillable glass bottle equals the production energy divided by the number of uses. If a glass bottle is used three times, it requires less energy than a plastic one that is thrown away after one use. A comparison of average energy requirements per use for various recycling options for plastic and glass bottles is shown in Fig. 4. Note that plastic and multitrip glass bottles consume the least energy among the soft-drink bottles.

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*Although the Food and Drug Administration forbids using recycled polyester for food applications, recycled polyester can displace virgin polyester in other polyester markets.