The Monthly UnEconomist

Recycling versus Incineration: an Energy Conservation Analysis

Part 2

Issues of sustainability, energy efficiency, and other product lifecycle resource impacts need to be raised when discussing source reduction, reuse and recycling. Although we all are aware that the US will not run out of landfill disposal capacity anytime soon, continued disposal of the majority of solid waste poses a substantial and serious threat to Earth's ecosystems. This threat comes from the need to continually acquire new raw materials from those ecosystems to replace the used materials that we continue to throw away in incinerators and landfills.

February, March and April issues of *The Monthly UnEconomist* serialize and summarize a Sound Resource Management study on energy conserved by recycling compared with energy generated from incinerating municipal solid waste (MSW).[1] This study illustrates that even the energy recovered by incinerating MSW pales in comparison to the energy saved by recycling rather than burning wastes.

February covered the study's methodology and general conclusions. This issue reports the tabular data and covers incremental energy usage needed to recycle MSW materials. April will cover the recycling versus incineration analysis for each separate waste material.

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Table 1 compares energy generated by energy-from-waste (EFW) incineration with energy conserved by recycling. The table shows that for virtually all waste materials, recycling saves more energy than is generated by burning the waste. On average, EFW incineration yields 6,132 kilojoules (kJ) of energy per kilogram (kg) of MSW incinerated. By comparison recycling conserves three to five times as much energy, between 20,060 kJ/kg and 31,270 kJ/kg on average. Material by material energy comparisons for recycling versus incineration will be discussed in April's *UnEconomist.*

Table 2 reports the incremental collection and processing energy required to recycle waste materials. Based on energy used by truck or rail transport, Table 2 also shows the distance that recycled materials can be shipped to market before using up the energy advantage versus incineration. Many recycled materials could be transported around the world without using up the energy savings recycling accrues over EFW incineration.

Collection and Processing System Energy Impacts from Recycling

This study was prepared as part of the adjudicatory review for Ontario (Canada) Hydro's Twenty-Five Year Demand-Supply plan to analyze the efficiency of generating energy by burning MSW. This section discusses incremental energy usage by recycling in the context of Ontario recycling programs. The data are thus specific to Ontario. However, many US recycling programs share similarities with Ontario recycling programs, so the results are for the most part applicable throughout North America.

Ontario's Blue Box recycling programs by now reach the vast majority of all households, including apartments, farms and cottages. The Blue Box collection system for recyclables targets most cans, glass and newspapers generated as household wastes. In addition, whether collected at curbside in Blue Boxes or at drop off depots, many recyclables collection systems now include additional materials, such as, corrugated cardboard, PET or HDPE plastic food/beverage containers, and junk mail.

The existence of these recycling programs means that for many waste stream materials a dual collection system is already in place, even in the industrial/commercial/institutional (ICI)

[1] Morris, Jeffrey, and Diana Canzoneri, *Recycling Versus Incineration: An Energy Conservation Analysis*, prepared for Pollution Probe (Toronto, Ontario) and Work on Waste USA (Canton, NY) by Sound Resource Management, September 1992. This study has also been summarized in two articles published elsewhere, Morris and Canzoneri, "Comparative lifecycle energy analysis: theory and practice," *Resource Recycling*, November 1992, Volume XI/Number 11; and Morris, "Recycling versus incineration: an energy conservation analysis," Journal of Hazardous Materials, Vol. 47 (1996), pp. 277-293.

sector. Whether a particular waste material is collected from the garbage can or dumpster and hauled to an incinerator, or collected from recycling bins and hauled to a materials recovery facility (MRF) or a composting plant, would not appear to substantially alter total energy expended to collect and transport waste materials. Communities in which incineration facilities might exist or be sited will be providing both garbage and recycling collection regardless.

Thus, any impacts on energy needed to collect and transport materials will occur because of greater or lesser relative distances to an EFW facility versus a recycling or composting facility, and because hauling a metric ton in a recycling truck is more or less energy intensive than hauling a metric ton of waste in a garbage truck. For purposes of the analysis herein, we assume that EFW, recycling and composting facilities will be equivalent distances from collection routes. We also assume that collecting and transporting a metric ton of mixed garbage, source separated recyclables or source separated yard wastes requires the same energy usage.

Available information on collection route lengths and times does not point to any particular collection system being unequivocally more efficient than another, as long as recyclables are not extensively sorted at each stop by the recycling truck crew. Nor does there appear to be any information that suggests substantial differences in fuel used to collect a metric ton of recyclables or compostables versus a metric ton of mixed garbage. Thus, whether a metric ton of a targeted material is collected in the garbage truck or the recycling truck will not matter in terms of energy expended to collect and transport materials to the facility where they will be managed.

Materials likely to be targeted for separate collection by recycling programs include newspaper, corrugated cardboard, office paper, PET and HDPE plastics, glass containers, aluminum beverage containers, tin food and beverage containers, and yard wastes. That leaves mixed paper, other container plastics, film/packaging plastics, other glass, other ferrous and non-ferrous metals, food wastes, wood wastes, leather, rubber, textiles and diapers as waste stream materials for which additional collection energy expenditures may be necessary to recycle rather than incinerate those materials.

Of these materials not targeted for separate collection by current and/or future programs, food waste, wood waste and diapers are the only ones for which a separate collection system is likely to be specified as part of its recycling program. The main exception to separate collection of food waste is in those communities where it would be co-collected with yard waste. The Ontario community of Guelph currently collects food waste in this manner. In that situation no additional collection network would be required to begin recycling this non-targeted material.

Otherwise, there almost certainly would be a net increase in energy used for collecting solid waste materials, because the garbage collection energy saved (avoided) when food waste is kept out of mixed garbage and set out for separate collection would be less than the energy required to send an additional truck out on a separate collection route picking up just food waste.

Low amounts of food waste are generated in households. Thus, food waste probably would be collected mainly from restaurants, hotels, hospitals, cafeterias and other businesses or institutions that provide meal preparation services to large numbers of customers. To the extent that residential units could be folded into collection routes without necessitating more collection trucks, then some residential food waste, especially from larger multi-family buildings, might also be recycled as part of a commercial food waste recycling program.

We assume that the typical truck used for collecting food waste (or recyclables, compostables or garbage) would use a fifth of a gallon of fuel for each kilometer of truck use, where a gallon of fuel has a kJ value of 144,400.[2]

[2] White, Allen L., *et al*, "Energy Implications of Alternative Solid Waste Management Systems," Boston, MA: Tellus Institute, prepared for the Coalition of Northeastern Governors Policy Research Center, Inc., Appendix page D1.

With the increase in fuel usage to collect food waste there would be a corresponding savings in fuel usage to collect food waste mixed in with garbage. The number and distribution of homes and businesses serviced by garbage collection would not be changed when separate food waste collection is instituted. But less mixed garbage would be collected at each stop, so that trucks could make more stops before a trip to the transfer station, incinerator or landfill to unload. Fewer trips to unload means fewer miles traveled and less fuel expended in garbage collection.

Estimates of the decrease in garbage collection energy when waste is recycled vary widely. For purposes of this study we use the range 20% to 40% to represent the amount of fuel savings in garbage collection associated with fuel expenditure to collect food waste.[3] As a result the net increase in fuel caused by food waste recycling is estimated to be .124 to .165 gallons of fuel per kilometer covered picking up food waste.

The amount of food waste generated by Ontario's food service businesses, the density of these businesses is terms of establishments per road mile, and the location of potential EFW incinerator sites or food waste compost facility sites are not specified as part of Ontario Hydro's NUG plan. We had to rely on data from other communities, as well as our own professional judgement, in making calculations for net energy impact of a separate food waste collection system.

First, we assume that the typical commercial food waste collection route would cover 40 to 48 kilometers in completing a daily route and hauling food waste to a composting facility. Second, we assume that the typical route would yield a 20-yard truckload at 340 kg per cubic yard, or 6.8 metric tons picked up, during the 40 to 48 kilometer route.[4] Increased system wide fuel usage, from the figures given above, then would be 5 to 7.9 gallons per day, or 0.74 to 1.16 gallons per metric ton collected. On a steam-electric power generation fuel equivalent kilojoule per kilogram basis, then, food collection would entail an incremental energy expenditure of 107 to 165 kJ/kg collected.[5] The midpoint of this range, 136 kJ/kg[6], is shown for food waste on Table 2 in the column labeled "Incremental Collection Energy."

For diapers, 81 kJ/kg incremental collection energy is reported in Table 2. This estimate reflects collection energy for commercial laundry service pickup and delivery of reusable diapers, and assumes zero collection energy is incurred for the 87% of reusable diapers that are home laundered.[7]

For wood waste, 163 kJ/kg incremental collection energy is reported in Table 2. This estimate reflects a wood recycler's estimate of energy required to collect wood from construction and demolition sites and landfills.

To develop estimates for incremental collection energy expenditure for the remaining non-targeted waste materials, we first assume that adding a material to existing source sepa-

[3]See White, *ibid*, p. 65-66. Also Seattle's residential garbage collection contracts with the two companies providing these services to the city specify that 50% of the fee paid for garbage collection services is based on tonnage collected, and decreases proportionally to any decrease in garbage tonnage collected from households.

[4]For some additional information on food waste collection see Appendix E, "Recycling Potential Assessment and Waste Stream Forecast," from the City of Seattle's Final Environmental Impact Statement-Waste Reduction, Recycling and Disposal Alternatives, July 1988.

[5]Kunz and Emmerson, *op. cit.*, p. 34, estimate curbside collection of recyclables requires 361 kJ/kg. This figure does not include any garbage collection energy savings. In another study (Hannon, Bruce, "System Energy and Recycling: A Study of the Beverage Industry," Urbana, IL: Center for Advanced Computation, University of Illinois at Urbana-Champaign, revised March 17, 1973), energy consumed hauling garbage was estimated at 207 kJ/kg, based on 3.6 metric tons in a truck load, average distance traveled 32 kilometers, and 11.2 kilometers per gallon of truck fuel. Hannon used 137,750 kJ per gallon for gasoline. At 144,400, energy usage for garbage collection would be 227 kJ/kg collected.

[6]Love, *op. cit.*, p. 58, estimates garbage collection energy usage at 198 kJ/kg collected in a densely populated urban center. At a 60 to 80% rate for incremental energy expenditure, Love's estimate implies additional energy costs between 119 and 158 kJ/kg collected.

[7] C. Lehrburger, *op. cit*., pp. 74-75.

rated collection will increase overall collection system energy usage at only half the rate for adding a separate system to collect food waste, i.e., at the rate of 68 kJ/kg for materials with the same density on a collection truck as food waste.

But added collection system energy will also depend on the density of the new material being picked up, with, say, plastics using more energy per kilogram collected than, say, small scrap metal, because plastics require more recycling truck space per kilogram than do scrap metals. To account for relative densities, we adjusted 50% of food waste collection energy -- 68 kJ/kg -- up or down in proportion to 20% of the ratio of the density of food waste to each remaining non-targeted material's density, and added or subtracted that figure to or from 68 kJ/kg.[8]

These calculated incremental collection energy figures for non-targeted materials are reported in Table 2 in the column labeled "Incremental Collection Energy." For example, the density of other recyclable paper is estimated to be only 68 kilograms per cubic yard. Thus, (50% x 136 kJ/kg for food waste) + (340/68=) 5 x 20% x (.5 x 136) = 136 kJ/kg to add other recyclable paper to an already existing curbside collection route.

According to the calculations reported in Table 2, we estimate that incremental collection energy for non-targeted waste materials will be between 84 and 323 kJ/kg. On average, including zero incremental collection energy for targeted materials, collecting an extra kilogram of recyclables or compostables from households or businesses in Ontario's denser population centers will add about 86 kilojoules to energy expended on solid waste management collection systems.

Table 2 also reports estimates of incremental energy to process and clean recyclable materials for shipment to markets. The processing energy necessary to compost food and yard wastes was included as a deduction to the energy savings reported in Table 1, so Table 2 does not include any processing energy for food and yard wastes.

The major categories of materials preparation are:

- Baling at 105 kJ/kg for paper, plastic, aluminum cans, tin cans, leather and textiles.
- Processing to remove contaminants at 79 kJ/kg for all recyclables.
- Ash landfilling avoidance at 33 kJ/kg recycled for the 30% of a pound of ash produced and needing landfilling if the recycled kilogram were burned instead.

Preparing materials for markets incurs an average incremental energy usage of 96 kJ/kg recycled. Incremental energy, as shown in Table 2, is 46 kJ/kg for materials that are not baled, and 151 kJ/kg for those that are baled for shipment to end users.

Energy for Shipping Recycled Materials to Market

After collection and processing, recycled materials or finished compost must be shipped to manufacturers, in the case of recyclables, or final users, in the case of finished compost. Energy required to ship by truck is estimated to be 1.82 kJ/kg per kilometer. Rail energy usage is much less, 0.41 kJ/kg per kilometer shipped.[9]

The amount by which recycling energy conservation exceeds incinerator energy generation, as shown on Table 1, less the incremental collection and processing energy usages reported on Table 2, is the amount of energy available for shipping materials to markets. For each material recycled or composted rather than incinerated, net energy saved will be partly used to transport materials to markets. The last four columns of Table 2 indicate the maximum mileage by truck or rail which each material could be shipped before energy saved by recycling was used up in shipping material to market. The table provides this breakeven shipping distance for both the

[8] The densities for various waste stream materials are from a source separation analysis we conducted as part of the Washington State Department of Ecology's Best Management Practices Analysis for Solid Waste. See, Section C, "Separation Analysis," in Matrix Management Group, *et al*, *Best Management Practices Analysis for Solid Waste - Statewide Findings and Recommendations*, Volume III, Washington State Department of Ecology, Publication Number 88-33C, January 1989.

[9] Love, *op. cit.*, p. 60.

lowest and highest of each material's recycling energy savings estimates that are given in the last three columns of Table 1.

As shown by the breakeven shipping distance estimates given on Table 2, most materials can be shipped long distances, half way round the globe and much further, to find a buyer/user. Even then the energy saved by recycling would still be greater than energy generated by burning the waste material.

The breakeven shipping distance estimates on Table 2 also agree with some commonly held notions and practices about which materials can go to distant markets. Glass and compost, for example, typically are used close to the community in which they are collected. But paper, plastics and aluminum cans can be (and are) shipped to quite distant markets.

About The Monthly UnEconomist

This monthly online newsletter available at www.SoundResource.com intends to provide insight and analysis on the everyday economics of recycling and the unpriced or underpriced environmental benefits of reducing waste disposal and replacing virgin-content products with products manufactured from recycled materials. Reader feedback is encouraged via email to info@ZeroWaste.com, and substantive comments will be published whenever they add to our understanding of recycling.

The *UnEconomist* also analyzes northwestern and northeastern U.S recycling market prices for nine recycled materials (mixed paper, ONP, OCC, glass containers, tin cans, UBC, PET bottles, HDPE natural bottles, and HDPE colored bottles) tracked by graphs available online at www.SoundResource.com. These graphs are updated at least quarterly. *The UnEconomist* will from time to time report on the accuracy of the annually updated five-year recycling price forecasts that are also provided online for each of the nine materials.

Table 1
Energy Generated by Energy-from-Waste (EFW) Incineration versus Energy Conserved by Recycling

	Residential Waste Comp.(1)	Mass Burn Incineration Energy from Waste: Heating Value(2) (kJ/kg)	Mass Burn Incineration Energy from Waste: Steam Electric Equivalent(3) (kJ/kg)	Energy Saved When Recycled Into(4) Same Material/Use(5): Low Est. (kJ/kg)		Energy Saved When Recycled Into(4) Same Material/Use(5): High Est. (kJ/kg)		Energy Saved When Recycled Into(4) Other Materials (kJ/kg)	
Waste Stream Materials									
Paper									
Newspaper	10.3%	18608	8444	21450	(a)	23346	(b)	38600	
Corrugated Cardboard	14.6%	16282	7388	13665	(c)	32108	(d)	38600	
Office (Ledger & CPO)	5.7%	18143	8233	34699	(a)	35786	(a)	38600	
Other Recyclable Paper	4.8%	16747	7600	10318	(e)	32108	(d)	38600	
Metal/Plastic/Wax Coated	0.5%	17910	8127					38600	
Total/Average	35.8%	17331	7865	18863		30264	(f)		
Plastic									
PET	0.3%	46287	21004	60825	(g)	110950			
HDPE	0.9%	46287	21004	66058		82573			
Other Containers	0.2%	36983	16782	61639		64198	(h)		
Film/Packaging	4.3%	32099	14566	66058		84899			
Other Rigid	1.8%	36983	16782	41868		95887	(i)		
Total/Average	7.5%	35669	16186	59934		87877			
Glass									
Containers	5.7%	233	106	907	(j)	5517		582	(k)
Other	2.1%	233	106					582	(k)
Total/Average	7.8%	233	106	907		4209	(l)		
Metal									
Aluminum Beverage Cans	0.4%	1628	739	201562	(m)	312098	(m)		
Other Aluminum	1.1%	698	317	201562	(m)	360900	(n)		
Other Non-ferrous	0.1%	698	317	110148	(o)	122429	(p)		
Tin and Bi-Metal Cans	3.1%	1628	739	7094	(m)	37100	(m)		
Other Ferrous	7.7%	698	317	14496	(n)	21218	(n)		
Vehicular Batteries	0.5%								
Household Batteries	0.1%								
White Goods	1.0%								
Total/Average	14.0%	889	403	35150		64155			
Organics	16.0%								
Food Waste		6048	2744					4215	(q)
Yard Waste		6978	3166					3556	(r)
Memo: MSW Compost								5548	(s)
Wood Waste	11.9%	15584	7072	6422	(t)	6422	(t)		
Leather	0.1%	16747	7600						
Rubber									
Tires	0.9%	32564	14777	16265	(u)	48796	(u)	147800	(v)
Other Rubber	0.7%	25353	11505	25672	(o)	25672	(o)		
Textile	2.6%	16049	7283						
Cotton								42101	(w)
Synthetic				58292	(x)	58292	(x)		
Diapers	1.1%	23609	10713	6801	(y)	15124	(z)		
C & D Debris	0.6%								
Small Quant. Hazardous	1.0%								
Total/Average	100.0%	13,514	6,132	20,060	(aa)	31,270	(aa)		

Table 2
Incremental Energy Required to Collect, Process and Transport Source Separated Recyclable or Compostable Materials

	Incremental Collection Energy (kJ/kg)		Incremental Energy to Process Materials for Markets (kJ/kg)		Energy Breakeven Kilometers to Markets(c): Low Energy Savings, Truck	Low Energy Savings, Rail	High Energy Savings, Truck	High Energy Savings, Rail
Waste Stream Materials								
Paper								
Newspaper	0		151	(a)	7063	31355	16486	73183
Corrugated Cardboard	0		151	(a)	3366	14941	17066	75757
Office (Ledger & CPO)	0		151	(a)	14459	64184	16602	73698
Other Recyclable Paper	136		151	(a)	1336	5931	16876	74911
Metal/Plastic/Wax Coated	136		151	(a)			16586	73624
Plastic								
PET	0		151	(a)	21796	96755	49338	219012
HDPE	0		151	(a)	24672	109520	33746	149799
Other Containers	323		151	(a)	24386	108250	25792	114491
Film/Packaging	272		151	(a)	28060	124560	38412	170513
Other Rigid	272		151	(a)	13551	60153	43232	191906
Glass								
Containers	0		46	(a)	236	1049	2948	13087
Other	85		46	(a)	190	841	190	841
Metal								
Aluminum Beverage Cans	0		151	(a)	110259	489444	170994	759044
Other Aluminum	94		46	(b)	110498	490502	198046	879131
Other Non-ferrous	94		46	(b)	60270	267540	67018	297495
Tin and Bi-Metal Cans	0		151	(a)	3409	15133	19896	88317
Other Ferrous	84		46	(b)	7719	34267	11413	50662
Vehicular Batteries								
Household Batteries								
White Goods								
Organics								
Food Waste	136		NA		733	3255	733	3255
Yard Waste	0		NA		214	950	214	950
Memo: MSW Compost					0	0	0	0
Wood Waste	163	(d)	46	(b)	0	0	0	0
Leather	119		151	(a)				
Rubber								
Tires	88		46	(b)	744	3303	73016	324119
Other Rubber	94		46	(b)	7708	34214	7708	34214
Textile								
Cotton	119		151	(a)	22984	102026	22984	102026
Synthetic	119		151	(a)	31880	141517	31880	141517
Diapers	81	(e)	NA		0	0	2379	10559
C & D Debris								
Small Quant. Hazardous								
Total/Average	86		96		8,166	36,250	16,305	72,377

Footnotes for Table 1

(1) Source: *Residential Waste Composition Study: Volume 1 of the Ontario Waste Composition Study*.

(2) Source: P.A. Vesilind and A.E. Rimer, *Unit Operations in Resource Recovery Engineering*, Prentice-Hall, Englewood Cliffs, NJ: 1981; except tires heating value from phone conversation with Stuart Natof, U.S. Dept. of Energy.

(3) Mass burn incineration generates 507 kWh per metric ton at 12,095 kJ/kg, or 1825 kJ of output energy (at 3600 kJ/kWh) per kg of input waste. Thus, almost 2 kg of waste are required to produce 1 kWh, an input kJ to output kWh conversion rate of 23,820 kJ of input waste per kWh of electrical energy produced. The kJ/kWh conversion factor for steam-electric power generation is typically 10,807. To put waste material heating values for EFW electric power generation on an equivalent basis to steam-electric power plant fuel energy, waste material heating values were adjusted down by 10,807/23,820 = 45.4%.

(4) Based on Office of Technology Assessment, *Facing America's Trash: What's Next for Municipal Solid Waste*, 1989 unless otherwise indicated. Energy savings for recycling into "Other Materials" are based on most productive use. E.g., tissue and toweling papers are made from all types of recycled paper, so that 45,450 kJ/kg energy savings for 100% recycled content tissue paper versus 100% virgin wood content tissue is available for all types of recycled paper. Adjusting for 85% tissue output to waste paper input gives about 38,600 kJ saved per kilogram of waste paper input.

(5) These columns report the low and high energy savings estimates (from primary and secondary data sources) closed-loop recycling (manufacturing the waste material back into the same type material - e.g., old newspapers into new newsprint). The "Other Materials" column reports energy savings for open-loop recycling (e.g., old newspapers into tissue paper).

(a) Peter Love, "Energy Savings from Solid Waste Management Options," *Resources Policy*, March 1978. Estimates include Love's calculation of the energy value of trees not used.

(b) Kunz, Regis D., and Mark R. Emmerson, *Energy Analysis of Secondary Material Use in Product Manufacture*, California Solid Waste Management Board, Nov.1979. Estimate of 5800 kJ/kg adjusted for the energy value of 2.18 metric tons of trees not used per metric ton of 100% recycled content newsprint, for old newspaper yield of 85% in manufacturing newsprint, and for steam-electric power generation fuel value of wood of 9.5 million kJ per metric ton. The fuel value of trees is from Gunn & Hannon, Energy Conservation and Recycling in the Paper Industry, *Resources and Energy*, Vol.5, 1983, Table 4-Total Energy, Wood and Scrap Required by Type of Paper & PaperBoard, p. 251.

(c) Tellus Institute, *CSG/Tellus Packaging Study*, "Report # 2: Inventory of Material and Energy Use & Air and Water Emissions from the Production of Packaging Materials," prepared for The Council of State Governments, US Environmental Protection Agency, and New Jersey Department of Environmental protection and Energy, 1992.

(d) OTA estimate (which is based on Gunn and Hannon, *op.cit.*) of 1093 kJ/kg adjusted to include the energy value of trees saved by recycling. According to Gunn & Hannon, 3.64 metric tons of tree wood are required to produce one metric ton of linerboard or food service board; 1.18 metric tons of recycled corrugated are necessary to make a metric ton of linerboard. The steam-electric power generation fuel value of wood is 9.5 million kJ/metric ton.

(e) OTA estimate (which is based on Gunn and Hannon, *op. cit.*) of 11,950 additional kJ to produce recycled boxboard adjusted to include energy value of trees saved by recycling. According to Gunn & Hannon, 2.53 metric tons of tree wood versus 1.08 metric tons of recycled paper are required to produce a metric ton of boxboard.

(f) High-end average includes use of metallic, plastic or wax coated papers in tissue making.

(g) Estimate from Jonathon Kimmelman, Natural Resources Defense Council.

(h) Based on 65% PVC, 25% polypropylene and 10% LDPE.

(i) Based on 25% each polystyrene, ABS, nylon, and polycarbonate. Production energy for latter three types from Martin Grayson (ed.), *Recycling, Fuel and Resource Recovery: Economic and Environmental Factors*, New York: John Wiley, 1984. Energy savings from recycling estimated at 90%.

(j) Stauffer, Roberta Forsell, "Energy Savings from Recycling," *Resource Recycling*, January-February 1989.

(k) Based on estimate by OTA, *op. cit.*, p. 152, of energy required to mine and transport sand raw material for glass making.

(l) Includes use of other glass as construction aggregate.

(m) Center for the Biology of Natural Systems, *Development and Pilot Test of an Intensive Municipal Solid Waste Recycling System for the Town of East Hampton*, Flushing, NY: Queens College, CUNY.

(n) Reid, George W., and Chan Hung Khuong, *Energy Conservation through Source Reduction*, Cincinnati, OH: Municipal Environmental Research Laboratory, U.S. EPA, EPA-600/8-78-015, November 1978.

(o) Leonard, LaVerne, "Specifying Metals for Recycling," *Materials Engineering*, September 1985.

(p) Energy savings for recycling copper from Reid, *op. cit*.

(q) Based on substituting an anaerobically produced soil amendment for peat. Estimates based on conversations in January and July of 1992 with Robert Legrand and David Chynoweth.

(r) Based on substituting an anaerobically produced soil amendment for peat. Estimates based on conversations in January and July of 1992 with Robert Legrand and David Chynoweth.
(s) Based on substituting an anaerobically produced soil amendment for peat and on information in R. Legrand, *et al*, "A Systems Analysis of the Biological Gasification of MSW and an Assessment of Proven Technologies," p.18. Updated estimates provided by Robert Legrand via telephone conversations in January & July of 1992.
(t) Reflects energy saved by using recycled wood in manufacture of particleboard as outlined in C. Boyd, Peter Koch, *et al*, "Highlights from Wood for Structural and Architectural Purposes," *Forest Products Journal*, Feb. 1977, Table 5. Also based on telephone conversation with Conor Boyd in January of 1992, and conversations with wood recyclers and a particleboard manufacturer. Extraction and transport of raw materials and preparation of particleboard finish in the form of planer shavings, plywood trim, and sawdust is reported to consume approximately 4.617 million Btu's per oven dry (OD) ton of particleboard, or 2,308 Btu's per oven dry pound of particleboard. Heating (i.e., drying) virgin wood requires 5.598 million Btu's per OD ton or 2,799 Btu's per OD pound of particleboard. (Conversion factor for Btu to kJ, one Btu = 1.054 kJ.) When comparing the use of virgin to recycled wood, it is assumed that it takes an average of 1.24 pounds of recycled wood to produce 1 pound of oven dry particleboard.
(u) Based on 5 to 6 gallons conventional fuel energy to produce one tire, 3 to 4 gallons to retread, and an average tire weight of 9.1 kg.
(v) Based on between 70,000 and 233,000 kJ/kg to produce polyurethane, and substitution of tire rubber for polyurethane in composite at an energy cost of 3700 kJ/kg to recycle tires into surface treated rubber.
(w) Based on cotton rags used in manufacture of writing paper, and energy savings for recycled content writing paper as reported by Peter Love, *op.cit*.
(x) Reid and Khuong, *op. cit*., p. 32, average energy consumed in manufacture of four synthetic textiles (polyester, nylon, acrylic modacrylic, and olefin). Energy savings are for use of synthetics as rags versus using new synthetic textiles as rags.
(y) Energy to recycle disposable diapers in hypothetical facility reclaiming 4.5 tons per day of unbleached kraft pulp, which could be used again in disposable diapers or in a variety of paper products. This information is from A. Little, Inc., "Report on Disposable Diaper Recycling Pilot Program," April 1991. The estimate for energy savings in manufacture of unbleached kraft pulp from recycled fiber rather than trees is given in Tellus Institute, *op. cit*., tables on pp. 2T-18 and 2T-22.
(z) Based on estimates in Carl Lehrburger, Jocelyn Mullen, and C.V. Jones, "Diapers: Environmental Impacts and Lifecycle Analysis," Report to The National Association of Diaper Services in Philadelphia, PA, Jan 91, reusable cloth diapers (at 167 uses per diaper) can be substituted for disposable diapers with 87 percent of reusable diapers home laundered and 13 percent washed by commercial diaper services. At the end of a reusable diaper's life approximately 50% of the original fiber remains and can be recycled into cotton rags which are then used to manufacture writing paper.
(aa) Includes energy savings from "Other Materials" column whenever "Same Material/Use" column energy savings estimates are unavailable.

Footnotes for Table 2

NA = not applicable: processing and market preparation energy usage deducted in estimates for recycling energy savings from remanufacturing/reuse included on Table 1.

(a) Includes 105 kJ/kg for baling (Love, *op.cit*., p. 58) + 79 kJ/kg for processing (White, Allen L., *et al*, "Energy Implications of Alternative Solid Waste Management Systems," Boston, MA: Tellus Institute, prepared for the Coalition of Northeastern Governors Policy Research Center, Appendix page D1) less 33 kJ/kg avoided landfilling energy usage. The latter figure is based on 109 kJ/kg for landfilling (White, *et al*, Appendix page D2) and a 70% weight reduction from incinerating waste so that only 30% remains as ash.
(b) Estimate same as explained in footnote (a) except no baling necessary to prepare material for markets.
(c) Love, *op. cit*., p.60, reports direct energy requirements for truck transport of 1.82 kJ/kg/km. Rail direct energy requirement is 0.41 kJ/kg/km.
(d) For wood waste, the kJ/kg incremental collection energy is based on a wood recycler's estimate to collect wood from construction and demolition sites and landfills.
(e) For diapers, the 81 kJ/kg incremental collection energy reflects commercial laundry service pickup and delivery of reusable diapers. Assumes zero collection energy for estimated 87% of reusable diapers home laundered. (C. Lehrburger, *op. cit*., pp. 74-75.)