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Recycling versus incineration: an energy conservation analysis

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Abstract

This paper shows that for 24 out of 25 solid waste materials, recycling saves more energy than is generated by incinerating mixed solid waste in an energy-from-waste facility. Recycling conserves energy that would otherwise be expended extracting virgin raw materials from the natural environment and transforming them to produce goods that can also be manufactured from recycled waste materials. Furthermore, energy conserved by recycling exceeds electricity generated by energy-from-waste incineration by much more than the additional energy necessary to collect recycled materials separetly from mixed solid waste, process recycled materials into manufacturing feedstocks, and ship them to manufacturers, some of whom are located thousands of miles away.

Keywords: Recycling; Energy conservation; Incineration energy generation

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1. Introduction

Incinerating municipal solid waste (MSW) in an energy-from-waste (EFW) facility recovers a portion of each waste material's heat value as electrical energy. Recycling waste materials conserves energy by replacing virgin raw materials in manufacturing products, thereby reducing acquisition of virgin materials from the natural environment. At the same time, recycling removes materials, some of which have high intrinsic energy content (e.g., paper and plastic), from the stream of MSW available for EFW incineration. Thus, the question: Does recycling waste conserve more energy than incinerating waste generates?

The analysis that follows shows that for 24 of 25 waste materials, recycling saves more energy than is produced by incinerating MSW in an EFW facility to generate electricity. This is because burning garbage to produce steam and spin turbines in EFW facilities captures only about 15% of a materials' intrinsic heat value. It is also because recycling saves substantial amounts of energy that would otherwise be

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expended extracting virgin materials from the natural environment and transforming them to produce goods that can also be manufactured from recycled waste materials.

Furthermore, energy conserved by manufacturing with recycled materials rather than virgin materials exceeds incineration generated energy by enough to cover incremental energy used collecting and processing recycled materials, as well as energy needed for shipping recycled materials to markets. In fact, the estimates reported in this paper are consistent with customary practices in the recycling industry. For example, recycled glass or compost made from yard or food wastes have lower energy savings and are typically used near the community from which they are recycled. But recycled paper, plastics, and aluminum cans have higher energy savings and often are shipped great distances to manufacturers of recycled-content products.

2. Methodological issues and simplifying assumptions

In order to compare net energy consumed by manufacturing with recycled MSW materials against net energy consumed by manufacturing with virgin materials and disposing of recyclable MSW materials via EFW incineration, several crucial methodological issues are confronted. This section outlines these issues, beginning with the most difficult – drawing equivalent analytical boundaries around the virgin and recycled materials manufacturing systems.

2.1. Treatment of direct vs. indirect energy requirements

The energy crunch during the 1970s produced many studies on ways to conserve energy, a number of which focused on using recycled waste materials as substitutes for virgin materials in manufacturing commonly used products, such as newsprint, aluminum cans, or glass food and beverage containers. These studies often had very different approaches to deciding what system boundaries would be used to define the energy consumption required to manufacture recycled- versus virgin-content products. For example, a study done by an electric power utility might focus just on electricity purchased by a manufacturer using virgin material inputs, and compare that with the electricity purchased to produce the same product with recycled (secondary) materials.[1] A more comprehensive manufacturing energy calculation would include the full heat, light and power requirements of the production process, regardless of whether the energy source is electricity generated off-site or steam generated on-site by burning conventional fuels such as oil and coal. Energy consumed extracting, processing and transporting material inputs, whether virgin or secondary,

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[1] For example, Temanex Consulting (North Vancouver, BC) in a report prepared for Ontario Hydro, *The Ontario Newsprint Industry to the Year 2005 – Impact of Deinked Newsprint Trends*, estimated savings from using secondary fiber to manufacture newsprint to be between 3600 and 3960 kJ/kg of finished newsprint versus virgin stone groundwood production of newsprint, and 6840 kJ/kg versus virgin thermomechanical pulp (TMP) production. These energy savings estimates are based on usage of purchased electricity by pulp and newsprint manufacturers. Energy used in harvesting and transporting trees to the pulp mill, energy used to collect and process recycled newspapers, non-electrical energy inputs to the pulping and newsprint manufacturing process, and energy generated by burning tree residues during the pulping process are all ignored in these estimates.

might or might not be included in a study attempting to compute total energy required to manufacture a product.

In addition to energy used to obtain direct material inputs and energy used in the production process itself, energy is needed to make production machinery and buildings, feed humans involved in the various stages of production, make the machine tools used to make machines, make the machines used to make intermediate goods, manufacture the gloves used by a worker who made a machine tool used to make a machine... ad infinitum. One needs vast amounts of data and complex calculations to reach across the industrial structure and back in time to sum up energy consumed in producing the cascade of direct and indirect inputs (including capital goods such as plant and equipment) used to manufacture a product.

Estimates reported in this paper include energy used to extract, process and transport major virgin or secondary materials used in manufacturing a product, as well as manufacturing heat, light and power requirements, regardless of the source of that energy. Energy used to produce input materials that are only consumed in minor amounts to manufacture a product typically is not counted. Indirect energy inputs, for example, energy used to make machines and buildings, or energy required to support the lifestyles of humans providing labor inputs, also are ignored.[2]

2.2. Treatment of process energy derived from raw material inputs

A second methodological problem is that some raw material inputs themselves have substantial intrinsic heat value and can be used to generate on-site power for the production process, rather than being incorporated entirely into the product itself. For example, chemically based wood pulping results in substantial wood residues that can be used to generate steam power.[3] Thus, some virgin-content paper products use less externally purchased energy than their recycled-content counterparts, because much of the process energy is generated by burning tree residues from the chemical pulping of trees.[4]

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[2] This assumption probably biases the analysis against recycling. For example, Peter Love in "Energy Savings from Solid Waste Management Options," *Resources Policy,* March 1978, p. 57, states," ...capital-related energy consumed by... newsprint... operations is less than 5% of the total energy consumed in the production of a ton of paper, and... capital-related energy consumption for energy recovery systems is about 1% of the fossil fuel equivalent energy produced. This order of magnitude has no substantial effect on the outcome of the comparison, especially since a large part of the capital for the two options is the same...

To the extent that the exclusion of capital-related energy does impart a bias to the analysis, the bias will be against reclamation and recycling. Energy recovery is more capital intensive than reclamation, and the harvesting and pulping of wood is more capital intensive than the preparation of waste paper for recycling."

[3] P. Ince and J. Klungness, Economics of increasing the use of recycled fiber in linerboard, *Tappi J.*, 67(8) (1984) p 62, estimate that in virgin kraft paperboard manufacturing the virgin kraft (sulfate) chemical pulping process yields only about 50% of input wood chips as output pulp product. Similarly, a recent report from International Paper by Wilfred Cote', *Life-Cycle Assessment: Proceed with Caution,* estimated that 56% of the energy requirements in the average paper mill are met by wood residues and byproducts.

[4] As an example of the impacts of this system boundary issue on calculations of energy and CO_2 emissions, in a study by the Institute for Energy and Environment (IFEU) in Heidelberg recently completed

Energy from these tree residues should be counted as part of total energy requirements for virgin-content paper products. In figures reported in this paper for energy savings from using recycled paper rather than trees to make paper, the intrinsic energy value of wood in the trees not used when making recycled-content paper is added to the net energy difference between recycled- and virgin-content paper making. This accounts for the wood energy saved by manufacturing with recycled paper rather than trees.

2.3. Adjustment for lower electrical generation efficiency of EFW

Perfectly efficient generation of electricity would yield 1 kilowatt hour (kWh) for each 3596 kilojoules (kJ) of heating value in the input fuel. However, due to heat loss and mechanical inefficiencies in converting fuel energy to electricity, 10 807 kJ are typically required to produce a kWh from conventional fuels such as petroleum or coal.[5] This is an average efficiency of just 33% (=3596/10 807).

Converting MSW into electricity is even less efficient than converting conventional fuels into electrical energy. Electricity from MSW typically is generated by injecting seasonally changing, heterogeneous, and often wet mixed solid waste materials into a mass burn furnace. The result is that only about 507 kWh of electricity are produced for each metric ton of garbage burned.

This electrical energy output is based on solid waste having an input heating value of about 12 100 kJ per kilogram (kg).[6] Thus, (12 100 kJ/kg × 1000 kg/metric ton =) 12.1 million kJ input heating value is required to produce (507 kWh/metric ton ×

Footnote 4 continued.
for the European Commission, energy used for planting, tending and harvesting timber, as well as CO_2 absorbed by growing trees, was excluded from the analysis of recycling versus incineration. "This made the combustion options appear more environmentally 'friendly'. If the system boundary had been moved back down the production cycle, proper account could have been taken of the fact that growing trees absorb CO_2, compensating for that released when paper is burned." (Quote from an article by one of the study team, Mike Flood, "Life Cycle Assessment: Understanding the Limits," *Warmer Bull.*, No. (1994) 5–6, published by The World Resource Foundation, Kent, UK.)

[5] Electrical generation factor from US Energy Information Administration, as reported in *1990 Statistical Abstract of the United States, p. 559.* See also, US Energy Information Administration, National Energy Information Center, *Energy Interrelationships, A Handbook of Tables and Conversion Factors for Combining and Comparing International Energy Data*, June 77.

[6] This estimate for average heating value of MSW is from Camp, Dresser and McKee, *Town of Oyster Bay Draft Environmental Impact Statement for a Proposed Resource Recovery Facility*, March 1988, pp. 4–125. Amir Shalaby, Ontario Hydro System Planning Division, in his paper "Role of Alternative Generation Sources in Ontario," presented at IEEE Power Engineering Society 1986 winter meeting in New York City, estimates that heating value of waste in urban areas is about 11 000 kJ/kg.

V. Pai, Ontario Hydro Mechanical and Equipment Engineering Department, "Energy From Municipal Solid Waste Issues," December 1989, p. 4, states, "The higher heating value of MSW, as received with typically 25% moisture is approximately 10 500 kJ/kg." Table 1 shows the composition of residential MSW for a typical residential waste stream, in this case residential waste in the Canadian province of Ontario. Based on this composition, Ontario's residential waste has an estimated average heating value of about 13 500 kJ/kg. However, the estimates of heating value for individual waste materials shown in Table 1 do not adjust for the 25% moisture content of mixed garbage.

3596 kJ/kWh =) 1.8 million kJ output electrical energy per metric ton of waste. This is an input/output efficiency of just 15%.[7] In other words, almost 2 Kg of waste, 23 820 kJ of input heating value from MSW, is necessary to generate 1 kWh.

To take into account the inefficiencies in burning solid waste to generate electricity versus burning a conventional fuel to generate electricity for a production process, heating values of the various waste stream materials are adjusted down by the ratio 10 807/23 820 = 45%. This yields heating values for EFW incineration of MSW materials that are comparable to heating values for energy inputs saved by manufacturing processes that use recycled instead of virgin material inputs.

2.4. Treatment of collection and processing energy for MSW and recycling

In this paper energy used to collect and haul MSW for incineration; to collect, haul and process MSW materials for recycling; and to transport processed recyclables to a manufacturing end user is accounted for separately from energy used to haul virgin materials to the manufacturing plant. For example, energy required to harvest trees and transport them to a pulping mill is accounted for in the net recycled versus virgin production energy calculation. But energy required to collect and process recycled paper and then transport it to a recycled paper mill is not included in the calculation of production energy conserved by recycling.

Rather, incremental energy necessary to collect recycled materials on a different truck then is used to collect garbage, energy used processing recyclables into commodities that can be used as manufacturing inputs, and energy required to transport recycled materials to manufacturers are used to determine how far recycled materials could be shipped before the energy savings from using recycled instead of virgin materials in manufacturing would be used up transporting them to market. Thus, transportation and processing energy usages are all taken into account for both recycling and incineration options; they just have been divided into two categories – manufacturing system and solid waste management system energy consumptions. The hauling of recycled materials from waste generator to market and the processing of recycled materials are included in the latter category, and used to calculate breakeven distance to market.

2.5. Calculation of average energy from incineration vs. recycling

As indicated above, just over 500 kWh are generated by incinerating a metric ton of garbage at an EFW facility – a conventional fuel equivalent heating value of less than 5500 kJ per kilogram (kg) of garbage. In Table 1, the composition mix of

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[7] Camp, Dresser and McKee, *op. cit.*, pp. 4–125, projected net electricity generation for sale per metric ton of incinerable solid waste to be 507 kWh. Oyster Bay's incinerable waste was projected to have a heating value of 12 095 kJ/kg, or 12.1 million kJ per metric ton. Thus, a 15% efficiency factor is specified in the engineering design of this particular EFW facility. A United States Environmental Protection Agency publication, "Reusable News," reported that EFW generates only about 475 kWh per metric ton (EPA/530-SW-91-022, Fall 1991, p. 5). The higher figure of 507 kWh per metric ton is used in this paper to calculate energy benefits for EFW incineration of MSW.

Ontario's residential garbage is shown to yield over 6100 kJ of conventional fuel equivalent heating value per kilogram. This is slightly higher than the heating value of waste typically received at incineration facilities, perhaps due to a different waste composition or to the fact that heating values used in Table 1 for individual waste materials do not adjust for the typical moisture content of mixed garbage. However, the difference is not critical to the results demonstrated in this paper.

What is important is to estimate average energy conserved by recycling and compare that estimate to the 5500 or 6100 kJ/kg of energy captured from garbage incinerated at an EFW facility. Table 1 provides this comparative figure by calculating the weighted average for energy conserved by manufacturing with recycled waste rather than virgin materials, where the weights are the relative proportions of waste materials in Ontario's residential waste stream.[8] Thus, Table 1 shows that recycling MSW materials on average conserves three to five times more energy than an EFW incinerator burning MSW generates.

It is important to understand that comparing the weighted average for energy conserved by recycling with average energy generated by incineration does not imply that waste must either be 100% recycled or 100% incinerated. The comparison is only meant to summarize the fact that for virtually every major waste material in MSW, recycling conserves more energy than is generated by incinerating that material in mixed garbage. However, the fact that 24 of 25 materials save more energy when recycled than they generate when burned does imply that, *ceteris paribus*, MSW materials should be recycled rather than incinerated whenever a choice is to be made between these two methods for managing MSW materials.[9]

3. Estimates of energy generated by incinerating MSW

Column 2 in Table 1 lists heat energy content for 26 materials typically found in residential MSW. Thirty-one residential waste materials are listed in Table 1, but energy values are not provided for five materials (vehicle and household batteries, white goods, residential construction and demolition debris and household hazardous waste) that are not, or should not be, burned in EFW facilities.

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[8] Ontario's residential waste stream is used because a portion of the study on which this paper is based was funded by Ontario Hydro as part of the adjudicatory hearings for Ontario's 25-year electrical power demand and supply plan. See Morris, Jeffrey, and, Canzoneri, Diana, *Recycling Versus Incineration: An Energy Conservation Analysis*, prepared for Pollution Probe (Toronto, Ontario) and Work on Waste USA (Canton, NY) by Sound Resource Management (Seattle, WA), September 92.

[9] A recent article, Lea, Reid, and Tittlebaum, Marty, Energy costs savings associated with municipal solid waste recycling, *J. Envir. Eng.,*, 119(6) (1993), comes to the same conclusion, except that the authors assumed that there were no economically viable production energy savings from recycling plastics. This led to the conclusion that plastics should be incinerated and other materials recycled to get the most energy benefit from MSW. However, there is a difficulty in recovering thermal energy only from plastics. MSW would need to be thoroughly sorted to burn just plastics and not burn any other materials. This sorting probably would add the economic viability to plastics recycling that Lea and Tittlebaum claim is absent.

As discussed in Section 2, an MSW-fired EFW facility is only 45% as efficient as a conventional fuel steam-electric power plant. Thus, MSW material heating values reported in column 2 of Table 1 are reduced by 55% to give energy values comparable to energy conservation estimates for recycling. Column 3 of Table 1 reports these adjusted EFW facility energy values.[10]

As shown at the bottom of column 3 in Table 1, residential MSW has an average electrical energy productivity of about 6100 kJ/kg incinerated. Individual material electrical energy equivalent values range from a high of about 21 000 kJ/kg for PET and HDPE plastics, to a low of about 100 kJ/kg for glass.

4. Estimates of production energy conserved by recycling

Table 1 lists 25 waste stream categories for which energy generated by burning waste is compared in this paper with energy conserved by recycling waste. No information could be found on energy savings from leather recycling.

The 25 categories include most commonly recycled materials. The energy estimates in Table 1 provide new information on potential energy savings from recycling certain major waste stream components, such as yard, food and wood wastes. For other waste materials, such as paper, plastics, glass and metals, secondary sources were used to estimate energy conservation through recycling. The diversity of estimates in these secondary sources is summarized in Table 1 by providing both the lowest and highest estimates for energy savings from recycling that were found in surveying the literature on energy conservation.

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[10] Conventional fuels used in steam-electric power generation include fossil fuels such as oil and coal. Stocks of fossil fuels in the natural environment are not replenishable within any human-scale time frame. For this reason fossil fuels are often termed "non-renewable" to distinguish them from fuel sources such as trees which can be regenerated. One reviewer of this paper suggested that saving renewable fuels is not nearly as important as saving non-renewable fossil fuels; thus, expending fossil fuels to save renewable fuels should not be viewed as a benefit.

While critical in other contexts, the distinction between renewables and non-renewables is not of primary concern in comparing the energy benefits for recycling versus incineration of MSW. In the first place, recycling most types of waste (e.g., plastics, glass, metals, organics, rubber and textiles) conserves non-renewable fuels almost exclusively, inasmuch as non-renewables provide the fuel source for most energy consumed in resource extraction, raw materials processing and manufacturing. It is mainly when recycled paper substitutes for virgin chemical pulp that non-renewable fuel usage may go up in order to reduce total energy consumed in manufacturing certain paper or paperboard products. Even in that case the trees saved could be substituted *in their entirety* for non-renewable fuels in the mix of energy sources used to supply energy for manufacturing. The result would be a reduction in non-renewable fuel usage as a result of paper recycling. Thus, the impact of MSW management choices on total energy consumption is much more significant than the impact of these choices on the mix of fuel sources used to meet total energy consumption needs.

In the second place, it is not at all clear what quantitative factor one would use to downgrade renewable kilojoules conserved relative to non-renewable kilojoules conserved by recycling. At a time when fossil fuel prices are at historically low levels and tree prices at historically high levels, any factor based on prices might actually favor renewable fuels.

Finally, other than their differences in heat value, an EFW facility certainly does not care whether it generates a kWh from paper or plastics. Yet the former is primarily formed from renewable, and the latter from non-renewable, energy sources.

Table 1
Energy generated by mass burn incineration versus energy conserved by recycling

Waste stream material	Residential waste composition (%)	Material heating value (kJ/kg)	EFW facility material energy equivalent to steam-electric power fuel energy[a] (kJ/kg)
Paper			
Newspaper	10.3	18 608	8444
Corrugated cardboard	14.6	16 282	7388
Office (Ledger & computer printout	5.7	18 143	8233
Other recyclable paper	4.8	16 747	7600
Metallic, plastic or wax coated	0.5	17 910	8127
Total	35.8	17 331	7865
Plastic			
PET	0.3	46 287	21 004
HDPE	0.9	46 287	21 004
Other containers	0.2	36 983	16 782
Film/packaging	4.3	32 099	14 566
Other rigid	1.8	36 983	16 782
Total	7.5	35 669	16 186
Glass			
Containers	5.7	233	106
Other	2.1	233	106
Total	7.8	233	106
Metal			
Aluminum beverage containers	0.4	1628	739
Other aluminum	1.1	698	317
Other non-ferrous	0.1	698	317
Tin and bi-metal cans	3.1	1628	739
Other ferrous	7.7	698	317
Vehicular batteries	0.5		
Household batteries	0.1		
White goods	1.0		
Total	14.0	889	403
Organics	16.0		
Food waste		6048	2744
Yard waste		6978	3166
Memo: MSW compost			
Wood waste	11.9	15 584	7072
Leather	0.1	16 747	7600
Rubber			
Tires	0.9	32 564	14 777
Other rubber	0.7	25 353	11 505
Textile	2.6	16 049	7283
Cotton			
Synthetic			
Diapers	1.1	23 609	10 713
Construction and demolition debris	0.6		
Small quantity hazardous	1.0		
Total/weighted average	100.0	13 514	6132

Table 1
Continued

Energy saved when recycled into		
same material/use		Other Materials[b] (kJ/kg)
Low est. (kJ/kg)	High est. (kJ/kg)	
21 450[c]	23 346[d]	38 600[b]
13 665[e]	32 108[f]	38 600[b]
34 699[c]	35 786[c]	38 600[b]
10 318[g]	32 108[f]	38 600[b]
		38 600[b]
18 863	30 264[h]	
60 825[i]	110 950	
66 058	82 573	
61 639	64 198[j]	
66 058	84 899	
41 868	95 887[k]	
59 934	87 877	
907[l]	5517	582[m]
		582[m]
907	4209[n]	
201 562[o]	312 098[o]	
201 562[o]	360 900[p]	
110 148[q]	122 429[r]	
7094[o]	37 100[o]	
14 496[p]	21 218[p]	
35 150	64 155	
		4215[s]
		3556[s]
		5548[t]
6422[u]	6422[u]	
No data	No data	No data
16 265[v]	48 796[v]	147 800
25 672[q]	25 672[q]	
		42 101[x]
58 292[y]	58 292[y]	
6801[z]	15 124[aa]	
20 060[bb]	31 270[bb]	

Source for residential waste composition: *Residential Waste Composition Study: Vol. 1 of the Ontario Waste Composition Study.*

Columns 4–6 in Table 1 provide estimates of energy saved for each type of waste when recycled material replaces virgin raw materials in manufacturing particular products. Many waste materials can be recycled into a wide variety of new products. For example, old newspapers (ONP) can be recycled into a variety of other products besides new newsprint – paperboard, gypsum wallboard backing or cellulose insulation, to name just a few. To account for this fact, columns 4 and 5 indicate energy saved when the product being manufactured is the same as the waste product being recycled, or can be used to fulfill the same final consumption need. For example, these columns give low and high estimates of energy saved by remanufacturing newsprint from ONP rather than manufacturing it from trees.

Estimates of energy conserved by recycling vary widely because estimated energy consumption in manufacturing products with either virgin or recycled materials is dependent on a wide variety of factors.[11] For example, the specific product being manufactured, the specific type of manufacturing equipment used, the age of the production facility, the accuracy of records kept on energy inputs, the extent to which machinery substitutes for human labor, and relative prices for various energy resources, all can have substantial impacts on estimated energy consumption.

Table footnotes continued.

Source for material heating values: 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, US Department of Energy.

Source for energy savings from recycling unless otherwise indicated: US Office of Technology Assessment, *Facing America's Trash: What's Next for Municipal Solid Waste*, US Government Printing Office, Washington, D.C. 1989.

[a] 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%.

[b] 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 the 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.

[c] P. Love, Energy savings from solid waste management options, *Resources Policy*, 1978. Estimates include Love's calculation of the energy value of trees not used.

[d] R.D. Kunz and M.R. Emmerson, *Energy Analysis of Secondary Material Use in Product Manufacture*, California Solid Waste Management Board, Nov 1979. Kunz and Emmerson's 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 remanufacturing 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

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[11] For an example of a study, based solely on secondary sources, in which the author chose to list a point estimate for energy savings from using secondary materials in manufacturing, see David C. Wilson, "Energy conservation through recycling," *Energy Res.*, 3 (1979) 307-323. Wilson's energy conservation estimates for recycled paper, glass and aluminum fall within the low-high ranges given in Table 1.

Column 6 in Table 1 provides an estimate of energy savings available by recycling a waste material into some product that is different from the waste material itself. For example, recycled-content paper or paperboard products are produced using many types of recycled paper and paperboard. Similarly, ceramics and other non-container glass items, as well as mixed-color broken glass can be recycled into asphalt. Tires can be recycled to replace a portion of polyurethane and produce a rubber–polyurethane composite material. Cotton textiles can be recycled into writing paper. Synthetic textiles can be reused as rags. Diapers can be processed to separate the various materials used in their manufacture, and those materials manufactured into new products.

Table footnotes continued

from Gunn and Hannon, Energy conservation and recycling in the paper industry, *Resources Energy*, 5 (1983) 245 and Table 4, p. 251.

[e] Tellus Institute, *CSG/Tellus Packaging Study*, "Report # 2: Inventory of Material and Energy Use and 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.

[f] 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 and Hannon, 3.64 metric tons of tree wood are required to produce 1 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.

[g] 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 and 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.

[h] High-end average includes use of metallic, plastic or wax coated papers in tissue making.

[i] Estimate from Jonathon Kimmelman, Natural Resources Defense Council.

[j] Based on 65% PVC, 25% polypropylene and 10% LDPE.

[k] 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*, Wiley, New York, 1984. Energy savings from recycling estimated at 90%.

[l] R.F. Stauffer, Energy savings from recycling, *Resource Recycling*, 1989.

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

[n] Includes use of other glass as construction aggregate.

[o] 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*, Queens College, CUNY, Flushing, NY.

[p] G.W. Reid and Chan Hung Khuong, *Energy Conservation Through Source Reduction*, Municipal Environmental Research Laboratory, Cincinnati, OI, U.S. EPA, EPA-600/8-78-015, 1978.

[q] Energy savings for recycling of copper from Leonard, LaVerne, Specifying metals for recycling, *Mater. Eng.*, 1985.

[r] Energy savings for recycling of copper from Reid, *op. cit.*

[s] 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.

[t] 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 and July of 1992.

[u] Based on C.W. Boyd, Peter Koch et al., Highlights from wood for structural and architectural purposes, *Forest Products J.*, 1977, Table 5; telephone conversation with Conor Boyd in January of 1992;

Just as the economic value of a resource typically should be represented by the price paid for its highest and best use, so should the energy value of a waste material be represented by kilojoules saved when the material is used in manufacturing that product which yields maximum energy savings. Where there exist estimates of energy savings for waste materials manufactured into more than one product, column 6 in Table 1 reports savings for that product in which energy conservation is highest. For example, recycled tissue and toweling saves more energy, 38 600 kJ/kg, versus its virgin content counterpart, than does any other major recycled-content paper type for which energy savings data are available. All categories of waste paper shown on Table 1 can be recycled into some type of tissue or toweling. Thus, 38 600 kJ/kg is listed as energy savings for tissue and toweling in column 6 for all five waste paper categories.

The remainder of this section provides a review of energy conserved by recycling each material. According to the averages given at the bottom of columns 4 and 5 in Table 1, recycling on average saves between 20 000 and 31 000 kJ/kg.

4.1. Paper

The energy saved when used paper or paperboard products are recycled into new paper or paperboard products ranges between 14 000 and 39 000 kJ/kg, where the

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Table footnotes continued.

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 2308 Btu's per oven dry pound of particleboard. Heating (i.e., drying) virgin wood requires 5.598 million Btu's per OD ton or 2799 Btu's per OD pound of particleboard. (Conversion factor for Btu to kJ, 1 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.

[v] 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.

[w] Based on 70 000–233 000 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.

[x] Based on cotton rags used in manufacture of writing paper as reported by Peter Love, *op. cit.*

[y] Reid and Khoung, *op. cit.*, p. 32, average energy consumed in manufacture of four synthetic textiles (polyester, nylon, acrylic modacrylic, and olefin). Energy savings is for use of synthetics as rags versus using new synthetic textiles as rags.

[z] 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," 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.

[aa] 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, 1991, reusable cloth diapers (at 167 uses per diaper) can be substituted for disposable diapers with 87% of reusable diapers home laundered and 13% 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.

[bb] Includes energy savings from column 6 whenever energy savings estimates are unavailable for columns 4 or 5.

high estimate is for manufacturing tissue and toweling papers. These energy savings estimates are from secondary sources listed in footnotes to Table 1, except that estimates were adjusted upward to include the energy value of trees not used when paper or paperboard products are made from recycled paper rather than trees.

For example, according to one source raw material transport and manufacturing energy savings alone would total 5800 kJ/kg of recycled-content newsprint, assuming that no incremental energy is expended to harvest trees for newsprint because the wood chips for pulping come from sawmill residues. To these energy savings is added the energy equivalent of the 2.13 kg of trees not used when a kilogram of recycled-content newsprint is produced, after adjusting for an estimated 85% yield in transforming ONP into newsprint.[12] This gives the high-end energy savings estimate for recycled-content newsprint manufacture. The secondary source for the low-end estimate for newsprint manufacture already included the energy value of trees.

As a second example of the energy savings from recycling paper and paperboard materials, metal/plastic/wax coated paper materials such as polycoated paperboard milk cartons are just beginning to be recycled. To account for the possibility of recycling polycoated papers into tissue, the 38 600 kJ/kg savings for recycled content tissue papers is included in column 6 of Table 1 opposite the metallic, plastic or wax coated paper waste material category.

4.2. Plastics

The energy saved when used plastic packaging or other plastic materials are recycled into new plastic products ranges between 42 000 and 111 000 kJ/kg. As indicated in footnotes to Table 1, these energy savings estimates are primarily from the US Congress Office of Technology Assessment (OTA). OTA based their estimates for energy savings from recycling the major commodity thermoplastics on the HDPE/PET reclamation process developed by the Center for Plastics Recycling Research at Rutgers University, and on the Extruder Technology 1 for manufacturing mixed post-consumer plastics into extruded plastic products. Because neither technology has as yet been widely applied in the US to the diverse range of plastics listed in Table 1, the energy savings estimates in Table 1 should be considered preliminary.

4.3. Glass

Energy saved when container glass is remanufactured into new containers is estimated to be between 900 and 5500 kJ/kg of recycled-content glass containers. Because most glass is manufactured using some recycled cullet, and because glass is seldom manufactured using only recycled cullet, these energy savings estimates do not compare 100% virgin glass versus 100% secondary glass containers.

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[12] See footnote d of Table 1.

Glass waste materials (e.g., ceramics and window glass) other than glass containers can be used in road surfacing (glasphalt) and road bed materials. These glass wastes also are being tried, along with mixed color container glass, as a substitute for construction aggregate. Based on estimated energy needed to produce sand, all types of glass yield energy savings of about 600 kJ/kg when recycled as a construction aggregate.

4.4. *Metals*

The energy saved when used metal packaging or other metal products are remelted into new metals ranges from a low of about 7000 kJ/kg for recycling tin-plated steel cans to 200000–360,000 kJ/kg for aluminum beverage containers and other aluminum scrap. Aluminum is extremely energy intensive when smelted from raw bauxite. However, aluminum cans and aluminum scrap metal are rather easily resmelted into, respectively, new aluminum sheet for cans and secondary ingot for use in other aluminum products.

4.5. *Organics*

The organic fraction of solid waste can be broken down biologically and transformed into compost. *Aerobic* composting involves biological transformation in the presence of oxygen. *Anaerobic* decomposition (also called "digestion" or "biogasification") involves biological transformation of organic wastes in the absence of oxygen. Though a newer technology, anaerobic digestion of solid waste offers potential net energy advantages over aerobic composting, since anaerobic systems produce methane (natural) gas in addition to producing a compost-like soil amendment.

Estimates for energy generated from composting organic wastes given in Table 1 are based on methane produced by anaerobic digestion being used as fuel for steam-electric power generation. The compost residue from anaerobic digestion is assumed to substitute for peat in use as a soil amendment.[13] In an assessment of anaerobic digestion, Robert Legrand and his associates calculated that anaerobic decomposition of MSW generates a net 5150 kJ/kg of material processed. When the humus-like residue from the digester is dewatered, screened and cured to produce a compost-like material, then substituted for peat, the anaerobically produced soil amendment increases the energy conserved by composting MSW to an estimated 5550 kJ/kg of MSW.[14]

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[13] For further detail on the energy conservation estimates for composting see Morris and Canzoneri, *op. cit.*

[14] Robert Legrand et al., "A Systems Analysis of the Biological Gassification of MSW and an Assessment of Proven Technologies." Estimates updated via phone conversations with Legrand in January and July of 1992.

Anaerobic digestion of yard waste produces a net estimated 3150 kJ/kg of waste digested. Substituting anaerobically digested yard waste for peat would increase energy savings to about 3550 kJ/kg of yard waste.[15]

Estimated energy savings from anaerobically digesting food waste assume that preprocessing food waste prior to anaerobic conversion requires only about 75% of the energy needed to preprocess MSW for anaerobic digestion, but that energy used at later stages of the process would be the same. The estimate also assumes that approximately 30% of food waste is dry and free of ash, and that 80% of the dry, ash free solids in food waste are converted into methane. Given these assumptions, anaerobic digestion of food waste produces a net 3800 kJ/kg of waste digested. Substituting the residue for peat could be expected to increase energy savings to 4,200 kJ/kg of food waste.

4.6. *Wood*

Using recycled wood in place of virgin wood in the manufacture of particleboard saves about 6400 kJ/kg of waste.[16]

4.7. *Rubber*

Retreading is the process by which tires can be recycled. It is really a combination of reuse and recycling in that the old tire's casing becomes the base for new tread material made from virgin rubber. Energy savings for retreading are estimated to be between 16 200 and 48 800 kJ/kg. The increasing popularity of radial tires, however, has complicated the retreading process and made retreading less common than in previous decades.

Stuart Natof, a Program Manager with the US Department of Energy, notes that the use of surface-treated rubber particles in polymer composites yields the greatest energy savings potential of all scrap tire uses. According to Natof, substituting surface treated rubber for a portion of the virgin polymers in composite materials yields a savings of between 67 000 and 229 000 kJ/kg of material substituted. Taking the mid-range of this estimate yields high-end energy savings of 148 000 kJ/kg.

Rubber products other than tires can be recycled at an estimated energy savings of 25 700 kJ/kg.

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[15] Based on conversations with Robert Legrand and David Chynoweth in January and July of 1992, and yard waste composting process energy consumption at Cedar Grove Compost Facility, King County, WA.

[16] Highlights from wood for structural and architectural purposes, *Forest Products J.*, (1977) by Conor W. Boyd, Peter Koch et al., Table 5; and telephone conversation with Conor Boyd (January, 1992). 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 2308 Btu's per oven dry pound of particleboard. Heating (i.e., drying) virgin wood requires 5.598 million Btu's per OD ton or 2799 Btu's per OD pound of particleboard. (Conversion factor for Btu to kJ: 1 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.

4.8. Textiles/diapers

One use for old cotton textiles is in manufacturing writing papers. Estimated energy savings in that use are 42 100 kJ/kg. The average energy consumed in manufacturing synthetic textiles is estimated at about 58 300 kJ/kg, based on polyester, nylon, acrylic modacrylic and olefin production. It is assumed that all this production energy would be saved if synthetics are reused as rags.

The low-end estimate of energy conservation from recycling disposable diapers considers only energy savings associated with the reclaimed pulp. This estimate ignores potential savings associated with reclaimed plastic and absorbent gel material, since only the pulp is currently marketable. Under these assumptions, recycling diapers instead of using virgin materials to produce kraft pulp saves about 62 600 kJ/kg of dry pulp, or 6800 kJ/kg of diapers recycled.

In recent work by Lehrburger and two associates, data was gathered on energy used during each step of the manufacturing process for both single-use and reusable diapers, as well as energy consumption during the laundering of reusables.[17] In the Lehrburger study it was assumed that 15% of the MSW waste stream, including single-use diapers, is burned for energy. This gave single-use diapers an incineration energy credit. To develop the high-end estimate reported in Table 1 for energy saved by recycling/reusing diapers, Lehrburger's figures were adjusted by deleting the incineration energy credit.

The manufacture and use of disposable diapers consumes 75% more energy than the manufacture and use of reusables. Reusables save 15 100 kJ/kg of diaper waste. To this figure is added 28 kJ, the energy savings that accrue if reusable diapers are recycled into cotton rags for paper production after their last use as diapers. With reusable diapers recycled into cotton rags at the end of their lives, substituting reusable for disposable diapers saves 15 100 kJ/kg of single use diaper waste.

5. Energy used to collect, process and market recycled materials

Table 1 shows that energy conserved by recycling is three to five times as great on average as the energy generated by incinerating MSW in an EFW facility. Only for food, yard and wood waste is energy generated from incineration close to or greater than the energy conserved when waste materials are recycled.[18] However, this comparison does not take into account the energy required to collect recyclable materials, clean and process them for market, and ship them to end users. At the same time, recycling diverts materials from the refuse stream and saves some of the energy necessary to collect and dispose of MSW.

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[17] Carl Lehrburger, Jocelyn Mullen, and C.V. Jones, January 1991, "Diapers: Environmental Impacts and Lifecycle Analysis," Report to The National Association of Diaper Services in Philadelphia, Pennsylvania. This report assumes 87% of reusable diapers are home laundered and 13% are washed by commercial diaper services.

[18] Table 1 may overestimate the energy generated by burning food and yard waste due to these materials being wetter on average than other components of MSW.

Incremental energy of under 300 kJ/kg is required to collect and prepare recyclables for market.[19] Shipping recyclables 1 km to market by truck requires 1.82 kJ/kg, while only 0.41 kJ/kg is required by rail.[20] Even less energy would be used by ship. Thus, most of the materials listed in Table 1 can be collected, processed and shipped to markets across the ocean. Recycling still saves energy versus simply collecting mixed refuse and disposing of it in an EFW facility.

In fact, the estimates in Table 1 of net raw material acquisition and production energy conserved by recycling conform quite well with customary practices in the recycling industry. Glass and compost, for example, are used near the community in which these waste materials are generated. But paper, plastics, and aluminum cans are often shipped to quite distant end-use markets.

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[19] Love, *op. cit.*, estimates baling at 105 kJ/kg. Allen L. White 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., estimates recyclables processing energy at 79 kJ/kg and landfilling energy at 109 kJ/kg. Based on a 70% weight reduction from incineration, only 30% of landfilling energy is saved when a kg of MSW is recycled rather than burned. Thus, for materials needing baling, the net energy used for recycling versus incineration, excluding collection, is $105+79-0.3*109=151$ kJ/kg. Net of savings in garbage collection energy, collecting recyclables is calculated to use on average less than 100 kJ/kg for the typical collection route. See White, *op. cit.*, pp. 65–66 and D1, and Morris and Canzoneri, *op. cit.*, pp. 33–36 and Table 2, for derivation of incremental collection energy for recyclables.

[20] Love, *op. cit.*