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ENVIRONMENTAL LIFE-CYCLE COMPARISONS OF RECYCLING, LANDFILLING, AND INCINERATION: A Review of Recent Studies

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ABSTRACT

This paper reviews and analyzes the major recent North American studies that have compared on an environmental basis the major options used to manage the materials that comprise municipal solid waste (MSW). The reviewed studies provide quantitative comparative information on one or more of the following environmental parameters: solid waste output, energy use, and releases of pollutants to the air and water. The review finds that all of the studies support the following conclusions: Systems based on recycled production plus recycling offer substantial system-wide or "life-cycle" environmental advantages over systems based on virgin production plus either incineration or landfilling, across all four parameters examined. Only when the material recovery or waste management activities are analyzed in isolation—which does not account for the system-wide consequences of choosing one system option over another—do the virgin material–based systems appear to offer advantages over recycled production plus recycling.

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OVERVIEW

This paper reviews and analyzes the major recent North American studies that have compared the energy use and environmental releases associated with each of the following three material acquisition, production, and management systems, as applied to the major material categories that comprise municipal solid waste (MSW):

1. recycled production plus recycling: material production processes that use recovered materials, coupled with recovery of the materials for recycling after use;

2. virgin production plus landfilling: material acquisition and production processes that use virgin materials, plus landfilling of such materials (after use) as part of MSW;

3. virgin production plus incineration: material acquisition and production processes that use virgin materials, plus incineration of such materials (after use) as part of MSW.

The reviewed studies provide quantitative comparative information on these systems for one or more of the following environmental parameters: solid waste output, energy use, and releases of pollutants to the air and water. Despite numerous differences in the methodology, assumptions, and data sources used by the authors of these studies, all of them support the following conclusions: Systems based on recycled production plus recycling offer substantial system-wide or life-cycle environmental advantages over systems based on virgin production plus either incineration or landfilling, across all four parameters examined. Only when the material recovery or waste management activities[1] are analyzed in isolation—which does not account for the system-wide consequences of

[1]Throughout this paper, recycling and materials recovery activities are distinguished from waste management; because materials collected and recovered for recycling serve as raw material for the production of new materials, they are not considered waste.

choosing one system option over another—do the virgin material–based systems appear to offer advantages over recycled production plus recycling.

Data from the most comprehensive study reviewed (1) show that when each parameter is summed across all of the material acquisition, production, and management activities that comprise each system, the three systems compare as follows: Recycled production plus recycling results in almost 1300 pounds less solid waste than virgin production plus incineration, and more than 2800 pounds less solid waste than virgin production plus landfilling, per ton of material processed. The reduction in energy use for the system based on recycled production plus recycling is more than three times greater than the net energy generated by virgin production plus incineration of MSW. Virgin production plus landfilling uses over 17 million Btus more energy per ton of material processed than does recycled production plus recycling and over 5 million Btus more per ton than does virgin production plus incineration.

Recycled production plus recycling results in the lowest air emissions of the three systems in 9 of 10 major pollutant categories. Virgin production plus incineration results in the lowest emissions in the remaining category. For all 10 categories, virgin production plus landfilling results in greater emissions than does recycled production plus recycling. Virgin production plus incineration results in the highest emissions of carbon dioxide of the three options, and for three of the other categories its emissions are only slightly lower than those from virgin production plus landfilling.

Recycled production plus recycling results in the lowest waterborne waste releases of the three options in six of eight major pollutant categories, while virgin production plus incineration results in the lowest releases in the remaining two categories. For all eight categories, virgin production plus landfilling results in greater releases than does recycled production plus recycling or virgin production plus incineration.

Relative to a composite virgin production plus waste management system comprised of a weighted average of the landfilling- and incineration-based virgin systems, recycled production plus recycling achieves the following relative reductions in energy use and environmental releases:

1. Recycling at the current rate of 26% reduces solid waste output by an amount equivalent to 32.9% of the total amount of MSW annually generated in the United States.

2. Recycling reduces energy use by an amount equal to the energy used by 8.95 million households.

3. Recycling reduces atmospheric emissions of several gases by amounts equal to the following percentages of the total emissions of such gases from all

sources in the United States: CO_2: 1.5%; CH_4: 9.0%; CO: 0.83%; NO_x: 1.3%; SO_2: 1.5%.

4. Recycling at the current rate of 26% reduces emissions of methane by an amount equal to 24.2% of the total emissions of methane from all MSW landfills in the United States.

This review reveals that all of the major recent comparative studies of recycling and waste management options demonstrate significant environmental advantages of recycling over landfilling and incineration, when the options are viewed from an appropriate system-wide perspective. This consistent finding stands in contrast to a more clouded public debate in which some observers have questioned the merits of recycling. Such questioning, however, is frequently based on assessments limited to material recovery and waste management activities, hence excluding the environmental impacts associated with material production activities.[2]

INTRODUCTION

As a social phenomenon and as an industry, recycling has grown dramatically in the past decade. In 1984, citizens, businesses, and trash haulers separated 10% of the nation's MSW for the purpose of recycling or composting it. A decade later, this percentage had more than doubled to make recycling the second most prominent MSW management method, after landfilling (2).

Despite this rapid growth, recycling is still under attack. Early opponents included solid waste officials who were resistant to change, and trash haulers and incinerator operators who resented the new competition, but the recent assault is led by a group of think tanks that, in response to what they see as the intrusive legislation and market distortion accompanying implementation of municipal recycling programs, have questioned the environmental benefits of recycling (see, for example, 3, 4).

Given this context, this paper provides a timely review of the major recent North American studies[3] that allow a life-cycle comparison of material acquisition, production, and management systems based on recycling, landfilling, and

[2]Some economists would justify this exclusion of the "upstream" impacts of materials acquisition and production by arguing that the market, i.e. the cost or price of materials and products, already incorporates or internalizes these impacts by including the costs incurred to control or mitigate them; others argue that the market is far from perfect in its ability to translate such environmental impacts into economic terms.

[3]The author is also a coauthor of another, more recent study that provides a similar life-cycle comparison of materials acquisition, production, and management systems, focused specifically on five major grades of paper (5).

Table 1 Major categories of recovered materials present in MSW: Percentage of all MSW, percentage recovered, and percentage of all materials recovered from MSW[a]

Material category	% of all materials present in MSW	% recovered	% of all materials recovered from MSW[b]
Paper and paperboard	38.9	35.3	68.7
Corrugated boxes/kraft paper	13.6	55.3	37.6
Newpapers	6.5	45.3	14.7
Office/computer paper	3.2	42.5	6.9
Mixed paper	7.1	17.6	6.3
Glass	6.3	23.4	7.4
Ferrous metals	5.5	32.3	8.9
Aluminum	1.5	37.6	2.9
Plastics	19.8	4.7	2.2
PET[c]	0.5	31.0	0.8
HDPE[c]	1.9	9.0	0.8

[a]Source: Based on Franklin Associates (2).
[b]Materials recovered from MSW are those in products, and exclude composted materials (yard trimmings and food waste).
[c]PET = polyethylene terephthalate; HDPE = high-density polyethylene.

incineration, across one or more of the following four environmental parameters: solid waste output, energy use, and release of air emissions and waterborne wastes. The comparisons focus on a collection of specific material components of MSW that are potentially recyclable and hence could be either recovered for recycling or managed as waste materials. These materials include various grades of paper, glass, steel cans, aluminum cans, and some types of plastic containers, all of which are materials commonly diverted and recovered from MSW for recycling. Table 1 shows the relative amounts of these materials present in MSW, the percentage of each currently recovered, and their relative contribution to all materials recovered from MSW for recycling.

Studies Reviewed

Each study reviewed here uses a life-cycle perspective in order to account for the full cycle of production of potentially recyclable materials and their management after use. The studies include the following:

1. Franklin Associates (FA) conducted a study for the Keep America Beautiful organization that provided estimates of energy use and environmental releases for systems based on landfilling, incineration, or recycling of various potentially recyclable materials (1). The materials were assumed to be collected from residences through a curbside collection program and managed in recycling or waste management facilities assumed to be typical of the United States as a whole, on the basis of national averages.

2. Tellus Institute conducted a study for the New York State Energy Research and Development Authority, based largely on conditions associated with recyclable material and MSW management in and around New York City (6). The Tellus study analyzed four different scenarios involving landfilling, incineration, and recycling of varying amounts of MSW. Unlike the FA study, this study included institutional and commercial as well as residential wastes.[4]

3. The US Department of Energy (DOE) commissioned a study by Stanford Research Institute, based on recyclable material and MSW management conditions for Palo Alto, California (7). As with FA, a curbside residential collection program was modeled.

4. A study examining incineration and recycling was done by Sound Resource Management Group (SRMG), based on recyclables and MSW management conditions in Ontario, Canada (8). SRMG's analysis is also based on residential curbside collection of recyclables.

Table 2 indicates the environmental parameters examined in each study and compares the mix of potentially recyclable materials collected through the programs modeled in each of the studies.

Where appropriate in this paper, other studies that examined only portions of the life cycles of the systems (e.g. manufacturing using virgin vs recycled materials) are reviewed to provide additional perspective.

Life-Cycle Systems to be Compared

The systems examined in the studies reviewed here are based on the three primary methods of managing MSW or components of MSW: landfilling, incineration (with energy recovery), and recycling. These three management methods are used to manage the overwhelming majority of materials found in MSW in the United States today.[5] Two recent reports that quantify materials recovery and waste management support this statement, although they use different methodologies and definitions of MSW and therefore arrive at somewhat different estimates of the fraction of MSW managed by each of the

[4]The values reported herein for a given component activity of a waste management option represent the average of the values determined for each of the four scenarios.

[5]The comparison here is limited to methods for managing materials that have already been generated. Other strategies, such as source reduction, increased efficiency of material production and use, and material reuse can reduce the amount of material generated that later requires management. These approaches are critical elements in reducing the overall environmental impact of material production, use, and postuse management, but they are beyond the scope of the studies reviewed here.

Table 2 Environmental parameters examined and assumed composition of recyclables in the reviewed studies

	Franklin Associates		Tellus		DOE/SRI		SRMG	
Environmental parameters examined	Energy use Air emissions	Solid waste output Waterborne wastes	Energy use		Energy use	Solid waste output	Energy use	
Material category	% of all recyclables	% of paper	% of all recyclables	% of paper	% of all recyclables	% of paper	% of all recyclables[a]	% of paper
Paper	50		80		64.5		36	
Corrugated boxes/kraft paper		—		41		7		42
Newspapers		100		19		93		28
Office/computer paper		—		18		—		17
Mixed paper		—		22		—		14
Plastic	6		5		0.5		7.5	
Glass	32		3		30		7.8	
Aluminum	3.5		2		2.5		0.5	
Steel	8.5		9		2.5		10	

[a]Composition of recyclables is not separately determined; rather, material categories are assumed to be recycled in the same proportion in which they are found in Ontario's waste stream.

three methods. FA estimates that, of the 209 million tons of MSW discarded in 1994, about 20% was recovered for recycling, 61% was landfilled, about 15.5% was burned in incinerators, and the remaining 3.5% was composted (2). *Biocycle*'s annual survey of recycling and waste management (for 1995) arrived at a higher estimate of MSW generated: 327 million tons. Of that total, an estimated 27% was recycled or composted, 63% landfilled, and 10% incinerated (9).[6]

BOUNDARIES OF THE SYSTEMS TO BE COMPARED To provide a consistent basis for comparison of the material acquisition, production, and management systems based on recycling and waste management methods, this analysis begins with an examination of the materials recovery and MSW management system components themselves: i.e. the analysis starts with the discard or recovery of potentially recyclable materials in MSW and follows them to the point where they are either (*a*) disposed of in a landfill, (*b*) burned in a MSW incinerator and the resulting ash residue disposed of in a landfill, or (*c*) processed and transported back to the site of remanufacture.

These boundary conditions do not provide a complete picture of environmental impacts associated with landfilling, incineration, and recycling, however. Indeed, such a limited perspective has the potential to distort one's view of actual environmental impacts, because of the close interplay between activities occurring within the immediate materials recovery and MSW management systems and certain activities lying outside those systems. For example, in tallying the amount of solid waste associated with recycling of used paper, we need to account not only for the amount of material diverted from disposal within the MSW management system (less any residuals generated during preparation of the material for remanufacturing), but also for the sludge produced during the manufacturing process, because processing recycled fibers generally produces more sludge than processing virgin fibers.

A full understanding of the environmental impacts of the various options, therefore, requires consideration of certain activities occurring outside of the immediate materials recovery and MSW management systems themselves. Two expansions of our view are needed:

1. Options that generate energy—namely, incineration at facilities that recover energy, and landfilling at facilities that employ methane recovery systems—are credited with reducing the amount of energy that would otherwise need

[6]*Biocycle*'s waste generation estimate is higher primarily because it is based on state-level generation data, and many states include industrial waste in their estimates if it is managed at the same facilities as MSW. This survey did not provide separate estimates for recycling and composting.

to be generated, typically at an electric utility. This credit offsets all of the environmental impacts associated with producing an equivalent amount of energy at the utility. Hence, the credit reduces not only the option's net energy use, but also its net solid wastes, air emissions, and waterborne wastes; this reduction occurs because the energy generated by the incinerator (or landfill) displaces some of the solid waste (e.g. coal ash), air emissions, and waterborne wastes that arise from the acquisition (extraction, refining, and transport) and consumption of fuels (oil, coal, etc) by the utility.[7]

2. For recycling, we need to account for changes in raw material acquisition and manufacturing processes due to the use of recycled rather than virgin materials. In most cases (as discussed in detail in this paper), acquiring and using recycled materials in manufacturing requires less energy and generates less solid waste and fewer air emissions and waterborne wastes than acquiring and using virgin materials. Hence, "credits" are earned for these reductions in energy, solid waste, and air and water releases; these credits reduce the amounts of energy, waste, and releases assigned to the recycling option.[8] Conversely, if more energy, solid waste, or air or water releases result from using recovered materials, "debits" are assigned to the recycling option.

To reflect these additional activities, therefore, we present findings for each option using two sets of boundary conditions: 1. the base case, limited to only those activities that lie within the materials recovery or MSW management system itself; 2. the system-wide view, which is the base case plus (*a*) the appropriate credits assigned to those options that generate energy (this expansion amounts to reducing certain electric utility–related impacts), and (*b*) the appropriate credits or debits assigned to raw materials acquisition and manufacturing using recycled rather than virgin materials. (This second expansion amounts to reducing or increasing certain acquisition- and manufacturing-related impacts.)

In this manner, our quantitative analysis of the materials recovery and waste management activities is expanded to a more complete life-cycle analysis that

[7]In the studies reviewed here, electricity generated by incineration is assumed to displace all sources of utility-generated electricity, in proportion to those sources' contribution to the nationwide generation of electricity at utilities. An alternative approach, used in some energy studies, is to assume that particular source types (e.g. coal-fired utilities) would be displaced first or exclusively, rather than all sources. The solid waste and emissions profiles of various electricity sources can differ dramatically; hence, the assumption used in the studies of average rather than marginal displacement—although easier to model—has the potential to produce a very different result.

[8]Here again, in the studies reviewed here, the reduction in energy use is assumed to displace all sources of electricity generation in proportions that are based on the national average electricity grid; the issues raised in Footnote 7 also apply here.

takes into consideration whole materials acquisition, production, and management systems.

SPECIFIC ACTIVITIES INCLUDED IN THE MATERIAL MANAGEMENT STAGES OF EACH SYSTEM Each of the options being compared here is comprised of numerous activities that each require energy and generate environmental releases. Some of these energy requirements or releases are directly associated with a specific activity, for example, the energy required to run a paper baling machine or the air emissions from an incinerator. Others are indirect, in that they may occur far removed from, but are nevertheless a consequence of, an activity within the system. For example, a full accounting of solid waste outputs associated with landfilling will include not only the amount of material directly managed, but also solid waste from the processes used to obtain the fuel needed to power landfill equipment (e.g. solid wastes from oil drilling and extraction). In this way, all activities associated with a given option that require fuel are assigned an amount of the solid waste associated with fuel acquisition that is in proportion to their fuel use.

For each option, Table 3 lists the direct and indirect activities that contribute to solid waste output, energy use, air emissions, and waterborne releases. Due to lack of data, the quantitative comparison (presented in the next section) omits some important activities involved in the landfilling- and incineration-based systems, most notably releases to the air and water from MSW landfills, except for carbon dioxide and methane emissions; releases of MSW incinerator ash or its constituents from ash landfills; and sludge generated by treatment of MSW or ash landfill leachate.

In contrast, essentially all activities comprising the recovered materials cycle are included within the scope of the quantitative comparison.[9]

Because of greater availability of data, most of the studies reviewed here model the collection of recovered materials through residential curbside collection programs. Other types of systems (e.g. drop-off centers and collection from commercial sources) contribute significantly to total recovery. As discussed in the next section, this assumption of curbside collection probably overstates the energy use and environmental impacts associated with collection of recyclables, especially for materials that are collected largely from commercial sources through more efficient systems. Similarly, most of the studies assume processing of recovered materials at material recovery facilities (MRFs). Because many recovered materials, especially those from commercial sources, bypass such intermediate processing and are delivered directly to the site of

[9]Our analysis does not include releases from disposal facilities for residuals from either the virgin or recycled fiber–based systems.

remanufacture, this assumption too probably overstates energy use associated with recycling.

MANUFACTURING PROCESSES COMPARED For each of the primary material classes considered in the reviewed studies—certain grades of paper, glass, aluminum, ferrous metals, and certain plastics—a comparison is made between a manufacturing process using 100% recovered material and its counterpart using 100% virgin material. When such materials contain recycled content, it is quite often at levels considerably lower than 100%. Using this basis for comparison, however, allows an assessment of the relative environmental impacts associated with the manufacture, use, and postuse management by various means of the recovered vs the virgin material. Products containing intermediate levels of recycled content would fall between the estimates provided in this paper for the 100% virgin and 100% recycled products.

Use of Average Values to Characterize Activities and Facilities

The environmental characteristics of the types of activities and facilities discussed in this paper will nearly always show considerable variation. In general, the data cited in the reviewed studies and presented in this paper represent national averages (means) or other values determined to be representative of the facilities and activities being characterized, and the comparisons are only valid for "typical" activities or facilities. These data may therefore overstate or understate the magnitude of a given environmental parameter for an activity in a specific location or for a particular facility. In most cases, however, average data are most appropriate for our purposes, because we are interested in comparing typical landfilling, incineration, and recycling practices, not best-case or worst-case practices. Moreover, one generally cannot dictate at precisely which facility, or by precisely what methods, recovered or discarded materials will be managed.

Limitations to the Analysis

The studies reviewed here are examples of life-cycle inventories, which seek to quantify inputs (energy and raw material requirements) and outputs (air emissions, waterborne effluent, and solid waste) incurred throughout the life cycle of a product, process, activity, or system. Such studies are incomplete descriptions of the environmental profile of the systems they analyze and compare. A particular shortcoming is that many of the environmental effects associated with obtaining virgin raw materials cannot be included because they are largely qualitative in nature. In addition to the energy required to extract and transport such materials (which typically is included in life-cycle inventories),

Table 3 Direct and indirect activities associated with landfilling, incineration and recycling that contribute to solid waste output, energy use, and air and water releases

Environmental parameter	Landfilling	Incineration	Recycling
Solid waste output	Waste from the acquisition of fuels (e.g. oil drilling wastes) used by MSW collection vehicles and landfill equipment Landfilled material itself	Waste from the acquisition of fuels (e.g. oil drilling wastes) used by: MSW collection vehicles utilities to generate the electricity used to operate incinerator equipment ash transport vehicles and ash landfill equipment Utility-related wastes (e.g. coal ash) Ash residue and scrubber wastes that are outputs of the combustion process	Waste from the acquistion of fuels (e.g. oil drilling wastes) used by: recycling collection vehicles utilities to generate electricity used to operate recyclable materials processing equipment residuals transport vehicles and residuals landfill equipment vehicles transporting processed recyclable materials to market Utility-related wasted (e.g. coal ash) Reject materials from recyclable materials processing (residuals)
Energy use	Energy consumed in the acquisition of fuels used by MSW collection vehicles and landfill equipment Energy represented by the fuels themselves consumed by the vehicles and equipment	Energy consumed in the acquisition of fuels used by: MSW collection vehicles utilities to generate the electricity used to operate incinerator equipment ash transport vehicles and ash landfill equipment Energy represented by the fuels actually consumed by: the MSW collection vehicles the utility the incinerator and associated equipment the ash transport vehicles and ash landfill equipment	Energy consumed in the acquisition of fuels used by: recycling vehicles utilities to generate the electricity used to operate recyclable materials processing equipment residuals transport vehicles and residuals landfill equipment vehicles transporting processed recyclable materials to market Energy represented by the fuels actually consumed by: the recycling collection vehicles the utility

			equipment used to process recyclable materials the residuals transport vehicles and landfill equipment the vehicles transporting recyclable materials to market
Air and water releases	Releases from combustion of fuels during the acquisition of fuels used by MSW collection vehicles and landfill equipment Releases from combustion of fuels themselves in the vehicles and equipment Volatilization to the air of products of waste decomposition, in the form of landfill gas	Releases from combustion of fuels during the acquisition of fuels used by: MSW collection vehicles utilities to generate the electricity used to operate incinerator equipment ash transport vehicles and ash landfill equipment Releases from the direct combustion of fuels by: the vehicles the utility the incinerator and associated equipment the ash transport vehicles and ash landfill equipment Releases directly from the incinerator arising from combustion waste	Releases from combustion of fuels during the acquisition of fuels used by: MSW collection vehicles utilities to generate electricity used to operate recyclable materials processing equipment residuals transport vehicles and residuals landfill equipment the vehicles transporting processed recyclable materials to market Releases from the combustion of fuels by: the MSW collection vehicles the utility the equipment used to process recyclable materials the residuals transport vehicles and residuals landfill equipment the vehicles transporting processed recyclable materials to market

raw materials extraction can have significant biological and ecological consequences, such as effects on biodiversity, wildlife habitat, and natural ecosystems. Such consequences create an important difference between recycled material– and virgin material–based systems that is not adequately captured by life-cycle inventories.

Significant sources of uncertainty are present in even the best studies, because data may be unavailable or of poor quality; a full methodology has yet to be precisely delineated; and numerous assumptions are needed to address these data deficiencies and methodological ambiguities. As a result, life-cycle inventories contain a significant degree of subjectivity.

The comparison of multiple inventory studies attempted here presents the additional challenge of identifying and understanding the differences in data sources, methodological choices, and assumptions made by different authors. Although space constraints do not allow a complete catalog of these differences, this paper does identify key differences and similarities among the studies' results and seeks to explain such differences on the basis of differences in the data sources, assumptions, or methodologies used in the studies.

No attempt is made in life-cycle inventories (including the studies reviewed in this paper) to assess the magnitude of actual environmental impacts from energy use and environmental releases; only the quantities of these parameters are reported. Actual impacts depend on site-specific and highly variable factors such as rate and location of releases, local climatic conditions, and population densities, which together determine the level of exposure to substances released to the environment. Such an assessment would require a detailed analysis of all sites where releases occur, which is well beyond the scope of an inventory-based study (and certainly this paper). The comparisons made here are of necessity limited to a quantitative comparison of data on the magnitude of energy use and environmental releases associated with the materials recovery and waste management options.

The comparison among the options applies to those materials in MSW that could be managed using any of the three options. The findings do not apply to other materials present in MSW that are not currently recycled to any significant extent and may be difficult or virtually impossible to recycle, at least with current technologies. Nor do the findings imply that the option with the lowest energy use or environmental releases is necessarily always the best or only option that should be used to manage MSW. In most if not all cases, a combination of management methods will be needed to manage all of the components of MSW, and one or more of the methods may be most appropriate for a given material depending on site- or time-specific factors. The comparison presented here is intended to help answer the following question: With respect to managing the next ton of potentially recyclable materials discarded, how do the environmental impacts of the three management options compare?

Differential Access to Materials Recovery and Waste Management Options

The three options being examined here differ in regional distribution and, therefore, in availability to a given community [The statistics in this subsection are taken from (9).]

1. Landfills (which receive more than 60% of all MSW in the United States) are ubiquitous in the United States, with active landfills numbering about 3200 in 1995 (down from 4500 in 1993) and present in every state.

2. Access to recycling programs has grown dramatically in recent years: In 1995, an estimated 7375 curbside programs, present in every state but Hawaii, served 121 million people in the United States—an increase of 44 million since 1992. Drop-off and buy-back centers and commercial recycling programs further extend the reach of these programs. About one quarter of all MSW in the United States is currently recycled.

3. MSW incineration is considerably less widespread, and it is used to manage 10–15% of all MSW in the United States. A total of 156 incinerators were operating in 1995, down from a peak of 171 incinerators in 1991. These facilities are concentrated in the Northeast, Florida, and some Great Lakes states; 15 states lack incinerators entirely.

4. Landfilling dominates as a waste management method in all regions except New England, where incineration edges it out; in all other regions, incineration is the least used of the three options.

Given these factors, in many areas of the country the practical choice is not among all three options, but rather between recycling and landfilling.

PRESENTATION OF COMPARATIVE DATA

The comparative data in this section include the net reductions in solid waste, energy, or air and water releases that result from: 1. activities that generate energy (e.g. incineration) and therefore reduce energy generation at utilities and its associated solid waste and air and water releases, and 2. remanufacturing using recovered rather than virgin materials. These net reductions will be shown as negative values as a means of accounting for them arithmetically. Even when negative values are assigned, however, the activities still have environmental impacts. The incineration and recycling processes still yield solid waste, require energy, and generate air and water releases. The negative values are intended to convey the fact that, on a net basis, incineration generates more energy than it uses, and manufacturing using recycled materials requires less energy and generates less solid waste and releases than does manufacturing using virgin materials.

In each of the following sections, results from the study conducted by FA will be presented first, followed by a comparison of these data to those from the other studies. Because the FA study is the most comprehensive in scope and the most recent, it provides a useful framework for discussing the results of all the studies.

Key assumptions of the FA study are listed below. Whenever the assumptions in the FA study are a factor in the differences in findings between this study and the other studies, the difference in assumptions is highlighted. The assumptions are as follows:

1. There is no recovery of landfill gas for energy generation; although some landfills do engage in this practice, most do not, so this assumption probably best typifies current practice (see below for more information on the energy potential of landfill gas recovery).

2. Mass-burn incinerator technology (the dominant technology in use today) is assumed. Electricity rather than steam is the energy product, and about 12.5% of generated electricity is used internally to run the process.[10]

3. A net amount of 480 kWh of electricity generated by a utility is assumed to be displaced by combusting one ton of MSW in an incinerator, after accounting for internal electricity use.[11]

[10]Mass-burn is the most common incineration technology, used at 109 of the 128 "waste-to-energy" incinerators operating in 1993 and accounting for more than 70% of the waste combusted in such facilities. An additional 34 incinerators that do not recover energy were in operation in 1993, also mostly mass-burn (30, 31).

[11]Energy generation from waste-to-energy incinerators varies with the particular facility design, age and other factors. FA cites a range of 500–600 kWh per ton of MSW combusted, before accounting for internal energy use, which it estimates to range between 10 and 15% of gross energy generated; the values used by FA to derive the incinerator energy estimates reported here correspond to the midpoints of those ranges. Other sources provide similar estimates for existing waste-to-energy incinerators. Berenyi & Gould (32) list gross and net power generation values for all operating mass-burn waste-to-energy incinerators. For the predominant mass-burn technology—waterwall furnace—the average gross output is 577 kWh per ton, the average net output is 526 kWh per ton, and the average net/gross ratio is 0.87. Values for other technologies (refractory and modular) are much lower. Argonne National Laboratory (23) models a somewhat lower generation rate for existing waste-to-energy incinerators (about 480 gross kWh per ton), as well as a higher

4. Ash is assumed to represent 20% by weight of MSW entering the incinerator, which, when adjusted for the typical 25% moisture content of the ash as it leaves the incinerator, results in 534 pounds of ash per ton of MSW burned; ash is assumed to be disposed of in a landfill.

5. Residential recyclables are collected commingled through a curbside program[12] and are separated and processed at a materials recovery facility (MRF) that is assumed to employ an average of the technologies used at high-tech and low-tech MRFs.

6. The amount of material rejected at the MRF and sent to landfill is 8% by weight of the incoming commingled recyclables.

7. Processed recyclables are shipped to end markets by a mix of truck and rail and over distances chosen as typical for a given material.

Solid Waste Output

FRANKLIN ASSOCIATES STUDY The recent study conducted by FA for Keep America Beautiful provides a relatively comprehensive framework for examining solid waste outputs associated with landfilling, incineration, and recycling of mixed recyclables collected in a residential curbside collection program. Table 4 displays the FA study estimates of the output of solid waste (or the amount of solid waste avoided, which is a negative value) per ton of material processed for each of the various activities involved in landfilling, incineration, and recycling. Several points are apparent from this table:

1. With all three methods, the bulk of the solid waste output is either MSW itself (for landfilling) or the predominant solid waste resulting from recovered materials or MSW management (ash in the case of incineration, and MRF reject materials in the case of recyclables), rather than solid wastes from activities separate from the materials recovery or MSW management system.

2. With all three methods, only very low amounts of solid waste result from acquisition and use of fuels and electricity in the transport-related activities

efficiency (about 680 gross kWh per ton) to represent planned facilities. Tellus (6) uses a value (also about gross 680 kWh per ton) based on its projection of the efficiency of facilities built in the year 2000. Finally, the 34 incinerators operating in 1993 that do not recover any energy, accounting for about 7% of national incinerator capacity, must be factored into an average energy generation estimate for MSW incineration. All incinerator energy generation estimates provided here are based on averages for existing incinerators, although newer facilities may generate more energy.

[12]This assumption of curbside collection probably overstates the energy use and associated environmental impacts of collection of recyclable materials, especially those collected largely from commercial sources through more efficient systems.

Table 4 Solid waste outputs from component activities of MSW landfilling, incineration, and recycling[a]

Landfilling		Incineration		Recycling	
Collection/ landfill equipment	0.2637	Collection	0.1484	Collection	0.4944
Landfill	2000.0	Combustion	534.0	MRF processing	163.8
		Electric utility	(88.1)[b]	Residue disposal	0.0211
		Ash disposal	0.0396	Transport to market	0.1066
				Manufacturing	(996.2)
Total	2000.3	Total	446.1	Total	(831.8)

[a]Values are in pounds per ton of material managed. Source: Based on (20).
[b]Values in parentheses are negative values and represent net reductions in utility solid waste due to energy generated by incineration and in manufacturing solid waste due to use of recovered rather than virgin materials.

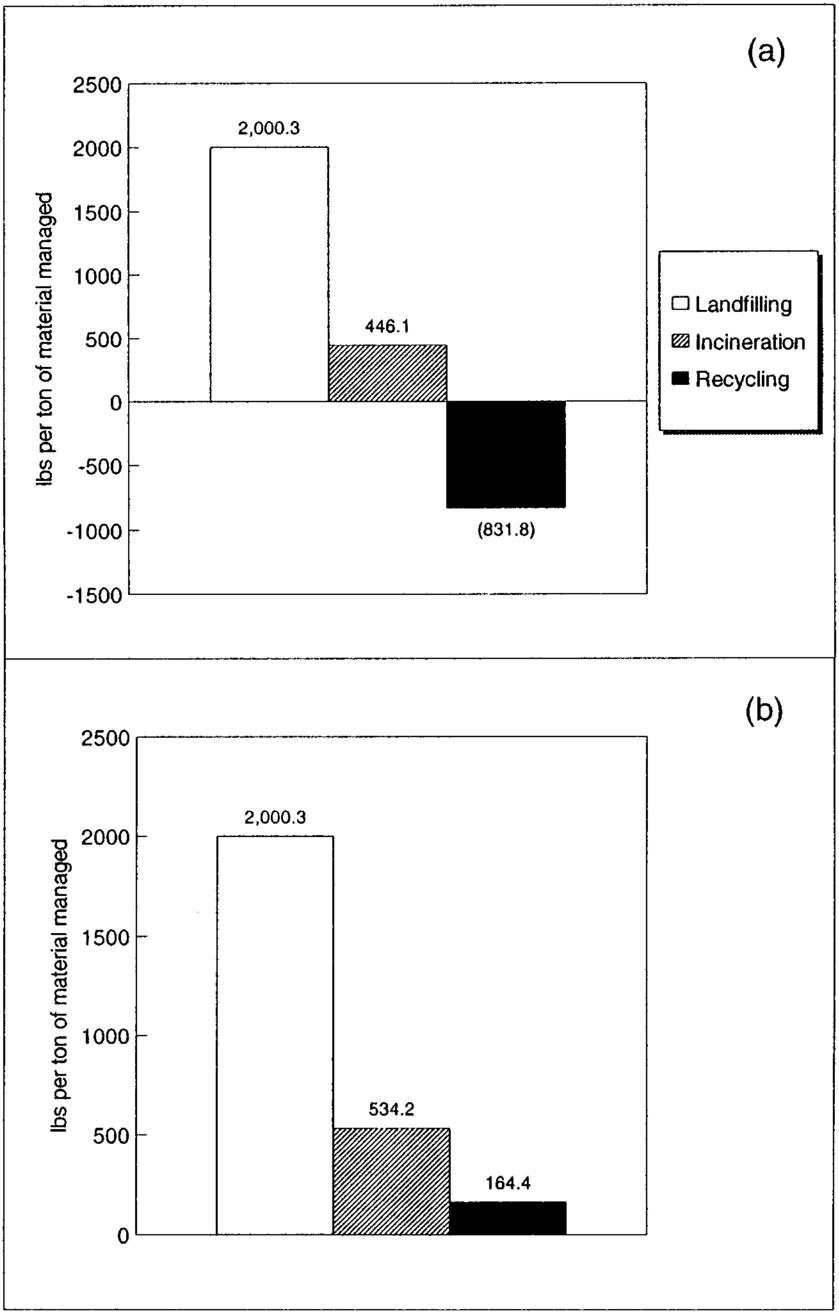
(collection of MSW or recyclables, transport of residual ash or MRF rejects, transport of processed recyclables to end markets) and in the material-handling activities (by processing equipment, landfilling equipment, etc).

3. The energy generated by incineration yields a substantial solid waste credit (88 pounds per ton of MSW incinerated) because the energy produced means that less energy, along with its associated solid waste (e.g. coal ash), has to be produced by an electric utility; nevertheless, for every ton of MSW incinerated, a net output of 446 pounds of solid waste results.

4. Recycling results in the lowest output of solid waste, even before accounting for the very large solid waste credit (almost 1000 pounds for every ton of material recycled) that results from use of recovered materials rather than virgin materials in manufacturing.

Figure 1 summarizes solid waste outputs for the three management methods, showing the effect of including or excluding reductions in waste from electric utilities and from remanufacturing. Under either of these boundary conditions, recycling clearly results in the least solid waste, and when viewed from a system-wide perspective (Figure 1*a*), recycling of MSW actually results in a net reduction in solid waste relative to a system based on virgin materials manufacture.

Figure 1 FA's estimates of solid waste output from MSW management. (*a*) Net solid waste output, including reduction in utility and manufacturing wastes. (*b*) Solid waste output, excluding reductions in utility and manufacturing wastes. Based on data from (1).


(a)
2,000.3
446.1
(831.8)
Landfilling
Incineration
Recycling
lbs per ton of material managed
2500
2000
1500
1000
500
0
-500
-1000
-1500
(b)
2,000.3
534.2
164.4
lbs per ton of material managed
2500
2000
1500
1000
500
0

OTHER STUDIES In the study by the DOE, reductions in utility or manufacturing wastes were not estimated, so the results are analogous to those from the FA study shown in Figure 1*b*. Transport-related wastes were not included either, although the report indicates that they are minor in comparison to the materials being managed. The DOE data further distinguish between the two major incinerator technologies: mass-burn (which was the basis for the FA estimates) and refuse-derived fuel (RDF), in which noncombustible materials are removed from waste to be incinerated and directly landfilled. DOE made the following assumptions about each technology:

1. For mass-burn, 27.25% by weight of the incoming MSW incinerated remains as ash (including scrubber waste).

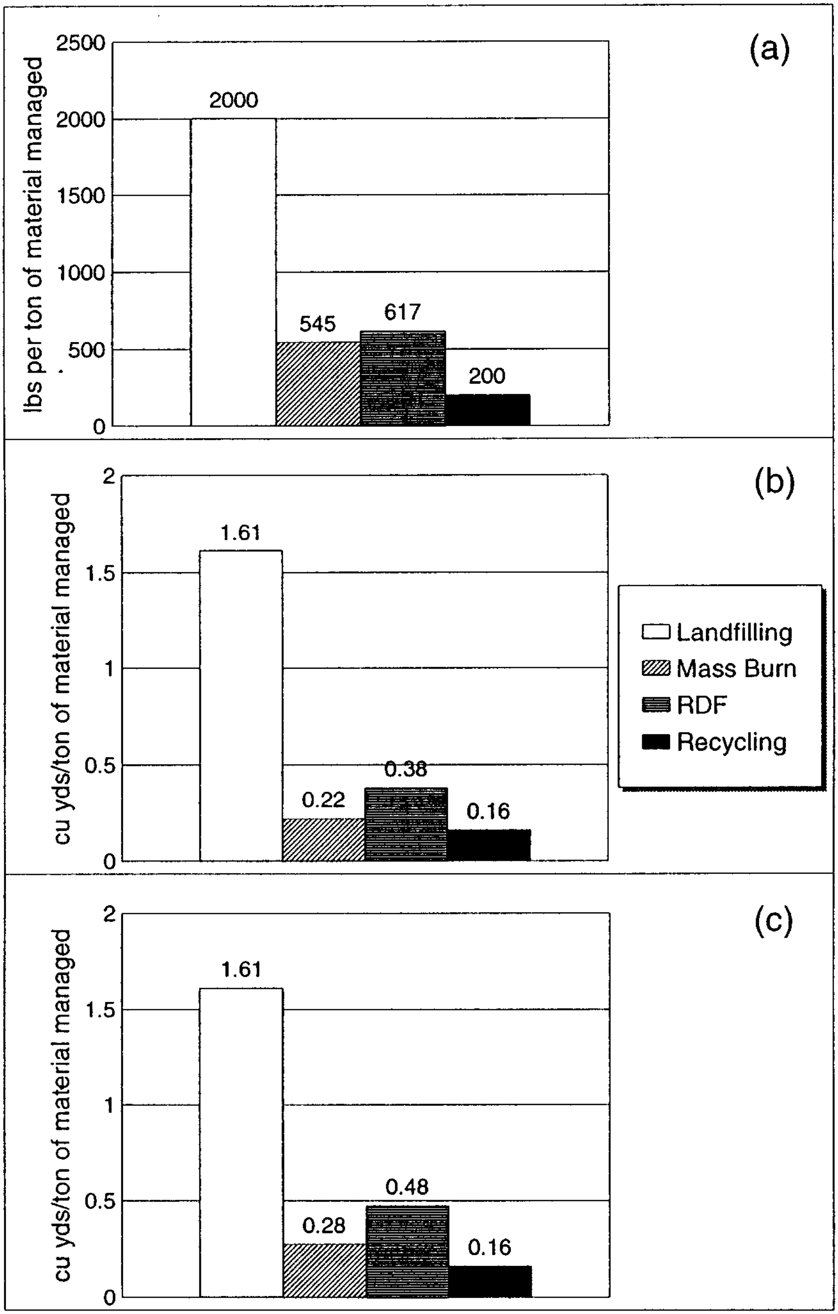
2. For RDF, 20% of the incoming waste is diverted from incineration: 16% is reject materials sent directly to a landfill, and 4% is ferrous metals separated for recycling. The remaining ash (including scrubber waste) is 18.6% of incoming RDF incinerated.

3. For recycling, 10% of collected recyclables is rejected and directly landfilled.

Figure 2*a* shows the results of the DOE study. As can be seen by comparison to Figure 1*b*, these results are quite similar to those from the FA study: Solid waste output from recycling is roughly one third that from incineration, which is in turn roughly one third that from landfilling.

The DOE study estimated not only the weight, but also the landfill volume that solid waste resulting from each option would occupy. Both MSW and RDF and MRF reject materials were assumed to have a landfill density of about 1240 pounds per cubic yard, whereas ash density was assumed to be more than twice as high, about 2500 pounds per cubic yard; the former value is roughly consistent with other estimates (10), whereas the latter value is 14–67% higher than other estimates (11–13). Despite this assumption, which makes incineration appear more preferable (Figure 2*b*), the DOE estimates still show that recycling generates the lowest volume of solid waste, before accounting for any manufacturing-related credits. Volumes using a more realistic density for ash of 2000 pounds per cubic yard are shown in Figure 1*c*.

Figure 2 DOE's estimates of solid waste output from MSW management. All values exclude reductions in utility and manufacturing wastes. (*a*) Solid waste output by weight. (*b*) Solid waste output by volume, using DOE's ash density value. (*c*) Solid waste output by volume, using a more realistic ash density value. Based on data from (7).



(a)
lbs per ton of material managed
2500
2000
1500
1000
500
0
2000
545
617
200
(b)
cu yds/ton of material managed
2
1.5
1
0.5
0
1.61
0.22
0.38
0.16
Landfilling
Mass Burn
RDF
Recycling
(c)
cu yds/ton of material managed
2
1.5
1
0.5
0
1.61
0.28
0.48
0.16

Energy Use

As with solid waste output, energy is used in many different component activities associated with landfilling, incineration, and recycling. Energy may be used in several different forms: as fuel consumed by vehicles or equipment (e.g. diesel oil), as fuel burned to generate electricity or steam (e.g. coal), and as electricity (typically purchased from an off-site utility) used to operate equipment.

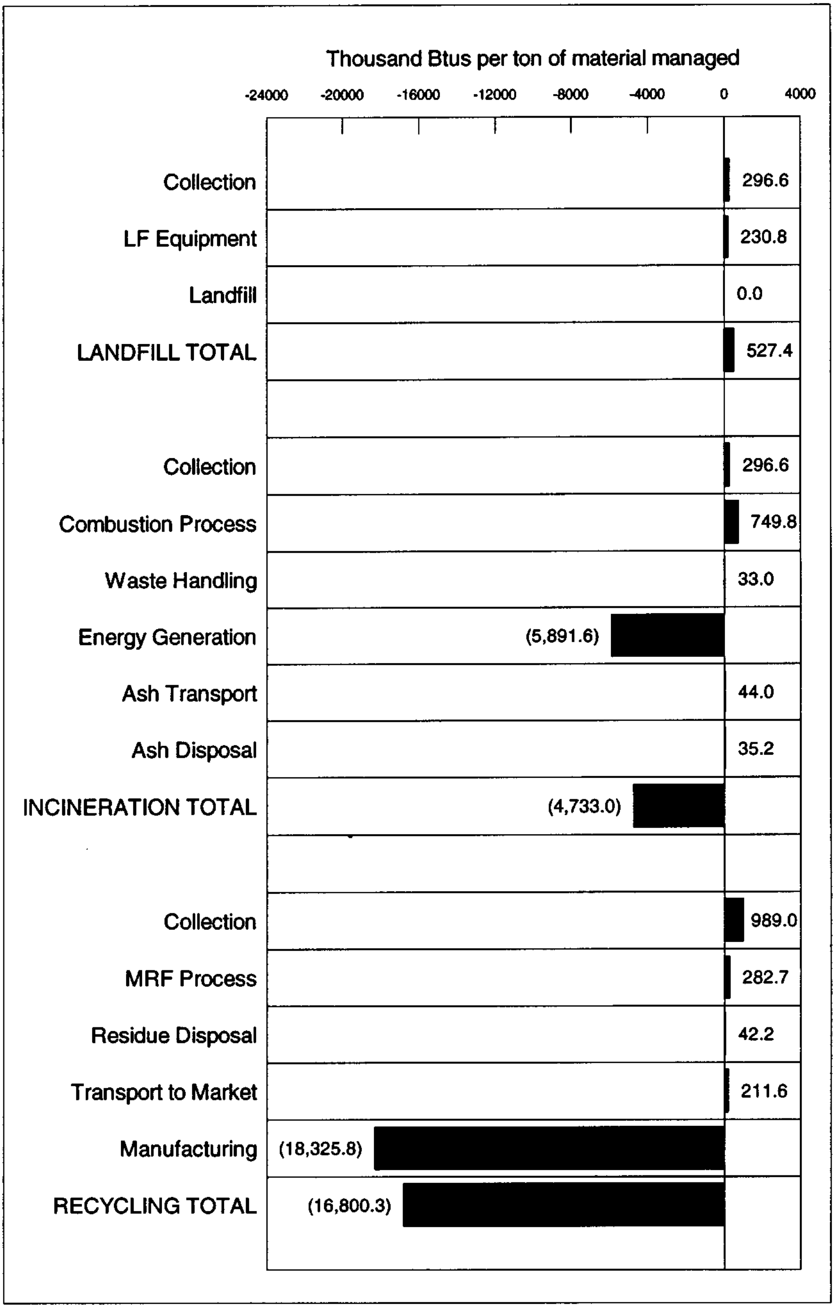
Energy use can be reduced in several ways as well: through production of a fuel produced by a facility for subsequent use to generate energy (e.g. landfill gas or RDF); through generation of electricity or steam produced by a facility for internal or external use (e.g. electricity produced by a waste-to-energy incinerator); and through a reduction in use of fuel, electricity, or both, that results from more energy-efficient processes (e.g. energy use reductions resulting from use of recycled vs virgin materials in manufacturing).

To provide a consistent basis for comparing energy use, energy generation, and energy use reductions, all energy data presented here are reported in terms of useable electric energy expressed in British thermal units (Btus); that is, regardless of whether energy is consumed or generated in the form of fuel (typically fossil fuel) or electricity, all values are converted to the equivalent amount of electric energy. This conversion is done using a typical heat rate (Btus per kWh) representative of all types of electric generating facilities based on the mix of different energy sources (coal, oil, hydropower, nuclear) that provide electric energy to the national grid. Typical conversion factors used for converting diesel fuel or fossil fuel–fired utility-generated electricity into Btus are as follows: (*a*) 1 gallon of diesel fuel is equivalent to 164,800 Btus, (*b*) 10,712 Btus are required to produce 1 kWh of electricity (1, 14).

FRANKLIN ASSOCIATES STUDY The recent FA study compares energy requirements for the various component activities associated with landfilling, incineration, and recycling. Figure 3 displays the study's estimates of the amount of energy required (or the reduction in energy use), per ton of material processed, for each of the activities involved in landfilling, incineration, and recycling. These data indicate the following:

1. Collection represents the highest (for landfilling and recycling) and the second highest (for incineration) use of energy. The identical collection energy

Figure 3 FA's estimates of energy use for component activities of MSW management. Negative values represent incinerator-generated energy or reduction in manufacturing energy. Based on data from (1).



Thousand Btus per ton of material managed
-24000
-20000
-16000
-12000
-8000
-4000
0
4000
Collection
296.6
LF Equipment
230.8
Landfill
0.0
LANDFILL TOTAL
527.4
Collection
296.6
Combustion Process
749.8
Waste Handling
33.0
Energy Generation
(5,891.6)
Ash Transport
44.0
Ash Disposal
35.2
INCINERATION TOTAL
(4,733.0)
Collection
989.0
MRF Process
282.7
Residue Disposal
42.2
Transport to Market
211.6
Manufacturing
(18,325.8)
RECYCLING TOTAL
(16,800.3)

seen for landfilling and incineration reflects the fact that they both involve the collection of essentially the same material. The collection energy for recycling is estimated by FA to be much (over threefold) higher. This estimate reflects an underlying assumption that collecting recyclables requires more trucks (and hence more fuel) than collecting the same weight of MSW. This difference is due largely to the fact that (*a*) trucks generally fill up by volume before they reach any applicable weight restrictions, and (*b*) MSW is compacted to high density by the packer trucks used to collect it, whereas commingled recyclables are transported uncompacted. Indeed, FA assumes that a typical packer truck used to collect MSW can carry 7.5 tons, whereas a truck collecting recyclables carries only 1.8 tons (15). These assumptions have been questioned by some observers (M Clarke and J Morris, personal communications). The figures used by FA may particularly overstate collection energy for paper, which has a considerably higher density than the mixed recyclables modeled by FA.[13] (See further discussion of this assumption in the discussion of other studies below.)

2. Running the incinerator also requires considerably more energy—about three times more per ton of material processed—than running landfilling or MRF processing equipment;[14] this difference reflects the generally capital- and technology-intensive nature of incineration.

3. Relatively low amounts of energy are required to dispose of residuals from incineration and recycling.

4. Transporting processed recyclables to end markets consumes only a modest amount of energy (even under the assumption used here that such materials are not backhauled by vehicles used to transport other goods or materials).

5. Recycling uses the most energy per ton of material processed, about 32% more than incineration; landfilling uses the least.

6. Energy use is low, however, compared to the amount of energy generated by incineration or the reduction in energy use resulting from manufacturing

[13]Some sources indicate that the first figure may be too high and/or the second too low, based on operating experience in some locations such as New York City and Portland, Oregon. Clarke (M Clarke, personal communication) reports that MSW packer trucks used to collect residential recovered paper can weigh as much as 12 tons, while an MSW packer truck averages about 10 tons. Morris (J Morris, personal communication) reports that MSW in full collection vehicles in Portland ranges in weight from 3.5–6.9 tons.

[14]FA calculates that a low-tech MRF would consume about 180,000 Btus per ton of recyclable material processed, whereas a more equipment-intensive high-tech MRF would consume over twice that amount, about 390,000 Btus per ton.

with recycled materials. Incineration generates five times more energy than it uses, and using recovered materials in place of virgin materials in manufacturing reduces energy use by 12 times more than is required to collect and process the recovered materials and transport them to market.

7. Under the assumptions of this study, using a ton of paper, metal, glass, and plastics collected in a curbside program as a substitute for virgin materials reduces manufacturing energy by 18 million Btus, a reduction more than three times higher than the energy generated by incinerating a ton of MSW. When all activities entailing energy use are tallied, MSW incineration results in only 28% of the net reduction in energy use realized through residential MSW recycling.

Figure 4 summarizes energy use for the three management methods, showing the effect of including the energy generated by incineration and the reduction in energy use due to use of recycled materials in manufacturing. Within the waste management system itself (Figure 4*b*), recycling uses somewhat more energy than the other options; system-wide, however (Figure 4*a*), recycling uses the least energy by a large margin.

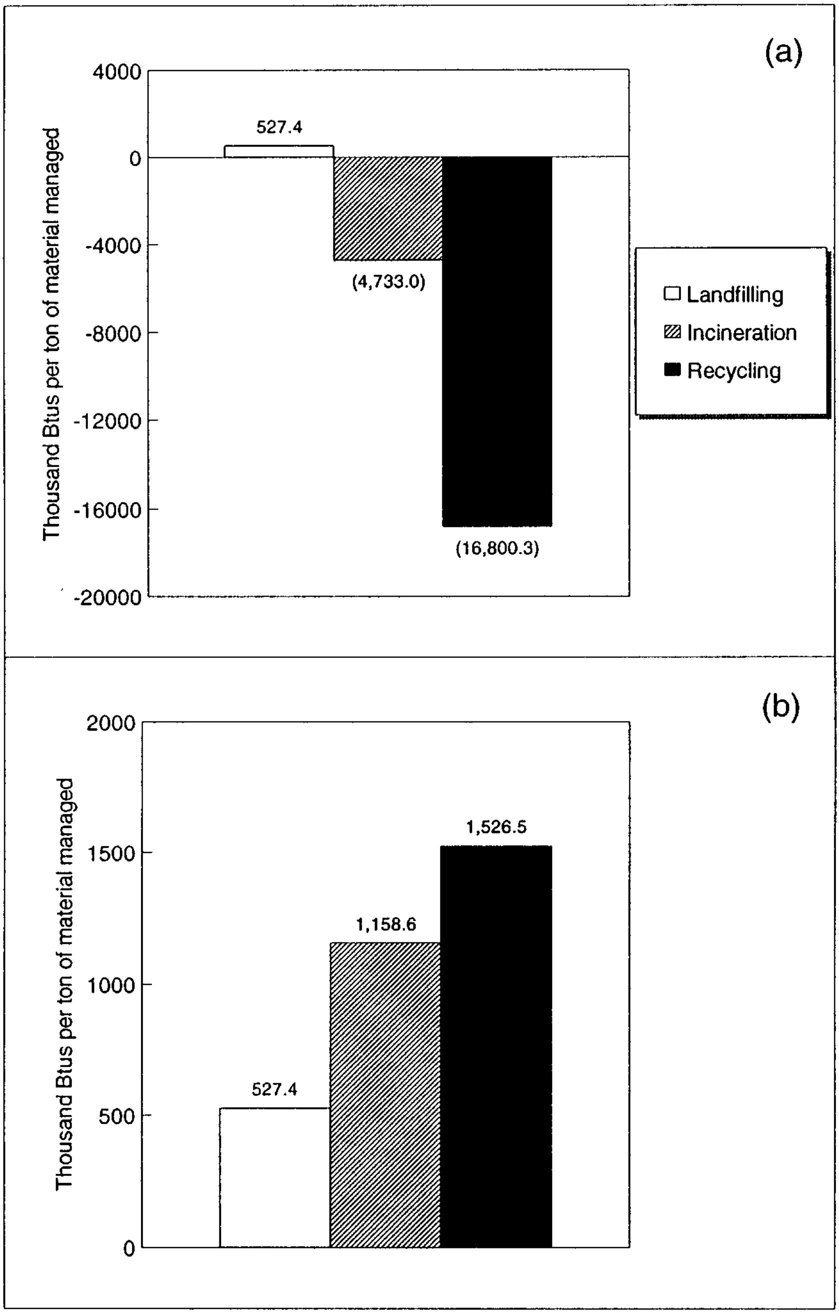
OTHER STUDIES The studies by the Tellus Institute, DOE, and SRMG also estimate energy requirements for landfilling, incinerating, and recycling MSW. Although the studies used different assumptions in many cases, a comparison of their estimates for energy use associated with the three management options is useful. Such a comparison is shown in Table 5.

The figures in Table 5 include estimates for generation of energy at landfills by recovery and burning of landfill gas. Of an estimated 4500 landfills operating in the United States in 1993 (18), 127 had gas-to-energy operations, and such operations were under construction or in planning stages at another 60 landfills (19). Due to this limited use of landfill gas recovery, this activity is not included in the primary environmental profile of landfilling presented in this section. However, estimates from the various reports of the potential amount of energy recoverable from the collection and burning of landfill gas are included here. As one example, FA (20) recently reported the following data on landfill energy potential:

1. 123.0 pounds of methane are produced per ton of MSW landfilled.

2. A typical recovery rate for methane from landfill gas is 66%.

3. A typical gas turbine can generate 1.75 kWh of electricity per pound of methane burned, based on an energy value of landfill gas (methane) of about 500 Btu per cubic ft of gas.


(a)
Thousand Btus per ton of material managed
4000
0
-4000
-8000
-12000
-16000
-20000
527.4
(4,733.0)
(16,800.3)
Landfilling
Incineration
Recycling
(b)
Thousand Btus per ton of material managed
2000
1500
1000
500
0
527.4
1,158.6
1,526.5

←

Figure 4 Summary of FA's estimates of energy use for MSW management. Negative values represent net energy after accounting for incinerator-generated energy or reduction in manufacturing energy. (*a*) Net energy, including incinerator-generated energy and reductions in manufacturing energy. (*b*) Energy use only, excluding incinerator-generated energy or reduction in manufacturing energy. Based on data from (1).

Table 5 Comparison of estimates derived from several recent studies for energy use for three MSW management option[a]

	Collection/ transport	Processing	Residuals transfer/ disposal	Total energy use	Generation or reduction	Net energy
Landfilling						
Franklin	296,600	—	230,800	527,400	(1,542,500)[b]	(1,015,100)
Tellus	86,914	—	10,001	96,915	(1,782,936)	(1,686 021)
DOE/SRI	79,000	—	2,000	81,000	(2,200,000)	(2,119,000)
Incineration						
Franklin	296,600	782,800	79,192	1,158,592	(5,891,600)	(4,733,008)
Tellus	69,456	942,580	6,178	1,018,214	(5,518,379)[c]	(4,500,165)
DOE/SRI	79,000	510,000[d]	300	589,300	(5,260,000)[d]	(4,670,700)
SRMG					(5,270,300)	
Recycling						
Franklin	989,000	282,700	42,200	1,313,900	(18,114,209)[e]	(16,800,309)
Tellus	58,555	286,611	18,907	364,073	(7,985,632)[e]	(7,621,559)
DOE/SRI	230,000	200,000	20,000	450,000	(8,000,000)[f]	(7,550,000)
SRMG	73,915	82,510		156,425	(22,088,500)[g]	(21,932,075)

[a] All values are in Btu/ton of material processed. Sources: Based on data from (6–8, 20).

[b] Values in parentheses reflect gross energy generated by incineration or landfill gas recovery, or net energy reduction due to manufacturing with recycled rather than virgin materials.

[c] Adjusted to reflect: 1. a typical current gross heat rate for incinerator-generated electricity (21,518 Btu/kWh), and 2. a typical current boiler efficiency of 65%; the values used by Tellus (15,035 Btu/kWh and 75% respectively) were chosen to reflect expected performance of an incinerator built in the year 2000.

[d] Corrected to reflect the equivalent useable electric energy production (i.e. the Btu value for the amount of utility-generated electric energy used or saved).

[e] Includes energy required to transport processed recyclables from a MRF to the point of remanufacture.

[f] Excludes energy required to transport processed recyclables from a MRF to the point of remanufacture (but study estimates such energy use to be small, only 1–5% of total manufacturing energy).

[g] Excludes energy required to transport processed recyclables from a MRF to the point of remanufacture (but study estimates such energy use to be small, only about 1% of recycling's energy savings).

4. Hence, 144 kWh of electricity could be produced per ton of MSW landfilled, the fossil-fuel equivalent of 1,542,500 Btus per ton.

Energy requirements to collect, process, and burn landfill gas are not included in this estimate, however.

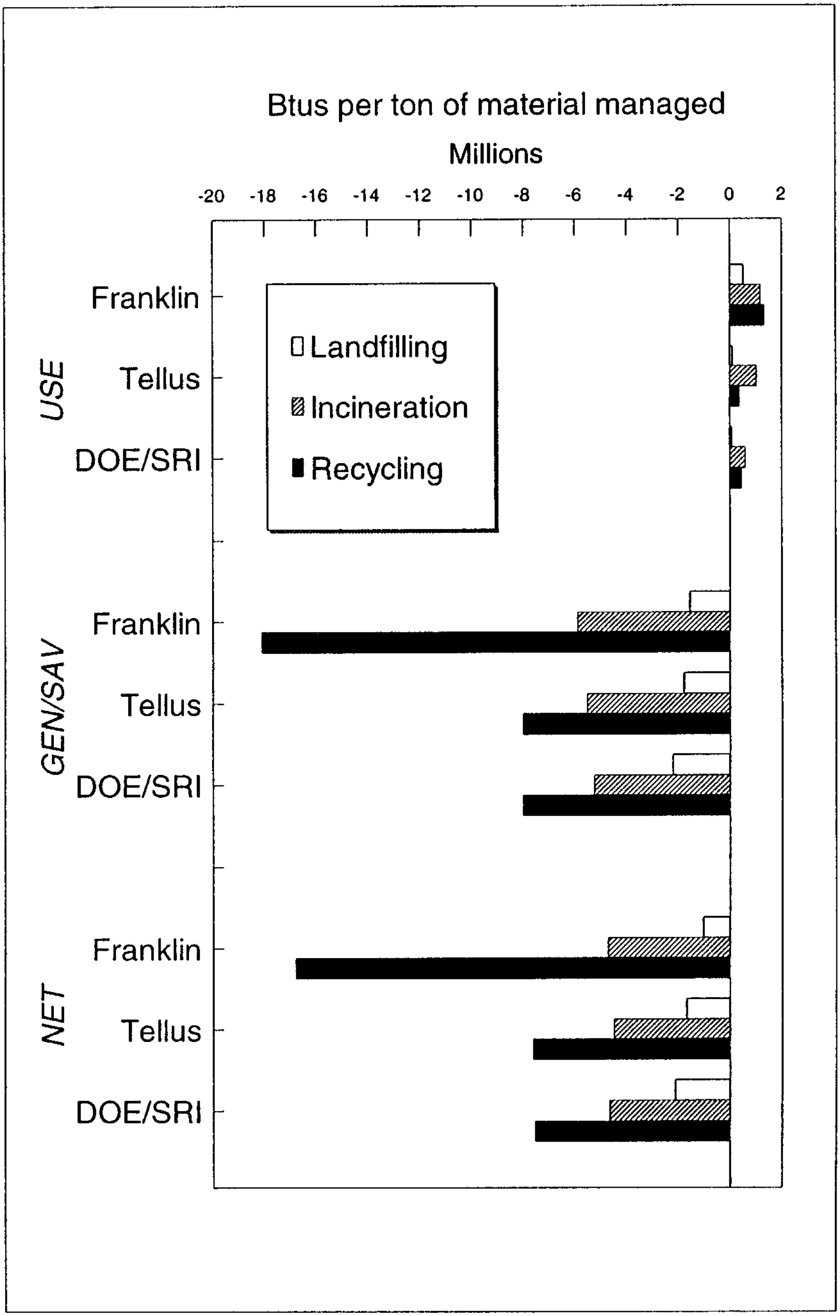
Summary data from all but the SRMG study (which has only incomplete information) are displayed graphically in Figure 5. Energy generation estimates from all of the studies are remarkably similar for landfills and incinerators, and the four estimates of reduced energy use from recycling appear to fall into two groups, one much higher than the other; the data in the studies are insufficient to provide an explanation for these differences in manufacturing-related energy.

For energy generation, energy use reductions, and net energy, all of the studies support the same rank ordering of the three options: Recycling uses the least energy, incineration an intermediate amount, and landfilling the most (even assuming landfill gas recovery).

The major differences among the studies are in their estimates of energy use. FA's estimates (20) for collection energy requirements are higher for all three options than those of the other studies. A partial explanation is FA's apparently unique inclusion of energy associated with acquisition of fuels as well as the fuels themselves; however, this energy is relatively low, adding on the order of 20% or less to the energy estimate based on fuel use alone (14). DOE (21) estimates that recycling collection energy is about 2.5 times higher than collection energy for landfilling or incineration owing to the smaller amounts collected per route; the 2.5 ratio is not very different from FA's (3.3), but FA's actual value (989,000 Btus per ton) is more than four times higher than DOE's (230,000 Btus per ton). Tellus (6) estimates a slightly lower collection energy for recycling relative to landfilling or incineration; this may in part reflect conditions specific to New York City.

One significant difference between the studies that may explain some of the difference in estimates for recyclables collection energy is that the Tellus study (that with the lowest estimate of collection energy) is based on collection of commercial and institutional, as well as residential, recyclables, whereas the other studies model residential curbside collection only. Collection efficiencies are indeed higher for commercial collection of recyclables, for several reasons (22). A larger quantity of material is typically collected at each stop of the

Figure 5 Energy use for three MSW management options: comparison of estimates from three recent studies. USE = energy required; GEN = energy generated or reduction in energy use; NET = net energy. Based on data from (1, 6, 7).


Btus per ton of material managed
Millions
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
Landfilling
Incineration
Recycling
USE
Franklin
Tellus
DOE/SRI
GEN/SAV
Franklin
Tellus
DOE/SRI
NET
Franklin
Tellus
DOE/SRI

collection vehicle. The density of collection points is typically higher (i.e. smaller distance between stops). Commercially generated materials tend to be more compacted (and therefore occupy less volume) because they are more homogeneous, and in some cases they are even preprocessed (e.g. baled) by the generator prior to collection. Finally, vehicles used for commercial collection frequently can compact materials they collect, a feature far less prevalent among residential collection vehicles.

Processing energy requirements, although they differ somewhat across studies, all support the finding that processing a ton of MSW at an incinerator requires two to three times more energy than processing a ton of recovered materials at a MRF. Estimates for transport and disposal of residuals were the most variable among the different studies, but they were also consistently the smallest component of energy use.

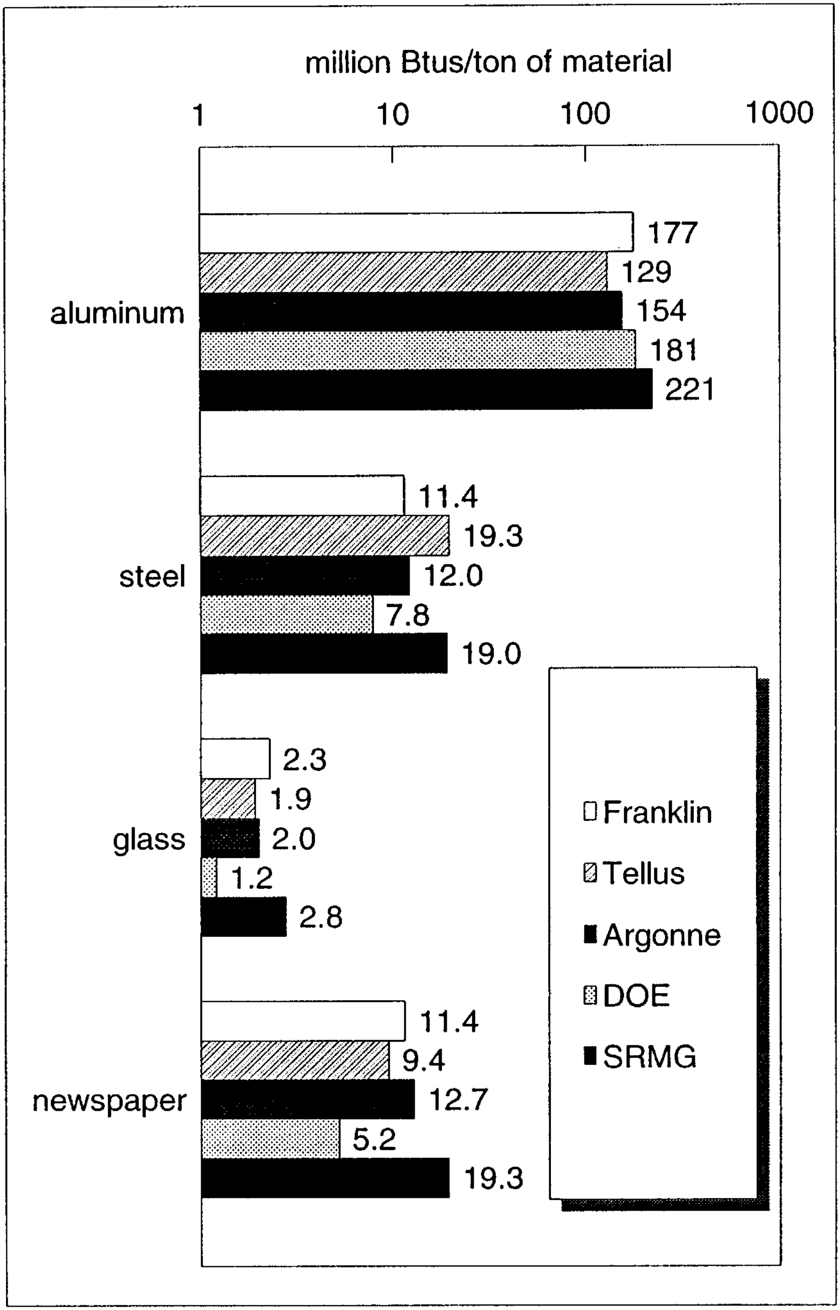
All of the studies found energy use to be lowest for landfilling. All of the studies except FA's found energy use to be highest for incineration; this difference is entirely attributable to FA's much higher estimate for recycling collection energy, discussed above.

Finally, as is most clearly illustrated in Figure 5, energy use for all three options is quite low in comparison to the energy generated by incineration or the reduction in energy use resulting from recycling.

VIRGIN VS RECYCLED MANUFACTURING ENERGY ESTIMATES FOR VARIOUS MATERIALS Each of the studies examined above provides estimates of the amount of energy saved in manufacturing through the substitution of recycled for virgin materials, for each of four materials: aluminum, steel, glass, and newspaper. A fifth study recently conducted by Argonne National Laboratory (23, 24) also provides such estimates. This study modeled a suburban residential curbside collection program. A comparison of all of the studies' estimates is provided in Figure 6.

Given the major differences in data sources and methodological assumptions of these five studies, their estimates of manufacturing energy savings from using recycled aluminum, steel, glass, and newspaper show remarkable similarity. Except for aluminum, Argonne's estimates are always the lowest, and SRMG's are always the highest. But with the exception of these two studies' estimates

Figure 6 Reductions in manufacturing energy from recycling various materials: comparison of estimates from five studies. Values represent the difference between energy required for virgin and for recycled manufacturing. Note the use of a logarithmic scale. Sources: (1, 6–8, 23, 24).


million Btus/ton of material
1
10
100
1000
aluminum
177
129
154
181
221
steel
11.4
19.3
12.0
7.8
19.0
glass
2.3
1.9
2.0
1.2
2.8
newspaper
11.4
9.4
12.7
5.2
19.3
Franklin
Tellus
Argonne
DOE
SRMG

for newspaper, which differ by almost fourfold, all of the values agree within a factor of about two.[15]

Air Emissions and Waterborne Wastes

Waste management activities that are responsible for the generation of air emissions and waterborne wastes include both 1. those that involve the use of energy, either in the form of electricity (which results in air emissions and waterborne wastes from an electric utility) or in the form of fuels (which results in air emissions and waterborne wastes during acquisition of the fuels and during their consumption); and 2. direct releases from waste management processes or facilities themselves. Sources of air emissions and waterborne wastes specific to each waste management option are listed in Table 3.

Many individual chemical substances are present in air emissions and waterborne wastes arising from any of the three options considered here. The substances or groups of substances considered here are only a limited subset of such chemicals. Those examined here are environmentally significant, owing to their association with human or environmental health impacts, and sufficiently characterized by available data to allow their quantification in relation to management of a particular quantity of MSW or recyclables.

Of course, many other substances of environmental significance may be present in air emissions and waterborne wastes associated with these management options, and they may be important even if they are not common to more than one option or cannot be expressed in terms of the quantity released per ton of material managed. Thus, their exclusion is an important limitation to the scope of the comparison presented below.

Even with such a limitation, however, numerous substances are represented in the data presented. Because such substances act independently and in concert in the environment to produce various effects at various concentrations, there is no scientifically defensible way of aggregating them into a single or even a few values, as was the case for solid waste generation and energy use. Furthermore, each of the component activities that comprise each of the waste management options entails releases of air emissions and waterborne wastes.

To avoid too much complexity in presenting this information without compromising the scientific integrity of the information, FA's detailed data are

[15]The energy savings found for production of recycled relative to virgin newspaper does not necessarily hold for other grades of paper, including those examined by some of the studies reviewed here. Because virgin production of some grades of paper is fueled in large part by wood-derived wastes (e.g. bark, pulping liquors), their requirements for purchased fuels or electricity may be lower than the analogous production process that uses recovered paper (which does not produce such wood-derived wastes). For an in-depth analysis of energy requirements associated with recycled and virgin paper production, see (25).

presented in tabular form, but the figures that serve as the basis for further discussion are based on a summation across the individual activities within a given option, for each of 10 substances (or groups of substances) released to the air, and each of 8 substances (or groups of substances) released to the water.

As was the case for solid waste and energy, data both including and excluding reductions in air emissions and waterborne wastes as a result of energy generation or manufacturing using recycled materials are presented in order to provide both a waste-management and a system-wide perspective.

LIMITATIONS TO THE ANALYSIS Data on air emissions and waterborne wastes must be interpreted with considerable caution. Data of this type are generally much more scarce and of lesser quality than in the areas of solid waste and energy use. In addition, such data frequently (as is sometimes the case in the current analysis) do not represent actual measured releases, but rather regulatory limits, engineering estimates, or other surrogates for actual values. Different activities may generate releases of the same class of substances (e.g. metals or suspended solids) that differ dramatically in their individual composition and potential to cause adverse health or environmental impacts. Such differences are obscured when data are reported or available only for the class of substances as a whole.

Even where data are available for releases of the same chemical from different activities, such estimates may still not be directly comparable: They do not necessarily serve as a measure of actual environmental impact. Impacts depend not only on how much of a given chemical is released, but also on the rate of release, the release route (e.g. by a mobile source such as a truck vs a point source such as an incinerator stack), and the location of release (e.g. in a rural vs urban setting). The fate of the release in the environment—its rate of degradation, how it moves, whether it accumulates in particular environmental "sinks"—is important in assessing impact. These major limitations should be kept in mind as the following subsections are read.

FRANKLIN ASSOCIATES STUDY In its recent report, FA provides estimates of air emissions and waterborne wastes for various steps that comprise each management option. Several assumptions (in addition to those listed above—see section on Presentation of Comparative Data) and limitations should be noted:

1. Facilities are assumed to be in compliance with all applicable regulations governing design, operation, and environmental releases.

2. MSW landfill gas emissions other than carbon dioxide and methane, and MSW landfill leachate, are not included, owing to a lack of data that would allow quantification of releases per ton of waste landfilled (26); FA provides

data indicating that methane and carbon dioxide are the dominant components of landfill gas. By one estimate cited by FA, each of these components comprises 47% of landfill gas, together accounting for 94% (by weight) of landfill gas. Landfill gas is assumed not to be recovered.

3. Incinerator air emissions are assumed to be at the level allowed under current regulations.

4. Estimates of differences in releases from recycled and virgin manufacturing processes are based primarily on differences in energy consumption by the processes, rather than on direct air emissions and waterborne wastes from the processes themselves, independent of fuel or electricity consumption. Data on direct releases are far more scarce and of uncertain quality.

Table 6 presents FA's detailed data on air emissions and waterborne wastes from individual component activities associated with landfilling, incineration, and recycling of MSW.

Air emissions Figure 7 graphically presents summary information on 10 categories of air emissions. Figure 7*b* presents only those air emissions associated with direct management of MSW or recyclables (i.e. it excludes reductions in emissions from utilities and manufacturing facilities). From this limited perspective, no clear choice of management options emerges:

1. Landfilling is the primary source of methane.

2. Incineration is the primary source of carbon dioxide, nitrogen oxides, and sulfur oxides.

3. Recycling is the primary source of aldehydes, ammonia, carbon monoxide, hydrocarbons, other organics, and particulates.

If one considers only displaced utility emissions resulting from the energy generated by incineration, the fact that incineration emerges as the apparent lowest emitter for all categories except carbon dioxide is not surprising. Even after accounting for this energy generation potential of MSW incineration, and before accounting for any reductions in emissions associated with recycling, incineration is the dominant source of carbon dioxide emissions. This finding is notable, given the role of carbon dioxide in global warming. The contribution of landfills to global warming potential is greater still: Methane is not only released in greater quantities per ton of MSW managed, but also is estimated to be on the order of 69 times more potent than carbon dioxide as a greenhouse gas (27). The 69-fold factor is based on equivalent weights of methane and carbon dioxide and thus allows a comparison of the quantities displayed in Table 6 and Figure 7. On a molecule-to-molecule basis, the ratio is 25 to 1.

From a system-wide view that also accounts for reductions in emissions from recycling (Figure 7*a*), a clear picture emerges: Recycling results in the lowest emissions in 9 of the 10 categories. Relative to a system based on virgin manufacturing, recycling reduces net emissions in all categories; incineration results in net reductions in emissions in 5 categories (although recycling results in greater reductions) but still generates net emissions in 4 categories; for one of these, carbon dioxide, it generates the greatest emissions of the three options. Landfilling (assuming no gas recovery) is the dominant source of emissions in 9 of the 10 categories; the exception is carbon dioxide.

Waterborne wastes[16] Figure 8 graphically presents summary information on eight categories of waterborne wastes. Figure 8*b* presents only those waterborne wastes associated with direct management of MSW or recyclables (i.e. it excludes reductions in releases from utilities and manufacturing facilities). This limited perspective shows that recycling produces the most waterborne wastes in all eight categories. (These releases arise not from the recycling process itself, but from the acquisition of fuels and the generation of electricity used by transport and processing equipment.) Incineration generates the lowest releases in five of the eight categories, and landfilling and incineration are tied for lowest releases in the other three categories (BOD, iron, and suspended solids).

If one considers only displaced utility emissions resulting from the energy generated by incineration, incineration still appears to produce the lowest, and recycling the highest, levels of waterborne wastes in all eight categories. Incineration results in net reductions in releases in six categories.

If the system is viewed as a whole, however, and reductions in releases from recycled manufacturing processes (Figure 8*a*) are accounted for, a very different picture emerges: Relative to a system based on virgin manufacturing, recycling results in net reductions in releases in all eight categories and produces the fewest releases in six of the eight categories. The two exceptions are iron and sulfuric acid, for which incineration yields the greatest net reduction. In two categories, incineration still yields net releases: dissolved solids and oil. Landfilling results in appreciable releases in three categories: dissolved solids, oil, and sulfuric acid.

OTHER STUDIES Other information that allows a direct comparison of air and water releases from landfilling, incineration, and recycling is scarce. In a

[16]Not included in waterborne wastes are those generated prior to collection by individuals through the rinsing out of containers and similar activities. No estimates of such releases were found.

Table 6 Franklin Associates' estimates of air emissions and waterborne wastes associated with component activities of three MSW management methods[a]

	Landfilling			Incineration					Recycling					
	Collection vehicle and landfill equipment	Landfill[b]	Total (per ton of MSW landfilled)	MSW collection	W-T-E combustion process[c]	Avoided utility emissions[d]	Ash landfill disposal[e]	Total (per ton of MSW combusted)	Recyclables collection[f]	MRF process[g]	Residue landfill disposal	Transportation to market[h]	Avoided manufacturing energy and emissions[h]	Total (per ton material recycled)
Environmental emissions (lbs/ton)														
Atmospheric emissions														
Aldehydes	0.0189		0.0189	0.0106	0.0012	(0.0005)	0.0028	0.0141	0.0356	0.0002	0.0015	0.0076	(0.5583)	(0.5134)
Ammonia	0.0001		0.0001	0.0000	0.0000	(0.0005)	0.0000	(0.0005)	0.0002	0.0002	0.0000	0.0000	(0.0080)	(0.0076)
Carbon dioxide	84.1	233.0	317.1	47.3	1,655.3	(736.1)	12.6	979.1	157.7	31.7	6.7	34.2	(2,724.6)	(2,494.3)
Carbon monoxide	0.9760		0.9760	0.5490	0.8610	(0.7560)	0.1466	0.8006	1.8300	0.0413	0.0781	0.2640	(27.4)	(25.2)
Chlorine									0.0000	0.0000	0.0000	0.0000	(0.0452)	(0.0452)
Hydrogen flouride									0.0000	0.0000	0.0000	0.0000	(0.1766)	(0.1766)
Lead									0.0000	0.0000	0.0000	0.0000	(0.0062)	(0.0062)
Hydrogen chloride				0.0000	0.2500	0.0000	0.0000	0.2500						
Metals			0.3872	0.0000	0.0002	0.0000	0.0000	0.0002						
Hydrocarbons	0.3872		0.2172	0.2178	0.0242	(0.6763)	0.0582	(0.3761)	0.7260	0.0726	0.0130	0.1438	(7.7)	(6.7)
Methane	0.0002	123.0	123.0	0.0000	0.0000	(0.0043)	0.0000	(0.0043)	0.0004	0.0002	0.0000	0.0000	(0.0106)	(0.0100)
Nitrogen oxides	1.0214		1.0214	0.5746	2.4038	(3.3557)	0.1534	(0.2239)	1.9152	0.1746	0.0817	0.2898	(11.9)	(9.4)
Other organics	0.5961		0.5961	0.3352	0.0372	(0.0005)	0.0895	0.4614	1.1176	0.0002	0.0477	0.1336	(1.5721)	(0.2730)
Particulates	0.2269		0.2269	0.1276	0.2742	(2.4115)	0.0341	(1.9756)	0.4256	0.1060	0.0182	0.0482	(11.9)	(11.3)
Sulfur oxides	0.1440		0.1440	0.0810	0.5490	(6.3350)	0.0216	(5.6834)	0.2700	0.2861	0.0115	0.0582	(11.5)	(10.9)

Waterborne Wastes												
Acid			0.0000	(0.5280)	0.0000	(0.5280)	0.0000	0.0228	0.0000	0.0000	(0.4644)	(0.4416)
Ammonia							0.0000	0.0000	0.0000	0.0000	(0.0944)	(0.0944)
BOD	0.0003	0.0003	0.0002	(0.0005)	0.0001	(0.0002)	0.0006	0.0002	0.0000	0.0002	(0.5386)	(0.5376)
COD	0.0016	0.0016	0.0008	(0.0014)	0.0002	(0.0004)	0.0030	0.0005	0.0001	0.0006	(1.4900)	(1.4858)
Cyanide							0.0000	0.0000	0.0000	0.0000	(0.0038)	(0.0038)
Dissolved solids	0.3264	0.3264	0.1836	(0.2232)	0.0490	0.0094	0.6120	0.0852	0.0261	0.1320	(6.2)	(5.3)
Fluorides							0.0000	0.0000	0.0000	0.0000	(0.1040)	(0.1040)
Iron	0.0003	0.0003	0.0002	(0.3955)	0.0001	(0.3952)	0.0004	0.0170	0.0000	0.0000	(0.0952)	(0.0778)
Metal ion	0.0006	0.0006	0.0004	(0.1320)	0.0001	(0.1315)	0.0010	0.0058	0.0000	0.0002	(0.2124)	(0.2054)
Oil	0.0039	0.0039	0.0022	(0.0005)	0.0006	0.0023	0.0074	0.0001	0.0003	0.0016	(0.0530)	(0.0436)
Phenol							0.0000	0.0000	0.0000	0.0000	(0.0024)	(0.0024)
Sulfuric acid	0.0010	0.0010	0.0006	(0.0048)	0.0002	(0.0040)	0.0018	0.0005	0.0001	0.0004	(0.0042)	(0.0014)
Suspended solids	0.0003	0.0003	0.0002	(0.0010)	0.0001	(0.0007)	0.0006	0.0000	0.0000	0.0002	(2.5)	(2.5)

[a]Source: Based on data from (1). Values in parentheses represent reductions in environmental emissions due to energy generated by incineration and to increased use of recovered materials in the manufacturing process.

[b]Landfill gas collected for energy recovery not included. Only methane and carbon dioxide landfill gas included in atmospheric emissions. Water wastes caused by leachate from landfills not included.

[c]Air emissions based on new source perfomance standards (NSPS) for combustors > 250 tons per day capacity. Actual air emissions from facility will likely be lower Metal emissions estimated as actual.

[d]Assuming 480 kwh of electricity generated by a utility is avoided by combusting one ton of MSW. Avoided emissions based on national electricity energy grid.

[e]Waterborne wastes caused by leachate from landfills not included.

[f]Assuming curbside collection of recyclables.

[g]Values based on average of low tech and high tech MRF.

[h]Based on the following mix (by weight) of recyclable materials: 50% paper, 32% glass, 8.5% steel, 3.5% aluminum, 4% HDPE, 2% PET.

separate study from the one discussed above, Tellus compiled limited data on landfill leachate (but not landfill gas), incinerator air emissions, recycling facility air emissions (based on only one limited sampling study), and air emissions from recyclables collection and garbage collection (28). Only the data on air emissions were reported for more than one option and can therefore facilitate comparison among options. The air emissions data from this study are displayed in Table 7.

The data in Table 7 indicate the following findings:

1. Incinerator stack emissions of heavy metals are far higher (by several orders of magnitude) than those from MRF operations (compare the first column to the second or third column in Table 7).

2. MSW and recyclables collection activities are comparable to incineration as a source of emissions of criteria air pollutants[17] (compare the first column with the fourth and fifth columns in Table 7).

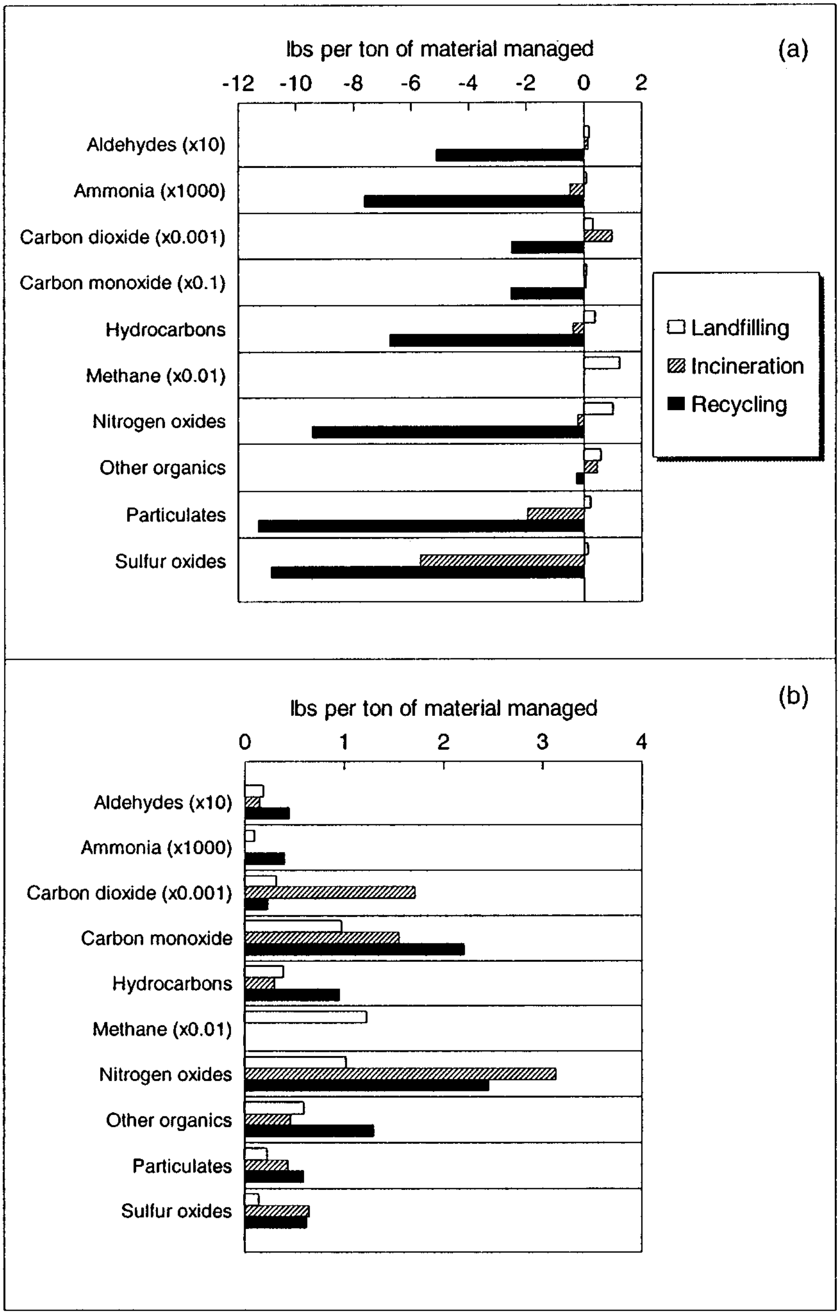
3. Collection of recyclables generates more (by a factor of 4-5) criteria air pollutants and organics than MSW collection (compare the fourth and fifth columns in Table 7). This finding reflects the need for more trucks and/or miles traveled to deliver a given weight of recyclables compared to the same weight of MSW; the magnitude of difference may be overstated, however, because emissions from MSW collection vehicles are actually higher per unit time than those from recyclables collection vehicles, owing to compaction cycles and the slightly larger engine needed to support compaction and hauling of a greater weight of material at full capacity.

4. For emissions of criteria pollutants, incineration plus MSW collection is comparable to recyclables collection (compare the sixth and seventh columns in Table 7).

The direct comparisons that are possible show that these findings are roughly consistent with those that can be drawn from the FA data presented in Table 6.

[17]The so-called criteria air pollutants include carbon monoxide, sulfur oxides, particulates, nitrogen oxides, and volatile organic chemicals (VOCs); ambient air quality criteria (hence the name "criteria" air pollutants) for these pollutants are established under Clean Air Act regulations (see *Code of Federal Regulations*, Vol. 40, Part 50).

Figure 7 FA's estimates of air emissions from MSW management. (*a*) Air emissions including reductions in utility and manufacturing emissions. (*b*) Air emissions excluding reductions in utility and manufacturing emissions. Based on data from (1).



(a)
lbs per ton of material managed
-12 -10 -8 -6 -4 -2 0 2
Aldehydes (x10)
Ammonia (x1000)
Carbon dioxide (x0.001)
Carbon monoxide (x0.1)
Hydrocarbons
Methane (x0.01)
Nitrogen oxides
Other organics
Particulates
Sulfur oxides
Landfilling
Incineration
Recycling
(b)
lbs per ton of material managed
0 1 2 3 4
Aldehydes (x10)
Ammonia (x1000)
Carbon dioxide (x0.001)
Carbon monoxide
Hydrocarbons
Methane (x0.01)
Nitrogen oxides
Other organics
Particulates
Sulfur oxides

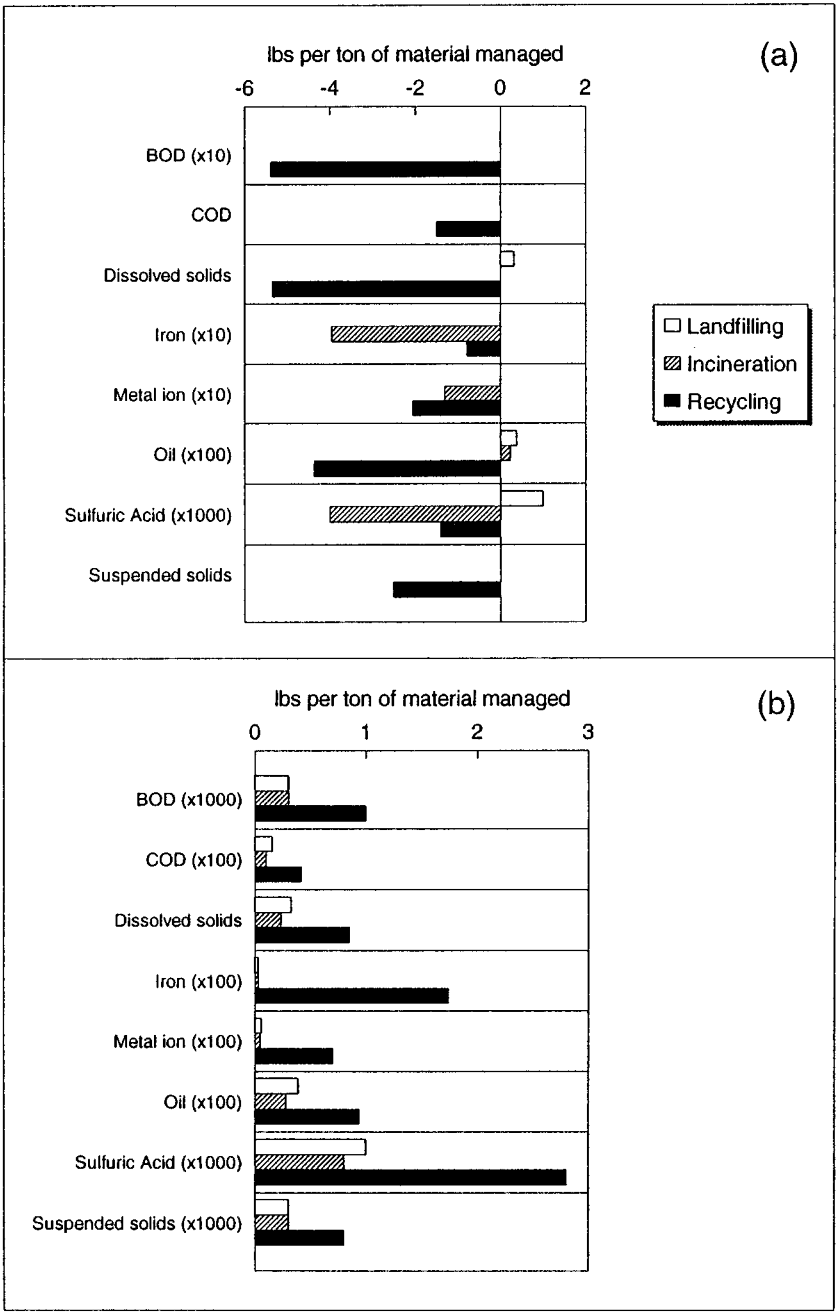

(a)
lbs per ton of material managed
-6
-4
-2
0
2
BOD (x10)
COD
Dissolved solids
Iron (x10)
Metal ion (x10)
Oil (x100)
Sulfuric Acid (x1000)
Suspended solids
Landfilling
Incineration
Recycling
(b)
lbs per ton of material managed
0
1
2
3
BOD (x1000)
COD (x100)
Dissolved solids
Iron (x100)
Metal ion (x100)
Oil (x100)
Sulfuric Acid (x1000)
Suspended solids (x1000)

Table 7 Tellus' estimates of comparative data on air emissions from facilities managing MSW and from collection of MSW and recyclables[a]

	Incinerator stack emissions[b]	Recycling (inactive; no sorting)[c]	Recycling (active sorting)[c]	Recyclables collection	MSW collection[d]	Incineration plus MSW collection[d]	Recyclables collection
Criteria pollutants							
CO	0.533			0.687	0.162	0.695	0.687
NOx	1.880			0.973	0.229	2.109	0.973
Particulars	0.132	0.0128	0.0128				
SOx	0.115			0.139	0.033	0.148	0.139
VOCs	0.044			0.234	0.055	0.099	0.234
Metals							
Arsenic ($\times 10^6$)	3.6	—	—				
Cadmium ($\times 10^6$)	13.1	0.001710	0.001710				
Chromium (total, $\times 10^6$)	15.2	0.005970	0.005970				
Lead ($\times 10^6$)	133	0.009810	0.009810				
Mercury ($\times 10^6$)	1760	0.000981	0.000981				
Nickel ($\times 10^6$)	34.9	0.000211	0.000211				
Organics							
Benzene ($\times 10^6$)		0.0213	0.2990	4180	980		
Ethyl benzene ($\times 10^6$)		0.1240	0.0597	140	30		
Toluene ($\times 10^6$)		0.3750	0.4180	4200	990		
Xylenes ($\times 10^6$)		3.0200	0.3880	1500	350		

[a]All values are in pounds per ton of material managed. Source: Based on data from (28).
[b]Assumes state-of-the-art incinerator equipped with a scrubber, fabric filter/baghouse, and thermal de-NOx.
[c]May be an underestimate because sampling device became saturated during sampling period.
[d]Underestimates because emissions from MSW collection vehicles are actually higher than assumed owing to compaction cycles and slightly larger engine requirements to support compaction and hauling of a greater weight of material at full capacity.

CONCLUSIONS

This section summarizes key conclusions from an examination of several studies that compare virgin production plus landfilling or incineration to recycled production plus recycling of potentially recyclable materials in MSW. Findings are presented for four environmental parameters: solid waste output, energy use, air emissions, and waterborne wastes.

Solid Waste Output

From a system-wide view, solid waste output from recycled production plus recycling is lower than it is from the other two options. In addition to recycling's

Figure 8 FA's estimates of waterborne wastes from MSW management. (*a*) Waterborne wastes including reductions in utility and manufacturing wastes. (*b*) Waterborne wastes excluding reductions in utility and manufacturing wastes. Based on data from (1).

direct diversion of solid waste from disposal, use of recovered materials rather than virgin materials in manufacturing results in far less solid waste [almost 1000 pounds less for every ton of material, according to one of the studies examined here (20)].

Even when the amount of solid waste resulting from incineration and landfilling is reduced to account for the energy they generate, and recycling is not credited with its manufacturing-related reductions in solid waste, recycling still results in the least amount of solid waste of the three options, whereas virgin production plus landfilling results in the most.

Energy Use

From a system-wide view, recycled production plus recycling uses the least energy, considerably less than virgin production plus incineration, whereas virgin production plus landfilling uses the most. This difference is due to the substantial reduction in energy use associated with manufacturing processes that use recycled materials relative to those that use virgin materials.

This rank ordering holds despite the fact that, because of higher fuel use, collection and processing for recycling uses the most energy of the three options, whereas collection and processing for landfilling uses the least. Energy use within the waste management system is low, however, compared to the amount of energy generated by incineration or the reduction in energy used in manufacturing using recycled materials.

Transportation energy required to ship processed recyclable materials to market (i.e. points of remanufacture) is quite modest, amounting to at most a few percent of manufacturing energy.

Air Emissions and Waterborne Wastes

AIR EMISSIONS From a system-wide view, recycled production plus recycling produces the lowest emissions of all but one of the major categories of air pollutants. Virgin production plus incineration produces more emissions than recycled production plus recycling in all categories except methane, of which both options produce only very low amounts. Virgin production plus incineration produces lower emissions than virgin production plus landfilling in all categories except carbon dioxide (significant for its role in global warming), of which the former produces the most of the three options. Despite its lower carbon dioxide emissions, landfilling contributes most to global warming potential of the three options because of its much higher methane emissions.

Only when we limit our view to the immediate materials recovery and waste management systems—a view that does not account for air emissions reductions from manufacturing with recycled rather than virgin materials—does recycled production plus recycling not appear to have clear advantages with respect to air emissions. The higher fuel use associated with recycling collection results in emissions of some categories of air pollutants comparable to or greater than the emissions from collection of MSW for purposes of incineration and landfilling.

WATERBORNE WASTES[18] If we take a system-wide view, recycled production plus recycling produces the lowest releases in a majority of the major categories of waterborne wastes. Virgin production plus incineration produces lower releases than recycling for two categories. Virgin production plus landfilling produces the highest releases of the three options in all major categories.

If we take the more limited view in which reductions in waterborne waste from manufacturing using recycled rather than virgin materials are not accounted for, only then does recycled production plus recycling not appear to have clear advantages with respect to waterborne wastes. The higher fuel use associated with recycling collection results in releases of some categories of waterborne wastes comparable to or greater than those from collection of MSW for purposes of incineration and landfilling.

Significance of Recycling's Energy Use and Environmental Release Reductions

To assess the relative significance of the effects that a recycling-based system has on energy use and environmental releases, several of the reductions quantified in this paper are compared in this section to measures of related uses or releases, as follows:

1. The reduction in solid waste output associated with the recycling-based system is compared to the total amount of MSW generated annually in the United States. Although some of the reduction is of wastes other than MSW (e.g. industrial process wastes), this comparison is useful in judging the net reduction in solid waste associated with recycling on a scale that is germane to the choice among recycling and waste management options.

2. The reduction in energy use associated with the recycling-based system is expressed in terms of the equivalent number of households' annual residential energy use.

3. For several categories of air emissions, reductions associated with the recycling-based system are compared to the total amount of emissions from all sources in the United States. In addition, reductions in methane emissions

[18] The studies examined here do not include direct releases of these pollutant categories from waste management facilities, owing to a lack of data.

are compared to the total emissions of methane from landfills in the United States.

4. For the remaining categories of air emissions and all of the categories of water pollutants, no relevant basis of comparison was identified.

To facilitate the comparisons, the per-ton energy use or releases for the virgin systems involving landfilling and incineration drawn from the 1994 FA study are first combined into a composite value for a "virgin production plus waste management" system. The composite value is a weighted average of the individual values, based on the relative use of landfilling and incineration to manage nonrecycled MSW in the United States. On a national basis, 80% of nonrecycled MSW is landfilled and 20% is incinerated (2); this 4:1 ratio is used to calculate the composite waste management value. Next, the difference between the recycling-based system and the virgin-based composite system is calculated; it represents the reductions in energy use and environmental releases associated with the recycling-based system. These per-ton reductions are then multiplied by the total number of tons of MSW-related materials recycled in the United States in 1995, which is estimated to be 55 million tons (29). The resulting values are the total annual reductions attributable to recycling of MSW in the United States at the current rate of about 26% (29). Finally, these values are compared to the measure of a related use or release indicated above.

The calculations just described are shown in detail in Table 8, and the results are as follows:

1. Recycling at the current rate of 26% reduces solid waste output by an amount equal to 32.9% of the amount of total MSW annually generated in the United States. The higher percentage reduction in solid waste output achieved by recycling is due to reductions in wastes in addition to MSW, primarily industrial process wastes.

2. Recycling reduces energy use by an amount equal to the energy used by 8.95 million households.

3. Recycling reduces atmospheric emissions of several gases by amounts equal to the following percentages of the total emissions of such gases from all sources in the United States: CO_2: 1.5%; CH_4: 9.0%; CO: 0.83%; NO_x: 1.3%; SO_2: 1.5%.

4. Recycling at the current rate of 26% reduces emissions of methane by an amount equal to 24.2% of the total emissions of methane from all landfills in the United States.

Table 8 Significance of reductions in solid waste, energy use, and certain air emissions resulting from use of a recycling vs waste management–based system

Solid waste (pounds per ton)					
Solid waste from recycling	−831.8				
Solid waste from landfilling	2000.3				
Solid waste from incineration	446.1				
Solid waste from waste management[a]	1689.5				
Reductions from recycling	2521.3				
Million tons per total recycled in the United States[b]	69.3				
Total MSW generated in United States (million tons)[c]	211				
Weight of total MSW reduced by recycling (%)	32.9				
Energy use (million Btus per ton)					
Energy use for recycling	−16.80				
Energy use for landfilling	0.53				
Energy use for incineration	−4.73				
Energy use for waste management[a]	−0.5				
Reductions from recycling	16.3				
Trillion Btus per total recycled in the United States[b]	895.2				
Energy used per household (million Btus/year)[d]	100				
Equivalent number of households' energy reduced by recycling	8.95 million				
Air Emissions (pounds per ton)					
	CO_2	CH_4	CO	NO_X	SO_2
Emissions from recycling	−2494.3	−0.0100	−25.2	−9.4	−10.9
Emissions from landfilling	317.1	123.0	0.98	1.0	0.14
Emissions from incineration	979.1	−0.0043	0.80	−0.22	−5.7
Emissions from waste management[a]	449.5	98.4	0.94	0.77	−1.0
Reductions from recycling	2943.8	98.4	26.1	10.2	9.9
Millions metric tons per total recycled in the United States[b]	73.6	2.5	0.7	0.3	0.2
Total emissions generated in the United States[e] (millions metric tons)	5069.2	27.3	79.0	20.0	16.4
Total US emissions reduced by recycling (%)	1.5	9.0	0.83	1.3	1.5
Total landfill emissions generated in the United states[f] (million metric tons)		10.2			
Total US landfill emissions reduced by recycling (%)		24.2			

[a]Based on a 4:1 ratio of usage of landfilling to incineration for nonrecycled MSW (2).
[b]Based on a total recycled of 55 million tons in 1995 (29).
[c]Based on (2).
[d]Based on *Household Energy Consumption and Expenditures*, US Energy Information Administration, 1990.
[e]Based on data for 1992 for CO_2, CH_4 and CO from (33) and data for 1995 for NO_x and SO_2 from (34).
[f]Based on data for 1992 from (33): US Energy Information Administration, 1994.

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