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# Application of Life-Cycle Management to Evaluate Integrated Municipal Solid Waste Management Strategies

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# Notice

The information contained in this document has been developed as part of ongoing research funded by the U.S. Environmental Protection Agency under Cooperative Agreement No. CR823052 with the Research Triangle Institute. The results from this study are intended for use in evaluating the relative cost and environmental burdens of integrated municipal solid waste management strategies. The information and results from this study are not intended for use in making comparative assertions about the environmental preferability of alternative materials or products. Use of the methods or data presented in this documentation does not constitute endorsement or recommendation for use. This document is subject to review and modification prior to conclusion of the research. Mention of trade names or commercial products does not constitute endorsement or recommendation.

# Abstract


Communities throughout the United States are struggling to develop efficient and cost-effective plans for managing their municipal solid waste (MSW). Today's MSW management systems often are complex and highly integrated systems that might include separate recyclables collection, recovery, composting, combustion, and disposal. Communities now must make complex decisions requiring an analysis of both cost and environmental burdens for these integrated systems. Despite the movement toward integrated systems, many of the existing techniques for analyzing the environmental and economic performance of MSW management systems focuses on the individual operations in isolation rather than as part of an integrated system.

To properly account for all of the environmental effects associated with integrated MSW management systems, planners must have tools that allow them to examine factors outside of the traditional MSW management framework of activities occurring from the point of waste collection to final disposal. This requires an examination of the "upstream" changes in resource use and pollutant generation from raw materials acquisition and manufacturing operations associated with recyclables recovery and transport. These upstream changes can be captured by taking a life cycle approach to MSW management.

The U.S. Environmental Protection Agency's (EPA's) Office of Research and Development, Air Pollution Prevention and Control Division, with cofunding from the U.S. Department of Energy, is working to apply life cycle concepts and tools to the analysis of MSW management systems in the United States. The project began in August of 1994 and is expected to be completed in 1999. The research team for this project includes life cycle assessment (LCA) and solid waste management experts from Research Triangle Institute, North Carolina State University, the University of Wisconsin-Madison, Franklin Associates, and Roy F. Weston. In addition, groups of internal advisors and external stakeholders are active participants in this unique forum. The information and tools resulting from this research will help solid waste practitioners identify integrated MSW management strategies that minimize both cost and environmental burdens.

This document has been prepared to provide the reader with a general overview of the research goals and objectives and summary of major research components and outputs. More detailed information for specific research components is provided in supporting project documentation.

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## Abbreviations and Symbols

| | |
|---|---|
| BTU | British Thermal Unit |
| U.S. DOE | United States Department of Energy |
| DQG | Data Quality Goal |
| DQI | Data Quality Indicator |
| DST | Decision Support Tool |
| EIA | Energy Information Administration |
| FAL | Franklin Associates, Limited |
| GUI | Graphical User Interface |
| KWH | Kilowatt Hour |
| LCA | Life-Cycle Assessment |
| LCI | Life-Cycle Inventory |
| MRF | Materials Recovery Facility |
| MSW | Municipal Solid Waste |
| NCSU | North Carolina State University |
| NERC | North American Electric Reliability Council |
| O&M | Operation and Maintenance |
| POTW | Publicly Owned Treatment Works |
| RCRA | Resource Conservation and Recovery Act |
| RDF | Refuse-Derived Fuel |
| RTI | Research Triangle Institute |
| SETAC | Society for Environmental Toxicology and Chemistry |
| TPD | Tons Per Day |
| U.S. EPA | United States Environmental Protection Agency |
| UW | University of Wisconsin - Madison |
| WTE | Waste-To-Energy Combustion |

# Key Terms and Definitions

**Allocation:** Technique for partitioning multiple inputs and outputs from a system.

**Cost:** Amount actually incurred for the provision of a product or service. Cost can include internal cost accrued by an organization, external costs accrued by society.

**Data Quality Indicator:** Measure which characterizes an attribute(s) of data or data sets.

**Function:** Performance characteristic of a system.

**Functional Unit:** Measure of performance of the main functional output of a system.

**Integrated Waste Management:** Interlinked stages of a system to collect, process, treat, and dispose of waste.

**Life Cycle:** Consecutive and interlinked stages of a system that extend from raw materials acquisition or generation of natural resources to final disposal.

**Life Cycle Assessment:** Compilation and evaluation, according to a systematic set of procedures, of the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the function of a product throughout its life cycle.

**Life Cycle Impact Assessment:** Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of environmental impacts based on a life cycle inventory analysis.

**Life Cycle Inventory Analysis:** Phase of life cycle assessment involving compilation, and quantification of inputs and outputs for a given product system throughout its life cycle.

**Municipal Solid Waste:** Waste generated in the residential, multifamily, and commercial sectors. Includes durable goods, nondurable goods, containers and packaging, food waste, and yard trimmings. Also includes ash from waste combustion. Excludes industrial process waste, sludge, construction and demolition waste, pathological waste, agricultural waste, mining waste and hazardous waste.

**Price:** Amount actually charged/paid for a product or service.

## Key Terms and Definitions (Cont.)

**Process Model:** Mathematical representation of a unit process to calculate cost and environmental burdens as a function of the quantity and composition of the waste or material processed.

**Raw Material:** Primary or secondary recovered or recycled material that is used in a system to produce a product.

**System:** Collection of unit processes which, when acting together, perform some defined function.

**Unit Process:** Component of the system being studied that is a collection of operations which transforms inputs into outputs, such as manufacturing, waste collection, materials recovery, etc.

# Executive Summary

In developing strategies for integrated MSW management, planners have a wide variety of available options to evaluate, from source reduction programs to different processes for collection, separation, treatment, and disposal.  To examine the complex interrelationships of mass flows and associated costs, resource consumption, and environmental releases of integrated MSW management strategies, and identify optimal management solutions, it is necessary to quantify the costs and environmental aspects associated with each unit process included in the strategy (see White et al., 1995).

When evaluating the environmental aspects of a particular MSW management strategy, planners should consider those burdens that occur outside of the traditional framework of activities from the point of waste collection to final disposal.  For example, when waste management strategies focus on recycling options, it is important to consider the net environmental performance of these options including offsets in primary materials and energy production sectors.  Similarly, when energy is recovered through combustion or landfills, the energy recovered will displace the production of fuels and generation of electricity from the utility sector.  As illustrated in Figure ES-1, these types of tradeoffs may be captured by taking a life cycle approach.

To address and examine the interrelationship and tradeoffs of integrated MSW management strategies, RTI and the U.S. EPA's Office of Research and Development, Air Pollution Prevention and Control Division, applied life cycle management concepts and tools to evaluate integrated MSW management systems in the United States.  RTI's research team for this effort included life cycle assessment (LCA) and solid waste management experts from North Carolina State University, the University of Wisconsin-Madison, Franklin Associates, and Roy F. Weston. In addition, project stakeholders from Federal, state, and local governments, industry, academia, and environmental advocacy organizations were very active participants in this effort.

This research effort provides information and tools that will enable local governments and solid waste planners to examine cost and life-cycle environmental aspects for a large number of possible MSW management operations for 42 distinct MSW components.  The primary outputs of this research include the following:

- **Life Cycle Database:** Data for individual waste management operations, materials production, and electrical energy generation are compiled in a publicly available computer database.  The database allows users to search for data specific to unit processes, structures, equipment, or various life cycle inventory (LCI) parameters.

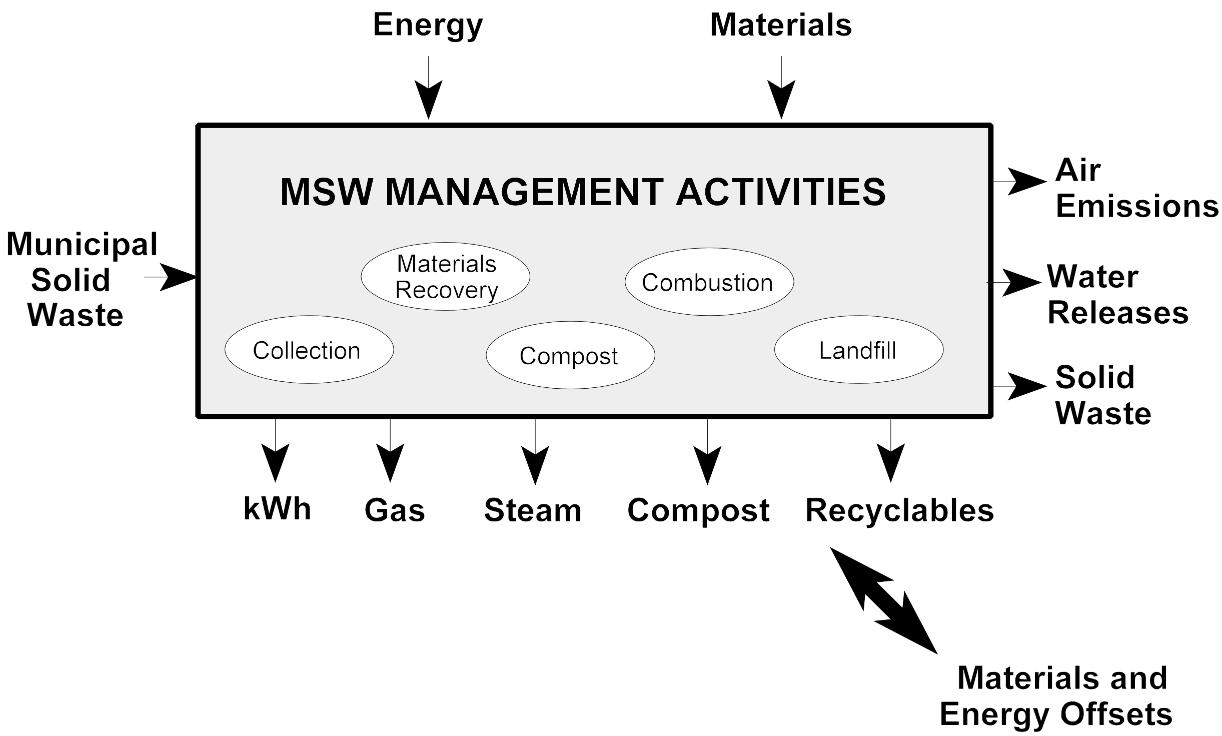



**Figure ES-1. Illustration of the MSW Management Life Cycle.**

- **Decision Support Tool:** A computer-based decision support tool (DST) to allow solid waste planners to enter site-specific data (or rely on supplied default data) for their community's waste quantity, composition, and other site-specific information to make screening level evaluations of alternative integrated MSW management strategies.

- **Community Case Studies:** Case study applications of the DST with local communities to test the cost and LCI methodologies, supporting data, and the overall DST. Studies were selected in a wide variety of rural and urban communities to investigate the flexibility of the DST for different settings.

To ensure the applicability and usefulness of the research products to local governments and other solid waste planners, an inclusive review process for all research activities and documentation was employed. The review process included three different levels:

1. Internal project team and U.S. EPA and U.S. Department of Energy advisors.

2. Project stakeholders from U.S. government, industry, academia, and

environmental organizations. A current listing of project stakeholders is included in Attachment 1 to this report.

3. External project peer reviews. Three separate peer reviewers were conducted and have included the following individuals:

   - David Allen, University of Texas at Austin
   - Robert Anex, University of Oklahoma
   - Kevin Brady, Demeter Environmental Inc.
   - Jürgen Giegrich, Ifeu- Institute
   - Allen Hershkowitz, Natural Resources Defense Council, Inc.
   - Gregory Keoleian, University of Michigan
   - Mitchell Kessler, TIA Solid Waste Management Consultants, Inc.
   - Jay Lund, University of California-Davis
   - Ruksana Mirza, Formerly with Proctor and Redfern, Ltd.
   - Debra Reinhart, University of Central Florida
   - Lynn Scarlett, Reason Foundation
   - Aarne Vesilind, Duke University and Bucknell University
   - Peter White, Proctor & Gamble
   - Steven Young, Five Winds International

This high level of involvement by project stakeholders and peer review committee members contributed greatly to the success of this project.

## GOAL AND SCOPE DEFINITION

The overall goal defined for this study is to develop information and tools to evaluate the relative cost and life-cycle environmental aspects of integrated MSW management strategies. For instance, how do the cost and environmental aspects of a MSW management system change if a specific material (e.g., glass, metal, paper, plastic) is added to or removed from a community's recycling program? And, what are the tradeoffs in cost and environmental aspects if paper is recycled versus combusted or landfilled with energy recovery? Until this research effort, information was unavailable or incomplete for adequately evaluating alternative MSW management options to answer these types of questions.

The primary audience for this study and its outputs is local governments and solid waste planners. However, we anticipate that the information and tools developed through this study will also be of value to Federal agencies, environmental and solid waste consultants, industry, LCA practitioners, and environmental advocacy organizations.

The function of the system under study is to manage MSW. Therefore, the functional unit for this study is defined as the management of a given quantity and composition MSW from a defined region. All activities required to manage the MSW from the time it is sent out for collection to its ultimate disposition, whether that be in a landfill, compost that is applied to the land, energy that is recovered from combustion, or materials that are recovered and reprocessed into new products.

The individual components that comprise MSW include those defined by the U.S. EPA's Office of Solid Waste (U.S. EPA, 2004). This definition includes waste generated in the residential, commercial, institutional, and industrial sectors but excludes industrial process waste, sludge, construction and demolition waste, pathological waste, agricultural waste, mining waste, and hazardous waste. Ash that is generated from the combustion of MSW is also included in the system, but is not included as part of EPA's definition of MSW. However, because waste combustion is included as a management option, the disposal of combustion ash must also be considered.

The MSW stream is divided into three different waste generation sectors: residential, multifamily dwelling, and commercial. The rationale for this separation is that different waste generation rates, composition, collection and recycling alternatives, etc. may apply to different generation sectors.

The major <u>unit processes</u> included in the system are:

**Waste Management:**
- Collection
- Transfer Station
- Materials Recovery Facility (MRF)
- Combustion (with or without energy recovery)
- Composting (yard and mixed waste)
- Refuse-Derived Fuel (RDF) and Processed Refuse Fuel (PRF)
- Landfill (traditional, bioreactor,, and ash)

**Other Operations:**
- Electrical Energy
- Inter-Unit Process Transportation
- Materials Production (primary and secondary production processes)

For each of these unit processes, models were developed that utilize generic design and operating parameters in conjunction with resource use and emission factors to estimate cost and LCI parameters, based on the quantity and composition of incoming material. Because the composition of MSW can greatly affect the cost and environmental results for different management options, these "process models" also contain methodologies for allocating LCI and cost parameters to individual MSW components. The boundaries were made as consistent as possible across all process models.

The cost and main LCI data categories included in the study are:

**Cost Categories:**
- Capital cost
- Operating cost

**LCI Categories:**
- Energy consumption
- Air emissions
- Waterborne releases
- Solid waste

To compare alternative MSW management options, we used only parameters that are comparable across all management operations. For example, although data for dioxin/furan emissions for waste combustors were readily available, comparable data do not exist for MRF, composting, and landfill operations. Thus, we cannot make comparative assertions based on dioxin/furan emissions. There are 32 different cost and LCI parameters for which consistent data was available and these 32 parameters are presented in the DST results.

Of the 32 parameters for which comparable data were available, 9 parameters were selected as initial parameters for optimization. These 9 parameters were selected based on discussion with project advisors and stakeholders and include:

- Cost
- Carbon monoxide
- Carbon dioxide - fossil (resulting from the combustion of fossil fuels)
- Carbon dioxide - biomass (resulting from the biodegradation or combustion of organic material)
- Electricity consumption
- Nitrogen oxides
- Particulate matter
- Sulfur dioxide

The remaining 23 air and water parameters that are tracked and reported in the DST can be made optimizable in the future if desired. In addition, as data becomes available to enable comparisons of other parameters across unit processes, future versions of the DST can be updated to include an expanded list of parameters.

## SYSTEM BOUNDARIES

The system has largely been defined through the description of the functional elements and unit processes and the manner in which each will be treated. These elements and processes are outlined in detail in a system description document and summarized in the following section.

### Boundaries for LCI Analysis

All activities that have a bearing on the management of MSW from collection through transportation, recycling, treatment, and disposal are included in the LCI. It is assumed that MSW enters the management system when it is set out or delivered to a collection site, whether it be a residential curbside, apartment collection site, or rural drop-off site. Thus, environmental aspects associated with the production of garbage bags and cans and recycling bins are *not* included in the LCI. Similarly, the transport of waste by residents to a collection point is *not* included in the LCI.

The functional elements of MSW management include numerous pieces of capital equipment from refuse collection vehicles to balers to major equipment at paper mills. Environmental aspects associated with operation of equipment and facilities are included in the LCI. For example, energy (fuel) that will be consumed during the operation of refuse collection vehicles is included in the LCI. In addition, electricity consumed for operation of the office through which the vehicle routes are developed and the collection workers are supervised is also included in the LCI. However, environmental aspects associated with the fabrication of capital equipment as well as the construction of facilities are *not* included in the LCI.

Where a material is recycled, the resources, energy, and environmental aspects associated with the manufacture of a new product are calculated, assuming a closed-loop recycling process, and included in the LCI results. These parameters are then compared against those from manufacturing the product using primary resources to estimate the net environmental savings (or addition burden). This procedure also applies to energy recovery from other unit processes including combustion, RDF, landfills.

Another system boundary is that at the waste treatment and disposal end of the system. Where liquid wastes are generated which require treatment, the energy associated with their treatment is considered. For example, if biological oxidation demand (BOD) is treated in an aerobic biological wastewater treatment facility, then energy is consumed to supply adequate oxygen for waste treatment. If a solid waste is produced which requires burial, energy will be consumed in the transport of that waste to a landfill, during its burial (e.g., bulldozer) and after its burial (e.g., gas collection and leachate treatment systems) in the landfill. Also, if compost is applied to the land, volatile and leachate emissions are considered.

### Boundaries for Cost Analysis

The system boundaries for cost analysis differ from that of the LCI analysis and are designed to provide a relative comparison of cost among alternative MSW management options as incurred by the public sector. Capital and operating costs are included for waste collection, transportation, transfer stations, MRFs, composting, combustion, RDF, and landfills. In addition, costs are allocated to individual MSW components. For example, the result of the cost analysis can illustrate the additional capital and operating costs to a MRF for processing and storing glass.

Where recyclables are shipped from a MRF, the cost analysis ends where the public sector receives revenue (or incurs a cost) in exchange for the recyclables. The same procedure applies to the sale of RDF, landfill gas, or electricity from combustion. In addition, where waste is produced as part of a waste management facility, the cost of waste disposal or treatment is included in the cost analysis of that facility. For example, we include the cost of leachate treatment in our cost analysis of landfills. The cost analysis also includes the cost of training, educational, or other materials associated with source reduction or other aspects of MSW management.

The boundaries for the cost analysis include the cost of waste management that would be experienced by a local government such as the costs associated with collection, transport, recycling, treatment, and disposal. These costs are intended to provide a relative ranking of the different alternatives as part of a screening tool to narrow the range of options associated with integrated waste management.

There is no distinction between public and private sector costs. All waste management operations are assumed to occur in the public sector and therefore costs are calculated as though they are accruing to the public sector. The cost analysis is intended to reflect the full costs associated with waste management alternatives based on U.S. EPA guidance from *Full Cost Accounting for Municipal Solid Waste Management: A Handbook* (U.S. EPA, 1997).

The boundaries for cost analysis do not include the costs associated with the manufacturing processes for different materials (i.e., aluminum, glass, paper, plastic, steel) or fuels production and electricity generation. These costs occur in the manufacturing and utility sectors and do not accrue to municipal or county governments. However, any revenues that are realized by the government body from the sale of recovered materials or fuels or electricity are included in the cost analysis.

## TECHNICAL APPROACH FOR UNIT PROCESSES

As discussed in the previous section, the methodologies for LCI and cost analysis for each unit process are implemented in process models. Process models include sets of equations that utilize the default (or user input) facility design information to calculate all LCI and cost parameters based on the quantity and composition of waste entering each MSW management unit process. A summary of key assumptions and issues, and the status for each process model are provided in Table ES-2.

The process models are linked in the DST through a set of mass flow equations. The LCI and cost coefficients resulting from process models are used in the DST to calculate the total system cost and environmental aspects for MSW management strategies. Summaries of the design and operating parameters and methods for LCI and cost analysis for each process model are published individually.

## PRIMARY RESEARCH PRODUCTS

Through this project we are developing information and tools that enable solid waste planners to evaluate the relative cost and environmental aspects of integrated MSW management strategies. The project is providing this information and tools through three main research products: life cycle database, DST, and community case studies. Each of these products is summarized in the following section.

### Life Cycle Database

The life cycle database is being developed to provide LCI related information for all unit processes included in the system (see Thorneloe et al., 1998 for a summary of data being collected). The approach used to build this database is as follows. First, data from publicly available and private MSW and LCA studies, and other relevant sources, were collected and reviewed against the data quality goals and data quality indicators established for this project. The data quality assessment is based on upon, to the extent possible, guidelines from the International Standards Organization (ISO) 14040 (ISO, 1996). These existing data are being compiled into a database management system using commonly available software (Microsoft Access™).

The database management system was established to enable users to view and manipulate information through predefined forms, as shown in Figure ES-2. In these forms, the main categories of data are predefined, and the user's options are limited to narrowing the focus of the predefined search criteria.

Data residing in the database is also used in the DST, but database and DST are *not* linked. Rather, the database is available as a stand-alone application that may be used as input data to other studies or models. If solid waste practitioners possess higher quality or more site-specific data than those provided in the database, users may add data to the database.

### Decision Support Tool (DST)

The DST provides a user-friendly interface that allows users to evaluate the cost and environmental burdens of existing solid waste management systems, entirely new systems, or some combination of both based on user-specified data on MSW generation, constraints, etc. The processes that can be modeled include waste generation, collection, transfer, separation (MRF and drop-off facilities), composting, combustion and RDF production, and disposal in a landfill. Existing facilities and/or equipment can be incorporated as model constraints to ensure that previous capital expenditures are not negated by the model solution.

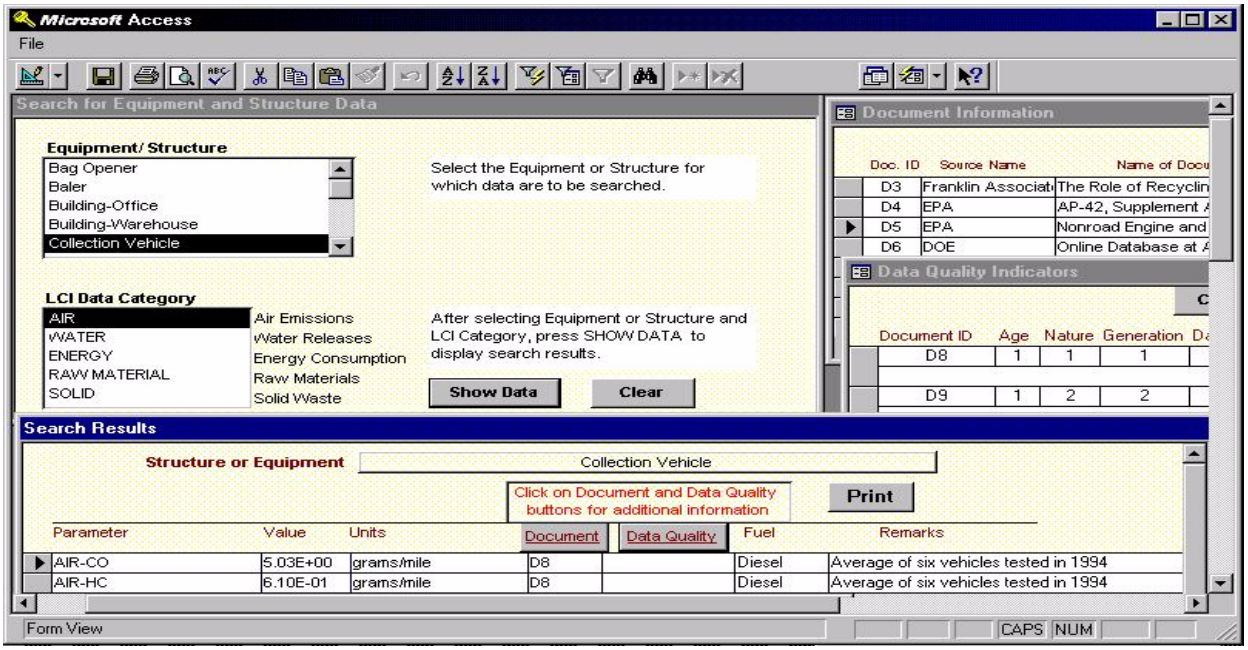



**Figure ES-2. Screen Capture from the Database.**

As illustrated in Figure ES-3, the decision support tool consists of several components including process models, waste flow equations, an optimization module, and a graphic user interface. The process models consist of a set of spreadsheets developed in Microsoft Excel. These spreadsheets use a combination of default and user supplied data to calculate the cost and life cycle coefficients on a per unit mass (ton) basis for each of the MSW components being modeled (see Table 1) for each solid waste management unit process (collection, transfer, etc.). For example, in the electric energy process model, the user may specify the fuel mix used to generate electricity in the geographic region of interest, or select a default grid. Based on this information and the emissions associated with generating electricity from each fuel type, the model calculates coefficients for emissions related to the use of 1 kWh of electricity. These emissions are then assigned to waste stream components for each facility that uses electricity and through which the mass flows. For example, MRFs use electricity for conveyors. The emissions associated with electricity generation would be assigned to the mass that flowed through that facility. The user will also have the ability to override the default data if more site-specific data are available.

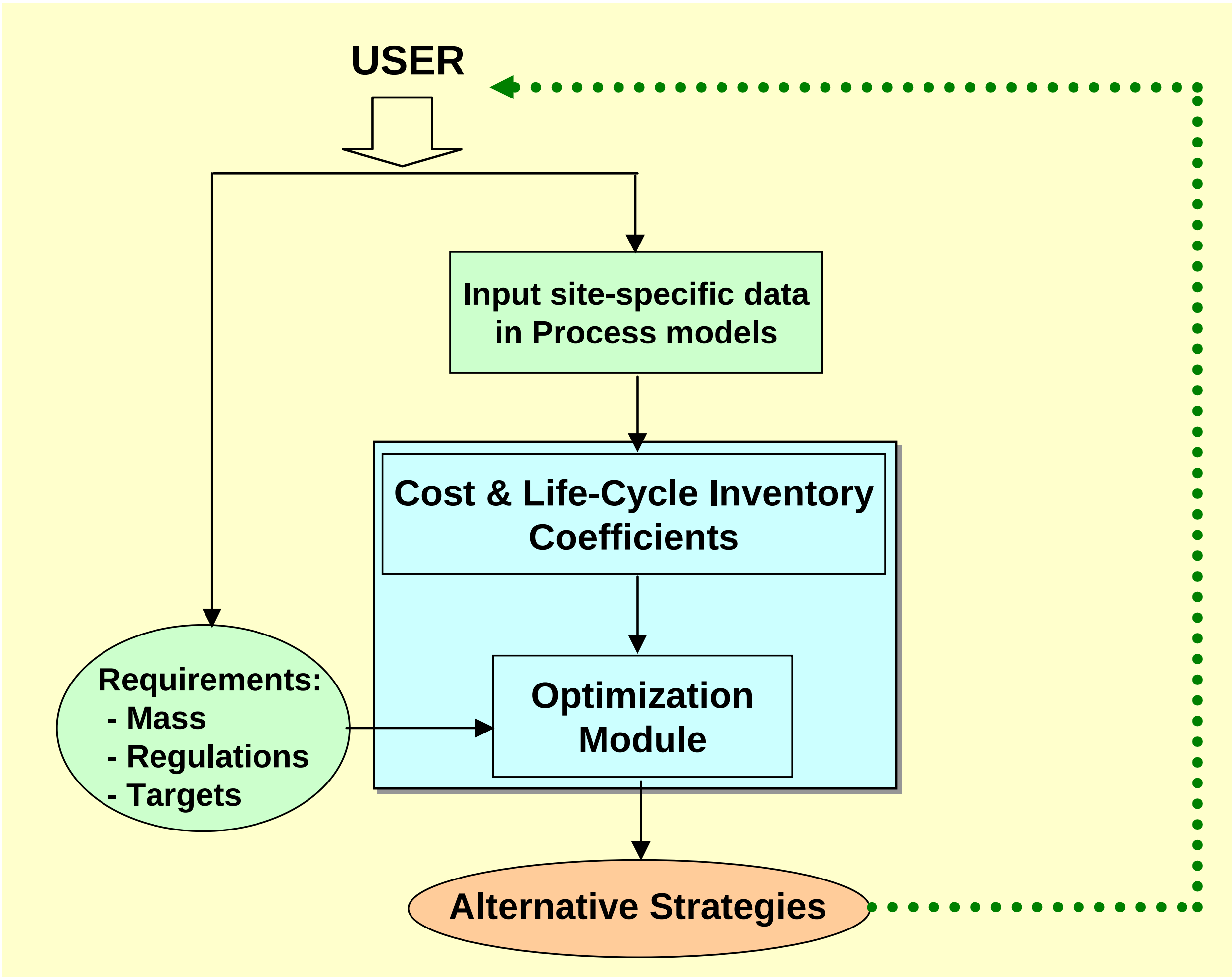



**Figure ES-3. Components of the Decision Support Tool**

The optimization module is implemented using a commercial linear programming solver called CPLEX. The model is governed by mass flow equations that are based on the quantity and composition of waste entering each unit process, and that intricately link the different unit processes in the waste management system (i.e., collection, transfer, recycling, treatment, and disposal options). The mass flow model constraints preclude impossible or nonsensical model solutions. For example, the mass flow constraints will exclude the possibility of removing aluminum from the waste stream via a mixed waste MRF and then sending the aluminum to a landfill. The user can identify the objective as minimizing total cost or LCI parameter (e.g., energy consumption). The optimization module uses linear programming techniques to determine the optimum solution consistent with the user-specified objective and mass flow and user-specified constraints. Examples of user-specified constraints might include the use of existing equipment/facilities and a minimum recycling percentage requirement.

The graphic user interface consists of a Microsoft Visual Basic routine that integrates the different components of the tool together to allow easy user manipulation of the spreadsheet models and the optimization module. It allows additional user constraints to be specified and provides a graphical representation of the solid waste management alternatives resulting from the optimization. Results
presented for the identified "optimal" solution include the annual per ton dollar cost, energy consumption, and pounds of various air, water, and solid waste releases. In addition, results can be viewed at the system, unit process, or MSW component levels.

Once the optimal solution is identified, the user is encouraged to use the modeling to generate alternatives (MGA) feature of the DST. Using this feature, the user can start with the optimal solution and then identify alternate solutions that are only marginally suboptimal and are different to the maximum extent possible. For example, the user may look at the least cost solution and have some concern about its political viability. Using the MGA feature, the user could then ask the DST to search for solutions that are no more than an allowable increase in cost, for example 10% more expensive than the least cost solution. The DST will then generate a solution that is different from the "optimal" solution but still attractive with respect to cost.

### Case Study Applications

The DST is being used in case study applications at local, State, Regional, and National levels. These studies are providing cost and environmental information about alternative waste management strategies to these assist these groups in developing waste management plans and policies. The case studies also are enabling the research team refine the methods and data used in the DST as well as the user interface to the DST. The following sample applications illustrate the flexibility of the DST to analyze a wide variety of MSW management issues and include the following:

- **U.S. Greenhouse Gas Emissions Analysis (National Level):** Climate change and greenhouse gas (GHG) emissions have become a focal environmental issue around the globe. Landfills represent the largest anthropogenic source of methane emissions (a potent greenhouse gas) in the U.S. The purpose of this study was to identify and assess the trends in GHG emissions associated with MSW management in the U.S. since the 1970's when the majority of waste was disposed in landfill without gas collection and control. The decision support tool helped to quantify GHG emisions and illustrated the amount of GHG emissions avoided in time through the employment of new MSW management techniques and technologies such as landfill gas collection and flaring, landfill gas-to-energy systems, recycling, composting, and WTE.

- **Island of Honolulu, Hawaii (Regional Level):** Many States and island communities are facing challenges as their MSW management needs grow and landfills reach capacity. This study focused on the island an Honolulu, HI and options for meeting the future MSW management needs of the Island. Four management options for the management of an additional 120,000 tons per year of MSW were investigated. These options included: (1) expanding the existing WTE facility for post-recycled MSW; (2) expanding the current recycling program; (3) disposing of wastes at a new landfill on Oahu; or (4) diverting post-recycled MSW from local landfill disposal to long-haul (West Coast U.S.) landfill operations. The goal of this study was to better understand the range of potential environmental burdens and tradeoffs of the four options using a life-cycle approach as provided by the decision support tool.

- **State of Minnesota (State Level):** In recent years, bioreactor landfills have gained prominence as an emerging technology in the management of MSW. Bioreactor technology differs from the conventional "dry tomb" landfill technology primarily through this addition of extra liquid. The desired effect of the bioreactor is that it produces landfill gas (LFG) at an earlier stage in the landfill's life and at a higher rate as compared to a conventional landfill.Bioreactor landfills were studied by the State of Minnesota to better understand their environmental significance as compared to more traditional MSW management options and technologies. The goal of this study was to apply the decision support tool better understand the range of potential environmental burdens and tradeoffs of using bioreactor versus conventional landfill technologies in the State.

- **City of Edmonton (Local Level):** With the growing focus on climate change and greenhouse gas (GHG) emissions, carbon trading markets have begun to develop. Kyoto-ratified countries can participate in the world-wide carbon trading market. In the U.S., groups of States in the northeast U.S. have started their own carbon market. In this study, the City of Edmonton sought to obtain accreditation for GHG emission reductions associated with the use of its compost facility as compared to the alternative of landfill disposal. The decision support tool was used to analyze the GHG emissions and emission reductions associated with Edmonton Compost Facility (ECF) as compared to baseline landfill options on a life cycle basis. The results of this analysis are intended for use in the verification of GHG emission offsets by a third-party verifier.

- **City of Tacoma (Local Level):** The City of Tacoma, Washington was interested in analyzing proposed upgrades to their waste-to-energy system and evaluating the environmental aspects of implementing these upgrades versus disposal of the waste in a landfill. Specifically, Tacoma was interested in comparing the conversion of 75% of their waste stream to refuse-derived fuel (RDF) and then burning the RDF in a WTE facility for energy versus landfill disposal of the waste. The data and results generated through this project were used to evaluate the cost and life-cycle environmental tradeoffs of the RDF versus disposal options for Tacoma, with the overall goal of identifying waste management strategies that are cost efficient and environmentally protective.

# Chapter 1
# Introduction

Most applications of life-cycle assessment (LCA) have generally focused on the evaluation of the environmental performance for a defined product system, while holding constant or altogether neglecting the mode of solid waste management. White et al. (1995) describe the application of LCA whereby the product system is held constant and the evaluation is done on the performance of alternatives for solid waste disposal. This concept has been implemented in programs throughout the world that are applying LCA concepts and methods to the evaluation of integrated municipal solid waste (MSW) management strategies. In evaluating such strategies, planners have a wide variety of available processes for waste collection, separation, treatment, and disposal to evaluate. Combining these processes in integrated systems forms complex interrelationships of mass flows with associated energy and resource consumption and environmental releases. Examining these interrelationships, and identifying optimal management solutions, can be accomplished by taking a life-cycle approach, as illustrated in Figure 1-1. Unlike traditional product LCAs which begin with raw materials extraction, our system begins with MSW generation and considers the inputs and effects to all life cycle stages resulting from the management of MSW.

The Research Triangle Institute (RTI) and the United States Environmental Protection Agency's (U.S. EPA's) Office of Research and Development applied LCA concepts and tools to evaluate the cost and environmental performance of integrated MSW management systems in the U.S. RTI's research team for this effort included LCA and solid waste management experts from North Carolina State University, the University of Wisconsin-Madison, Franklin Associates, and Roy F. Weston.

## 1.1 WHY TAKE A LIFE CYCLE APPROACH TO MSW MANAGEMENT?

A life-cycle perspective encourages waste planners to consider the environmental aspects of the entire system including activities that occur outside of the traditional framework of activities from the point of waste collection to final disposal. For example, when evaluating options for recycling, it is important to consider the net environmental benefits (or additional burdens) including any potential displacement of raw materials or energy. Similarly, when electricity is recovered through the combustion of waste or landfill gas, the production of fuels and generation of electricity from the utility sector is displaced.

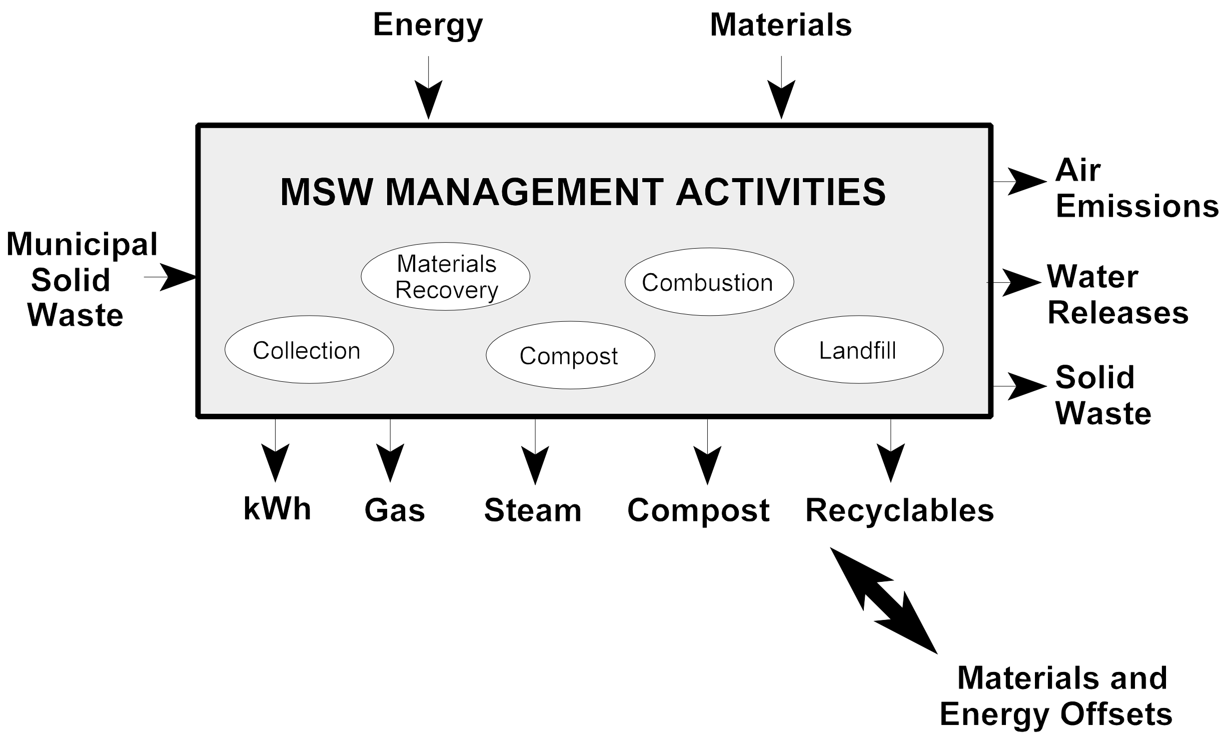



**Figure 1-1. Illustration of the Municipal Solid Waste Life Cycle.**

## 1.2 HOW DOES THIS RESEARCH HELP TO ANALYZE MSW MANAGEMENT STRATEGIES?

This research provides information and tools that will enable local governments and solid waste planners to examine cost and environmental aspects for a large number of possible MSW management operations for 42 distinct MSW components. The primary outputs of this research will include the following:

- **Decision support tool:** is being designed to allow MSW planners to enter site-specific data (or rely on the default data) to compare alternative MSW management strategies for their communities' waste quantity and composition and other constraints. This enables users to evaluate cost, energy consumption, and environmental emissions for a large number of possible MSW management operations including MSW collection, transfer, separation (MRF and drop-off facilities), composting, combustion, and landfill disposal.

**Using A Life-Cycle Approach to Study Solid Waste Management Systems**

RTI has initiated case studies of the DST with communities, States, and other solid waste management organizations. These case studies are providing cost and environmental information about alternative waste management strategies to these groups to assist in the development of management plans and policies. The case studies also are enabling the research team refine the methods and data used in the DST as well as the user interface to the DST. Some examples of the issues being analyzed with the DST for these different groups and studies are as follows:

- Lucas County, Ohio is currently developing a 15 year plan for their solid waste management system. They feel their current waste operations are not cost effective and ignore pollution and life-cycle implications. The analyses and results of this case study are helping them in the development of integrated, cost-effective, and environmentally preferable plans and targeting opportunities for improving recycling.

- The Great River Regional Waste Authority in Iowa is exploring the efficiency of integrated collection system versus multiple collection options, to evaluate effects of reconfiguring service areas and applying existing systems to them, and to develop a waste management plan for a 50% recycling scenario that is to be presented to the State authority.

- Anderson County, South Carolina is evaluating the cost and environmental implications of implementing a residential curbside recycling program for the more densely populated areas of the county as well as setting up a yard waste composting program. The results of this study will assist the County in determining the most cost effective strategies for implementing the programs.

- The State of Georgia used the DST to analyze the affects of a yard waste ban on air emissions for Gwinnett County. Current NOx emissions attributable to yard waste collection were estimated to be 105 tons per year and the elimination of a yard waste ban would result in an 11% decrease in NOx. The number of collection trucks needed for collecting commingled yard waste with MSW increases from 171 trucks (with no yard waste collected with MSW) to 201 trucks.

- The State of Wisconsin is investigating the environmental benefits of State-wide recycling programs. We are using the DST to analyzing how changes in levels of State mandated recycling goals can potentially affect environmental burdens. We are also analyzing how landfill tip fee surcharges can affect the role of recycling. The results of this study will assist the State in deciding what solid waste strategies should be used in the future to meet environmental improvement goals.

- **Database:** includes environmental data for individual MSW management operations, materials manufacturing operations, energy (fuels and electricity) production, and various types of vehicles and equipment. Environmental data include energy consumption and emissions (air, water, solid waste). The database allows users to search for data specific to a system unit process, structure, piece of equipment and or environmental parameter.

- **Community Case Studies:** Case study applications of the DST with local communities to test the cost and LCI methodologies, supporting data, and the overall DST. Studies were selected in a wide variety of rural and urban communities to investigate the flexibility of the DST for different settings.

The information and tools developed through this effort were designed with local governments and solid waste planners in mind as the primary users. For example, at the local level, the decision support tool can be used to evaluate, for example, the affects of changes in the existing MSW management on cost and environmental burdens, identify least cost ways to manage recycling and waste diversion, evaluate options for reducing greenhouse gases or air toxics, or estimate the environmental benefit of recycling. The information and tools from this research will also be of value to other user groups such as Federal agencies, environmental and solid waste consultants, industry, LCA practitioners, and environmental advocacy organizations. These users can use the decision support tool, for example, to evaluate recycling policies and programs, policies and technologies for reducing environmental burdens, and strategies for optimizing energy recovery from MSW.

## 1.3 WHAT TYPE OF REVIEW HAS THE RESEARCH UNDERGONE?

To ensure the applicability and usefulness of the research products to local governments and other solid waste planners, we employed an inclusive review process for all research activities and documentation. The review process entailed various levels of review by different groups, including the following:

1) Internal project team and U.S. EPA and U.S. Department of Energy advisors.

2) Project stakeholders from U.S. government, industry, academia, and environmental organizations. A current listing of project stakeholders is included in Attachment 1 to this report.

3) External project peer reviews. Three separate peer reviewers were conducted and have included the following individuals:

    - ♦ David Allen, University of Texas at Austin
    - ♦ Robert Anex, University of Oklahoma
    - ♦ Kevin Brady, Demeter Environmental Inc.
    - ♦ Jürgen Giegrich, Ifeu- Institute
    - ♦ Allen Hershkowitz, Natural Resources Defense Council, Inc.
    - ♦ Gregory Keoleian, University of Michigan
    - ♦ Mitchell Kessler, TIA Solid Waste Management Consultants, Inc.
    - ♦ Jay Lund, University of California-Davis
    - ♦ Ruksana Mirza, Formerly with Proctor and Redfern, Ltd.
    - ♦ Debra Reinhart, University of Central Florida

- Lynn Scarlett, Reason Foundation
- Aarne Vesilind, Duke University and Bucknell University
- Peter White, Proctor & Gamble
- Steven Young, Five Winds International

All research activities and outputs have been reviewed at each of these levels. Annual stakeholder meetings and stakeholder workgroup meetings were held to present the research activities and outputs and to solicit feedback and comments. Three external project peer reviews were conducted with experts in LCA and MSW management that were not already part of the project stakeholder group. Comments and suggestions from the stakeholder and peer review meetings have been documented and the research team has provided written responses. Attachments 1 through 3 to this document contain the comments from the three peer reviews and responses provided by the research team. Although considerable effort was made to address all comments received through these reviews, it is impossible to adequately address all comments due to technical, budget and schedule constraints. Issues that we were not able to address at the time were noted as issues for future research. The high level of involvement by project stakeholders and peer review committee members has contributed greatly to the success of this project.

## 1.4 WHAT ARE THE LIMITATIONS OF THE RESEARCH PRODUCTS?

Considerable effort was expended to make the products of the this research useful and easy-to-use so users could quickly obtain information that is accurate and as up-to-date as possible. However, as tools, they cannot address every situation and are limited in use for some applications. This section discusses some identified limitations of the data, process models, and DST.

### 1.4.1 Limitations of the Data

The goal of the data collection effort was to rely on existing and available sources of data to the extent possible and to develop data for areas where gaps existed. The areas in which it was necessary to develop data included landfills and composting operations. Although we consider the data presented in the database to be the best possible data that can be developed from the available secondary data sources and from our primary data collection efforts, the data is not without limitations. Our hope is that ongoing and future data development efforts by the different industries and organizations will be made publicly available and can be used to update the data provided in the database over time.

To assess environmental aspects of recycling, we require information on the production of a materials from primary and secondary (recycled) resources. The LCI data for primary materials production includes all processes and activities from the extraction of raw materials to the manufacture of a product or material commodity. The data for secondary materials production includes all processes and activities associated with reprocessing the recycled resources to produce a “new” material commodity.

*Data Represent Averages Across Industry*

The data compiled and developed for this project, including data for waste management, materials production, fuels production, electrical energy generation, and transportation activities represent national averages. In this respect, the data included in the database and DST assume a current level of technology where as in reality cost and emissions will be facility specific based on their location, level of technology, etc. The DST was designed so that users could input their own data if they have more site-specific information, however the data in the database can only be changed by the developer.

*The Materials Production LCI Data Sets Cannot Be Used To Directly Evaluate Recycling*

Data for collecting and processing the recyclables at a materials recovery facility (MRF) and then transporting the materials to a remanufacturing site are not included in the upstream LCI data sets because this information is developed in other modules of the DST. Therefore, these data sets cannot be used directly to compare the use of virgin and recycled materials. To conduct a more accurate evaluation of recycling, the materials collection, separation, and transportation processes also need to be considered.

*Data Assumptions for Primary and Secondary Materials Production*

The terms primary and secondary refer to the source of resources used to produce the materials and should be interpreted as being predominately primary or secondary. We have made assumptions, which are presented in a supporting materials production LCI data document (RTI, 2002) as to the types of resources that comprise these predominately primary and secondary materials production processes. In addition, for each material, a common manufacturing endpoint had to be defined and applied consistently for the primary and secondary system. For example, the endpoint for aluminum could be an aluminum can or an sheet/coil. In this case, we chose the endpoint to be at the sheet/coil stage and after that point.

*Materials Production Data Can Only Be Reviewed to a Limited Extent*

Due to the aggregated manner in which the materials production LCI data was made available for use in this research, data for specific processes is not available. This limits the level of review that can take place on the data sets. For example, reviewers can compare the LCI totals for the manufacture of primary steel compiled for this project to those developed for another project, but cannot compare the process-level (e.g., iron ore mining, coke production) data for the production of that steel. Although the materials data sets have been reviewed by industry representatives and peer reviewers, their ability to review and comment on the data according to ISO 14040 recommendations was not always possible.

### 1.4.2 Limitations Associated with the Process Models

Process models have been written to calculate the costs and LCI of each solid waste management unit operation in consideration of the quantity and composition of the waste processed. Separate process models are incorporated in the DST for collection, transfer stations, transportation, separation, composting, combustion, RDF, landfills (traditional, bioreactor, ash) and remanufacturing. An overview of each process model is presented in Chapter 3 and full descriptions of each unit operation model are available separately. Some general comments on the structure of the process models and their importance are presented in this section.

***The DST and the Cost and LCI Estimates are Based on Linear Relationships.***

The DST is a linear model. This is the feature that allows for the evaluation of large numbers of alternate solid waste management strategies quickly on a personal computer. Thus, all process model coefficients must be linear, meaning that coefficients must be of the form of $ per ton MSW-component or mass $NO_X$ per ton MSW-component. The resulting limitation of the model is that economies of scale cannot be considered mathematically. Thus, it is quite possible that a model solution will specify a unit operation to process an unreasonably small quantity of waste. For example, the model solution could include a combustion facility to process 20 TPD. This might occur if the user included combustion in the definition of diversion and was attempting to minimize cost while still meeting a diversion objective. It could also occur if the user wanted to maximize energy recovery while imposing a cost constraint. In these scenarios, the "optimal" solution might include combustion of enough waste to meet the diversion or energy objective, and a landfill for the remainder of the waste, assuming the cost of a landfill is below that of a combustion facility. The user should inspect a model solution for obvious problems such as an unreasonably small facility. Should this occur, the user should rerun the model after constraining it to generate a management strategy without using the facility (combustion in this example) that was originally proposed or require the use of combustion at some minimum tonnage.

***The Process Models Were Not Designed for Optimization of Individual Unit Operations***

The DST can identify optimal solid waste management strategies given an objective to optimize one of 9 optimizable parameters. However, the model is not designed to identify the optimal designs of individual solid waste unit operations. For example, aluminum cans can be separated from a stream of commingled recyclables either manually or by use of an eddy current separator. The user must select the separation technology to be used. The process model will not identify one alternative as being favorable. Similarly in the collection process model, the model estimates average truck transportation costs, but it is not meant to identify the optimal routing strategy for waste collection.

***Only one process is currently considered for each recyclable in the remanufacturing process model***

As described in the system definition in Chapter 2, an offset analysis is used to account for the difference in the LCI associated with manufacturing processes for primary and secondary materials. The product manufactured from each recyclable is unique and was selected to facilitate use of an offset analysis. For example, old newsprint (ONP) is assumed to be converted to new newsprint but the actual printing process is not considered for either primary or secondary material production as it is the same for both. Similarly, recycled aluminum is converted back to sheet/coil from which many products can be made.

In many cases, a secondary material can be used in a number of ways. For example, ONP can be converted to new newsprint, animal bedding, or cellulose insulation among other products. For this project, ONP was assumed to be converted to new newsprint and the offset analysis was conducted on that basis. To the extent that ONP is converted to another product, the offset analysis would change. It should also be noted that many fiber recyclables are exported prior to the remanufacturing step. For this model, the location of the reprocessing step, even if it was in another country, was not considered.

***The Offset Analysis Assumes Closed-Loop Recycling and Direct Product Substitution***

The offset analysis used to analyze the reprocessing of recovered materials assumes that the production of a product from a secondary (recycled) material replaces the same product manufactured from the primary materials in a closed-loop recycling type system. This may not always be true. One project stakeholder presented an example where secondary HDPE was used in place of primary LDPE, which would have a slightly different LCI than primary HDPE. Similarly, discarded newspaper could be remanufactured into a variety of products other than newsprint.

***Beneficial Reuse of Ash Is Not Included in the Combustion and RDF Process Models***

Ash is produced from MSW during its combustion in either a combustion facility or RDF plant. The only management alternative available for such ash is burial in a landfill. The beneficial use of ash in construction materials is increasing, thus reducing the disposal of ash in a landfill. Thus, for a specific locality, the cost and environmental emissions associated with ash burial may not be relevant. Emissions from an ash landfill are reported in the DST results output and can be subtracted from the total LCI if appropriate.

***Landfill Life Assumes a Typical Design Life***

While there exists a relationship between landfill diversion and landfill life, and hence, unit landfilling costs, this effect is minimal in the context of a high level screening tool. It is assumed that the landfill life is sufficiently long so that unit landfilling costs are minimized. That is, the discounted landfill replacement costs are insensitive to the assumed landfill life for a typical design life of a landfill.

***The Cost and Price May Differ***

The process models calculate the cost of each solid waste management unit operation in units of $/mass of a MSW component processed. These values are based on estimates of the cost for a particular unit operation and make no allowance for whether the unit operation is built and operated by the public or private sector. Where a part of the solid waste management system is built and/or operated by the private sector, the actual price (tipping fee) will likely be higher than the cost to account for a profit. Thus, the costs calculated in the model may not represent price.

***Use of Engineering Economics for Cost Modeling***

All economic modeling is performed using standard engineering economics. This means that the capital cost of a facility is amortized over the useful life of the facility at a user input interest rate. This annualized cost is combined with annual operating costs to estimate total costs. The economic model does not address issues of cash flow, taxes and the like.

***Costs Borne by the Private Sector***

The total solid waste management system cost includes the cost to manage all waste generated and managed within the 2 residential, 2 multifamily and 10 commercial sectors. Certain of these costs, specifically the cost to manage waste generated in the commercial sectors which are presumably privately owned, may be borne by the private sector. To obtain estimates of total public sector cost, the costs borne by the private sector, as identified by the model user, can be subtracted out. The model results are presented to allow the user to make this type of calculation. Alternately, wastes generated in sectors for which disposal is paid by the private sector can be excluded from the model to obtain public sector costs. However, private sector waste should not be included in the model at zero cost as the model will not properly evaluate cost-effective solutions for the private sector waste at zero disposal cost.

***Decommissioning Costs Are Not Included***

The economic analysis does not include the cost to return a site to its initial condition at the end of the useful life of the facility. In the case of a landfill, the economic analysis does include the cost for site closure and post-closure monitoring and maintenance.

### 1.4.3 Limitations of the Decision Support Tool

The DST is a mathematical representation of a highly complex solid waste management system. Given the complexities of the solid waste management system, it must be recognized that no model can completely describe an actual system. By necessity, some simplifications were required in its development. The first and most basic level of simplification is described in system description (see Chapter 2). The system description notes, for example, that MSW is divided into a finite number of components that includes the major components of MSW and the major recyclables. Nonetheless, there are hundreds if not thousands of components in MSW and they could not all be itemized in this model.

A second example of the basic system simplification inherent in the DST is the use of sectors. The DST can accommodate up to 2 residential, 2 multifamily and 10 commercial sectors. In reality, a MSW management district may include many residential and multifamily sectors and more than 10 commercial sectors. While there is no one strategy that will address this limitation for all users, an example of how this limitation was addressed in a recent case study for Lucas County, Ohio. In that study, it was determined that their MSW management system included about 28 separate residential sectors. These sectors included Toledo, which contained approximately 70% of the total population of the county-wide solid waste management district, and 27 smaller communities, each with its own collection contract. For the Lucas County case study, we devoted one residential sector in the DST to represent Toledo and a second to represent average or typical data for the 27 smaller communities aggregated as one. This is just one example of the need for some creative use of the DST in modeling existing solid waste management districts.

Additional limitations of the DST are:

***The DST Is a Planning and Screening Tool***

The DST is a screening tool and not a design tool. It is designed to be used to evaluate the entire solid waste management system, particularly when there is the potential to redesign a substantial part of the system. The model will identify a solid waste management solution that is optimal for a user defined objective and user defined constraints. A suggested use of the DST is illustrated as follows. After specifying location-specific information and accepting or modifying process model inputs, the user may use the optimization capabilities of the model. For example, the user may run the model with the objective of identifying a solid waste management alternative that has the least cost (model objective) and meets a landfill diversion rate of 25% (a constraint). Based on this objective and constraint, the model will identify the least expensive solid waste management alternative in which 25% diversion can be accomplished. [Note that diversion can be defined by the user to include or exclude recycling, yard waste composting and combustion]. Similarly, the model could be given an objective to identify the solid waste management alternative that minimizes $NO_X$ emissions (objective) while not exceeding a total annualized cost of 25 million dollars (constraint).

Once an “optimal” solution is identified, the user is encouraged to use the modeling to generate alternatives (MGA) feature of the DST. Using this feature, the user can start with the optimal solution and then identify alternate solutions that are only marginally suboptimal and are different to the maximum extent possible. For example, the user may look at the least cost solution and have some concern about its political viability. Using the MGA feature, the user could then ask the DST to search for solutions that are no more than an allowable increase in cost, for example 10% more expensive than the least cost solution. The DST will then generate a solution that is different from the “optimal” solution but still attractive with respect to cost. Similarly, if the objective function is to minimize $NO_X$ emissions, then the user can start with this "optimal" solution and, using the MGA feature, identify solutions that might lower the total waste management cost by allowing 15% (a user input value) higher $NO_X$ emissions.

Note that the DST cannot simultaneously optimize for minimum values of two LCI parameters. Rather, tradeoffs associated with multiple objectives such as cost and $NO_X$ emissions should be obtained by multiple runs of the model with the appropriate objective functions and constraints.

The DST should be used to identify multiple favorable solutions to a given problem. The user should then inspect the proposed solid waste management strategies to identify those that appear viable for a given community in consideration of factors that were not modeled. Such factors could include political and social considerations, or the divergence between the current solid waste management system and that proposed by the model.

Once a series of potentially viable MSW management alternatives is identified, designs and cost estimates for these alternatives should be developed in detailed engineering studies. Final decisions on the implementation of a solid waste management system should be based on the results of these more detailed studies and not on the model results alone. In this respect, the model is a screening tool that should be used to narrow down the focus of a detailed engineering study. The model is not a design tool that should be used as the basis for how many collection vehicles to order or the acres of land to purchase for a solid waste management facility.

### *There Is Uncertainty Associated with the DST Results*

Model results should be interpreted in consideration of the fact that they are not 100% precise. Two alternatives with slightly different costs or emissions may not be significantly different. It is not possible to state that cost or LCI are within some percentage as the results represent the combination of thousands of individual parameters, many of which will vary from scenario to scenario. With this in mind, the model is best used to identify several potentially favorable alternatives for detailed analysis that may include assessments of the uncertainty. Note also that to the extent that the data are imperfect, the model may still generate alternatives in the appropriate rank order as imprecision will affect all unit operations equally in the system.

While uncertainty estimates of the outputs are not provided by the DST, the user is encouraged to perform sensitivity analysis on key variables. The DST has been structured to make it easy for the user to change user-defined inputs and can perform a sensitivity analysis by repeated runs of the model. For example, if the user knows that labor wage rates may vary by 20% over the next year, then the model can be run with different wage rates in that range. While the user may have a reasonable idea of variability in the economics of solid waste management systems, many users will have little familiarity with variability in the life-cycle data. Some data quality information on the life-cycle parameters can be obtained from the stand alone database and users may apply this is in sensitivity analysis of the LCI parameters.

### *The DST is a Steady-State Model*

The DST is strictly a steady-state model. This means that only one value for each model input parameter can be entered and the model solution assumes that this parameter remains constant with time over the planning horizon.

A community is likely to experience many changes over the useful life of a solid waste management system. Potential changes include increased population and community size, labor rate increases and volatility in the unit revenues for the sale of recyclables and recovered energy. The sensitivity of model results to these and other changes should be explored by the user by making multiple runs of the model with varying values for specific input parameters.

The revenue associated with recyclable sales is perhaps the most volatile input and warrants some further consideration. In the economic portion of the model, the net cost of a solid waste management program is the cost after the realization of income from the sale of recyclables. While accurate, in actuality, a contract for the collection and or separation of recyclables may be based on the costs for collection and separation, with some agreement to share the associated revenue. Thus, the cost calculated in the model, which is a net cost, may be lower than the cost of a contract that separates the collection and separation cost from the revenues from recyclables. From a business perspective, such separation may be essential given the volatility in recyclable prices.

***The Calculated LCI Results Represent Global Emissions***

The calculated value for each LCI parameter represents the total for the entire MSW management system. While the amount of a given emission that can be attributed to a specific unit operation, such as collection, landfill or remanufacturing is presented, the amount of a given emission that is attributable to sources within and outside of a community is not available. In actuality, only a fraction of each emission can be attributed to local activities. Some notable examples are discussed here.

In the case of collection, there are emissions associated with the collection vehicle that are clearly local. However, there are also emissions associated with the production of the diesel used to fuel the collection vehicle (precombustion emissions) and these emissions occur at the sites of petroleum extraction and refining followed by its transport to the local community. Emissions reported by the DST will simply report the sum of emissions for a particular pollutant.

In addition, electricity is consumed due to activities associated with the administrative office and maintenance activities for refuse collection. The emissions associated with this power generation occur over a wide area. As described in the electrical energy process model, the electrical energy in the power grid is produced from a number of fuels at a number of distinct production facilities. These facilities are almost certainly not all within the local community.

With respect to recyclable manufacturing, note that the LCI is calculated as the difference between the value of the LCI parameter for primary and secondary materials production processes. In a case where the manufacturing location is different for the primary and secondary processes, changes in emissions at the facility handling secondary materials and at the facility handling primary materials will be different. For example, as the mass of a material that is recycled increases, emissions may increase at the facility handling these materials and decrease at the facility producing primary materials. Therefore, while the global emissions associated with a unit of material recycling may be negative, the local community emissions may be positive depending on the geographic location of the associated manufacturing facilities. Nonetheless, from a global perspective, all emissions are summed to present one emission value that may be negative if there is a savings attributable to the secondary materials production process.

***The DST Represent an LCI and Not an Impact Assessment***

According to ISO 14040 (1996), an LCA includes a definition of goal and scope, an inventory analysis in which all emissions are quantified, an impact assessment in which the potential environmental impacts of the product system are calculated, and an interpretation of the results of the inventory or inventory and impact assessment to reach conclusions and recommendations. The DST provides results for inventory analysis. Efforts have been made to present the data in a manner that will support environmental impact assessment as appropriate impact tools become available. In considering the impact assessment stage, the discussion of local versus global emissions must be considered.

***The DST Addresses Source Reduction in a Limited Manner***

Source reduction includes a reduction in the mass, volume or toxicity of a waste. Examples of source reduction include a lighter aluminum can that holds the same amount of product, the development of substitutes for chlorofluorocarbons as refrigerants given their severe environmental impact, or the use of double sided copies for the distribution of reports. Although an important part of solid waste management, a specific source reduction process model was not included in the DST. Rather a simple calculator tool was added to estimate the benefits of not producing a user-defined quantity of material that has been source reduced. However, this is only half of the source reduction equation. Users must also run the DST a second time with a reduced waste generation rate (based on the source reduced materials). While this may be appropriate for some cases, it represents a highly simplistic approach and one that may not be accurate. For example, if the waste generation rate is decreased due to a substitution of cloth diapers for disposal diapers, then the extra activity associated with the washing of cloth diapers must also be considered. Similarly, if a manufacturing process is modified to reduce the mass of a product or to reduce the presence of a toxic metal in the product, then the modifications to the manufacturing process must also be considered. A full life cycle model of production processes is needed to analyze such tradeoffs. Users are cautioned to use the model to evaluate source reduction only when they can fully consider all of its environmental emission implications.

***The MSW Management System That Was Modeled Begins at Curbside***

The solid waste management system that was modeled is based on the management of waste set out at curbside or brought to drop off facilities for composting and yard waste. Activities associated with solid waste management that occur at the site of waste generation are not considered.  Examples of such activities include the manufacture of collection bags and bins, backyard composting, rinsing of recyclables, and fuel used to transport materials to drop-off sites.

***Construction Related LCI Effects Are Not Included.***

A decision to exclude construction from the overall model was made during the system definition phase of this research.  Estimates of the significance of construction have shown that for most waste management facilities, this assumption is appropriate.  However, for landfills, the total energy consumption for construction were found to represent 25% and 2% of the total landfill LCI for scenarios without and with energy recovery, respectively.  The parallel energy values for  combustion without and with energy recovery were estimated to be 0.2 and 3.2%, respectively.    To the extent that the model solution includes a traditional landfill, the overall LCI values will be low due to the exclusion of its construction.

***The DST Only Allows for One of Each Type of Facility***

The overall model that is embedded in the DST only allows for the presence of one of each type of solid waste management facility.  For example, a large solid waste management district might have two landfills or two MRFs.  However, the model would only allow for one of each facility.  Of course, the model does allow for multiple types of the same type of facility.  For example, the model allows for up to five different MRFs, three landfills (traditional, bioreactor, ash), yard waste and mixed waste composting, etc.  This could lead to MSW management cost estimates that are somewhat higher than actual.  For example, the optimal solution could include two MRFs, one receiving commingled recyclables and one receiving mixed refuse.  If a solid waste district were to construct these two MRFs, then it is possible that they would be located at the same site and would share certain facilities such as a parking area, gatehouse, some rolling stock and personnel associated with marketing recyclables.  The economies of scale associated with locating two facilities on one site are not accounted for in the model.

***The DST Does Not Consider How Cost Savings Associated with MSW Management Might Be Spent***

Solid waste management may be provided as a public sector service financed through property taxes, through private subscription, or through some combination of the two.  Funds not spent on solid waste management in the public sector may be returned to the taxpayers through a tax rate decrease, or used for other publicly funded programs.  Similarly, cost savings associated with private subscription should result in individuals having more disposable income.  This income, whether in the hands of the public sector or the private citizen, may result in spending money on something else.  This alternative use of money will have its own LCI that is beyond the scope of the DST.

***The DST Is Not A Dynamic Model***

The DST assumes that any facility can be replaced at the same cost, corrected for inflation, as the cost at which a facility can be built initially. Further, the model assumes that equipment and facilities are repeatedly replaced at the end of their useful life with equivalent units of equal value. The DST does not address issues such as a transition from an existing MSW management system to a new management strategy. In particular, the model is not designed to optimize integrated waste management in the short term given an existing landfill with little remaining capacity.

To explore the importance of changes in variables such as the revenue from a recyclable, the generation rate, a collection parameter associated with a city growing - the user is encouraged to play "what if" games by deliberately changing various input parameters to explore the significance of the change on the model solution and the values of the cost and LCI parameters. The tool is designed to make this easy.

## 1.5 ORGANIZATION OF THIS DOCUMENT

This document is designed to provide readers with the essential information to gain a better understanding of the research and research products.

Any life-cycle study must begin with a rigorous definition of the goals and system boundaries that are to be modeled. The system description for this study is summarized in Chapter 2. A stand-alone system description document was prepared and is available separately. An overview of the process models embedded in the DST and describes the general facility designs, cost methodology, and LCI methodology for each model is presented in Chapter 3. Again, stand-alone and fully detailed documentation for each process model was prepared and is available separately. Chapter 4 contains a discussion of the main research products and Chapter 5 walks the reader through examples of how the DST was used in case study applications.

The attachments to this document contain the individual reports from the three peer reviews conducted for this project. The reports include comments from the peer reviewers and responses provided by the research team.

A number of supporting documents are available from EPA if you would like to know more detail about the methodologies, data, database, and DST. These supporting documents are made available as appendices to this report and include:

| | | |
|---|---|---|
| Appendix | A: | Collection Process Model |
| Appendix | B: | Transfer Station Process Model |
| Appendix | C: | Materials Recovery Facility Process Model |
| Appendix | D: | Combustion Process Model |
| Appendix | E: | Mixed and Yard Waste Composting Process Model |
| Appendix | F: | Landfill Process Model |
| Appendix | G: | Inter-unit Operation Transportation Model |
| Appendix | H: | Reprocessing Model |

# Appendix I: Electric Energy Model

# Chapter 2
# Goal and Scope Definition

The objective of this chapter is to describe the overall goal and scope for this research and to present the functional elements that comprise the system under study as well as system boundaries. This system description is a small but critical part of the overall project. Additional detail about the functional elements are provided in Chapter 3 of this document as well as in the supporting process model documentation available from EPA.

## 2.1 GOAL DEFINITION

The ***overall goal*** for this research was defined to develop information and tools to evaluate the relative cost and environmental performance of integrated MSW management strategies. For instance, how does the cost and environmental performance of a MSW management system change if a specific material (e.g., glass, metal, paper, plastic) is added to or removed from a community's recycling program? And, what are the tradeoffs in cost and environmental performance if paper is recycled versus combusted or landfilled with energy recovery?

The ***primary audience*** for this effort is local governments and solid waste planners. However, we anticipate that the information and tools developed through this study will also be of value to Federal agencies, environmental and solid waste consultants, industry, LCA practitioners, and environmental advocacy organizations.

The function of the system under study is to manage MSW of a given quantity and composition. Therefore, we have defined the ***functional unit*** as the management of a defined quantity and composition of MSW. We consider all activities required to manage this waste from the time it is sent out for collection to its ultimate disposition, whether that be disposal in a landfill, compost that is applied to the land, energy that is recovered from combustion and landfills, or materials that are recovered and remanufactured into new products.

## 2.2 SCOPE DEFINITION

The ***overall scope*** of the project includes all major processes and activities that are involved with, or are affected by, the management of MSW. The system is divided into a number of distinct solid waste management processes linked together as illustrated in Figure 1-1 in the previous Chapter. These processes include waste generation, collection and transfer, separation, treatment (which may include composting, combustion or RDF production) and burial. Remanufacturing is considered to the extent that a specific component of the waste stream is recycled. In this case, the LCI includes energy and resource consumption and the environmental releases involved in the remanufacturing process, as well as the energy, resources, or releases offset by virtue of using recycled versus virgin materials.

Although Figure 1-1 illustrates the functional elements which comprise the integrated MSW system, the key unit processes in the system and the manner in which waste can flow between these unit operations are illustrated in Figure 2-1. As presented in Figure 2-1, there is a lot of interrelatedness between the individual unit operations. For example, decisions made with respect to waste separation influence downstream processes such as combustion. An example of waste management alternatives for one waste component is presented in Figure 2-3. This figure illustrates the possible paths for old newsprint (ONP) through the system.

In defining the solid waste management system, our objective was to be as flexible as possible. However, given the large diversity of settings in which MSW is generated in the United States, development of a single system definition to address all situations would make the project unnecessarily complicated. Thus, there are likely to be situations where this system definition cannot be applied.

The remainder of this Chapter is structured to follow the order of the functional elements as presented in Figure 2-1. The discussion of system boundaries is summarized in the final section by which time the reader will have a more complete understanding of the proposed system.

## 2.3 WASTE COMPONENTS

The 42 MSW components include those defined by the U.S. EPA's Office of Solid Waste (U.S. EPA, 2004) and are listed in Table 2-1. This definition includes mixed MSW generated in the residential, commercial, institutional, and industrial sectors but excludes industrial process waste, sludge, construction and demolition waste, pathological waste, agricultural waste, mining waste, and hazardous waste. We have also included ash that is generated from the combustion of MSW in our system, but combustion ash is not included as part of EPA's definition of MSW. As shown in Table 2-1, we have divided the MSW stream into three different waste generation sectors: residential, multifamily dwelling, and commercial. The rationale for this separation is that different collection and separation alternatives may apply to each sector.

## 2.4 UNIT PROCESSES

Unit processes are the building blocks of any LCA. The focus of this research was on the waste management end of the life and thus the majority of unit processes included are those dealing with waste management. Additional upstream processes are also included as needed. The major unit processes included in the overall system under study are:

## Table 2-1. Components of MSW Considered in this Study[a]

| Residential Waste | Multifamily Dwelling Waste | Commercial Waste |
|---|---|---|
| **Yard Waste** | **Yard Waste** | 1. office paper |
| 1. grass | 1. grass | 2. old corrugated containers |
| 2. leaves | 2. leaves | 3. phone books |
| 3. branches | 3. branches | 4. third class mail |
| 4. food waste | 4. food waste | 5. aluminum cans |
| **Ferrous Metal** | **Ferrous Metal** | 6. clear glass |
| 5. cans | 5. cans | 7. brown glass |
| 6. other ferrous metal | 6. other ferrous metal | 8. green glass |
| 7. non-recyclables | 7. non-recyclables | 9. PET beverage bottles[c] |
| **Aluminum** | **Aluminum** | 10. newspaper |
| 8. cans | 8. cans | 11-12. other recyclables |
| 9-10. other - aluminum | 9-10. other - aluminum | 13-15. other non-recyclables |
| 11. non-recyclables | 11. non-recyclables | |
| **Glass** | **Glass** | |
| 12. clear | 12. clear | |
| 13. brown | 13. brown | |
| 14. green | 14. green | |
| 15. non-recyclable glass | 15. non-recyclable | |
| **Plastic** | **Plastic** | |
| 16. translucent-HDPE[b] | 16. translucent-HDPE[b] | |
| 17. pigmented-HDPE[b] | 17. pigmented-HDPE[b] | |
| 18. PET beverage bottles[c] | 18. PET beverage bottles[c] | |
| 19-24. other plastic | 19-24. other plastic | |
| 25. non-recyclable plastic | 25. non-recyclable plastic | |
| **Paper** | **Paper** | |
| 26. newspaper | 26. newspaper | |
| 27. office paper | 27. office paper | |
| 28. corrugated containers | 28. corrugated containers | |
| 29. phone books | 29. phone books | |
| 30. books | 30. books | |
| 31. magazines | 31. magazines | |
| 32. third class mail | 32. third class mail | |
| 33-37. other paper | 33-37. other paper | |
| 38. non-recyclable paper | 38. non-recyclable paper | |
| 39. miscellaneous | 39. miscellaneous | |

[a]Numbers represent the number of individual MSW components that can be included in the decision support tool.
[b]HDPE = high density polyethylene
[c]PET = polyethylene terephthalate

**Waste Management:**
- Collection
- Transfer Station
- Materials Recovery Facility (MRF)
- Combustion (with or without energy recovery)
- Refuse-Derived Fuel (traditional and process refuse fuel)
- Composting (yard waste and mixed MSW)
- Landfill (traditional, enhanced bioreactor, and ash)

**Other Processes:**
- Electrical Energy
- Inter-Unit Process Transportation
- Manufacturing of Materials from Virgin Resources and Remanufacturing of materials from Recycled Resources

For each of these unit processes, "process models" were developed that utilize generic design and operating parameters in conjunction with resource and energy consumption and emission factors to estimate cost and environmental (LCI) parameters. The cost and LCI results are highly dependent on the quantity and composition of incoming material to each unit process and thus the process models also contain methodologies for allocating cost and environmental parameters to each of the MSW components as listed in Table 2-1. The boundaries and methods used in the process models were made as consistent as possible across all unit operations. In cases where the boundaries and methods differ, the difference is noted and justified. Chapter 3 contains summaries for each process model and includes discussion of unique features to specific models. A brief description of each model is provided below.

**Collection:** There are a number of options for the collection of refuse generated in the residential, multifamily dwelling and commercial sectors. The manner in which refuse is collected affects the cost, resource utilization, releases and design of both the collection operation and potential down stream processing facilities such as a materials recovery facility (MRF). Multifamily dwelling waste may or may not be collected by the city in a manner similar to residential refuse collection. Whether this waste is collected by the city or a private contractor should not affect the LCI. We assume that commercial waste and recyclables are collected by private contractors. However, the energy and resource consumption, and environmental releases associated with commercial waste and recyclables collection will be accounted for in the proposed system. The construction of waste or recyclables collection bins is not included in the system boundaries.

**Transfer Stations:** Once refuse has been collected, there are a number of facilities to which it may be transported including a transfer station, MRF, a combustion facility, RDF plant, composting facility or a landfill.

**Material Recovery Facilities**: In MSW management strategies where materials recycling is utilized, recyclables will require processing in a MRF. The design of a MRF is dependent upon the manner in which refuse is collected and subsequently delivered to the MRF. Thus, the collection and recycling of MSW are interrelated. This interrelatedness is captured in the system.

**Composting:** Composting is the aerobic biodegradation of organic matter and is considered as a treatment alternative. The compost process model can consider the composting of yard waste and mixed waste. Yard waste composting may occur in either a centralized municipal facility or in a generator's backyard. Here, we consider a centralized composting facility. Backyard composting is not included in the system boundaries. We propose to consider two alternatives for yard waste composting; a low medium technology facility. The major difference between these two facilities is the degradation rate of the yard waste as influenced by the turning frequency. The design of the mixed waste composting facility can be based on mechanical or static aeration.

**Combustion**: Combustion represents a treatment alternative in which the volume of MSW requiring burial is significantly reduced. We consider a waste-to-energy (WTE) combustion facility in which MSW is burned with subsequent energy recovery in the form of electricity. Facilities in which energy is not recovered as well as facilities in which energy is recovered as steam are excluded from the system. The rationale for this selection is that the majority of combustion facilities constructed today include energy recovery as electricity.

**Refuse Derived Fuel And Process Refuse Fuel:** In addition to combustion as discussed in the previous section, two alternatives for recovery of the energy value of MSW will be considered in the solid waste management system, RDF and co-combustion. In the system described here, RDF production refers to the separation of MSW into a product stream with a relatively high BTU value and a residual stream with a relatively low BTU value. Of course, the efficiency of the separation of MSW into these streams will be less than 100%. There are many variations on the RDF theme including the production of shredded refuse for direct combustion, and the production of pellets for shipment over longer distances. The most common RDF processes will be identified in future work so that one or more generic RDF plant designs can be developed. These designs will be used as the basis for which cost, energy, and emission factors are developed.

**Landfills:** Three types of landfills will be considered in the system; one designed as a traditional mixed waste landfill, one enhanced bioreactor landfill, and a second designed for the receipt of ash only. The mixed refuse landfill will be designed according to RCRA Subtitle D and Clean Air Act standards. However, the user will have the opportunity to specify either a more lenient or stricter design with respect to the liner and cover systems. The landfill will be operated as a dry landfill. Consideration of the operation of a landfill with leachate recycle for enhanced decomposition and methane production was discussed in the previous section. The system will include both gaseous and liquid releases from the landfill. The user will be required to specify whether gas is flared, recovered for energy, vented to the atmosphere or allowed to diffuse out of the landfill. This information, coupled with data on landfill gas production, will be used to estimate atmospheric emissions. Estimates will also be developed for the amount of leachate requiring treatment. This leachate will be treated in an offsite treatment facility. Energy and emissions associated with leachate treatment will be considered in the LCI.

**Electrical Energy:** The electric energy model provides an accounting of the total energy consumption and emissions resulting from the use of electric energy. Precombustion and combustion energy consumption and emissions on a per unit fuel basis are used in conjunction with unit efficiencies, transmission and distribution line losses, and electric generation fuel usage percentages to allocate energy consumption and emissions to the usage of an electric kilo-watt hour (kWh) based on the contribution to the generation of that kwh by each fuel type. Emissions and energy consumption per kwh are calculated for the national grid fuel mix as well as for the nine major electrical generating regions in the United States. Default values for parameters used in these calculations are provided with optional user override capability for the majority of these parameters.

**Transportation:** Transportation (separate from waste collection) modes included in the system are rail, heavy-duty diesel (tractor trailers), light-duty diesel vehicles and light-duty gasoline vehicles. Cost and LCI factors for transport of mixed refuse, fuel, and compost are calculated per ton of aggregate mass flow between nodes. In contrast, recyclable materials are often shipped separately and have item-specific densities. For example, loose glass has a density nine to ten times that of plastic. For this reason, item-specific cost and LCI factors are calculated for recyclables transport. Connections for which item-specific factors are determined for recyclables include transport from transfer stations to separation facilities and from separation facilities to remanufacturing.

**Remanufacturing:** As part of the LCI, we must account for all resources, energy, and environmental releases associated with the recycling and reprocessing of a waste component. This section presents the conceptual framework which we propose to use to account for resource expenditures and potential savings due to the use of recycled materials. In management strategies where some portion of the MSW is recycled, the recyclables will ultimately be delivered to a facility for remanufacturing. Separation will occur during collection, at a MRF, or at another waste management facility. In addition to recycled materials, an offset will also be required in management strategies where energy is recovered from either the direct combustion of MSW, RDF, or landfill gas. The conceptual framework described above may be applied here as well. Energy recovered from the MSW will be credited to that management strategy. In calculating emissions reductions associated with energy recovery, we assume that any “saved” electrical energy resulted from fossil fuel (coal, oil, or natural gas) and not from hydro or nuclear power.

## 2.5 DATA PARAMETERS TRACKED

The main categories for cost and environmental parameters tracked as part of the research included:

**Cost Categories:**
- Annual capital cost
- Annual operating cost

**Environmental (LCI) Categories:**
- Energy consumption
- Air emissions
- Waterborne releases
- Solid waste

To compare across alternative MSW management options, we can only use parameters for which comparable data exists across all unit processes. For example, although data for dioxin/furan emissions for MSW combustion facilities are readily available, comparable data do not exist for MRF, composting, and landfill operations. Thus, we cannot directly compare these unit processes based on dioxin/furan emissions.

A subset of the parameters in the DST for which we currently have consistent data on can be optimized:

- Annual cost
- Carbon monoxide
- Carbon dioxide (fossil - resulting from the combustion of fossil fuels)
- Carbon dioxide (biomass - resulting from the biodegradation or combustion of organic material)
- Electricity consumption
- Greenhouse gas equivalents
- Nitrogen oxides
- Particulate matter
- Sulfur dioxide

These parameters can be optimized on as part of the decision support tool (DST) solution. Additional air and water parameters are tracked and reported in the DST, but cannot be optimized on at this time. Based on the need of user to optimize on additional parameters, future versions of the DST can be updated to include an expanded list of optimizable parameters.

## 2.6 SYSTEM BOUNDARIES

The system boundaries for this study have largely been defined through the description of the functional elements and unit processes and the manner in which each will be treated. These elements and processes are outlined in detail in a draft system description document and summarized in the following section. Unlike traditional LCAs, however, our study integrates cost and environmental data and the boundaries for each are slightly different as described below.

### 2.6.1 Boundaries for LCI Analysis

All activities which have a bearing on the management of MSW from collection through transportation, recovery and separation of materials, treatment, and disposal are included in the environmental analysis. It is assumed that MSW enters the system boundaries when it is set out or delivered to a collection site, whether it be a residential curbside, apartment collection site, or rural drop-off site. All "upstream" life cycle activities (raw materials extraction, manufacturing, and use) are assumed to be held constant. Thus, the production of garbage bags and cans and recycling bins are *not* included in the study. Similarly, the transport of waste by residents to a collection point have *not* been included.

The functional elements of MSW management include numerous pieces of capital equipment from refuse collection vehicles, to balers for recycled materials, to major equipment at combustion facilities. Resource and energy consumption and environmental releases associated with operation of equipment and facilities are included in the study. For example, energy (fuel) that will be consumed during the operation of refuse collection vehicles is included in the study. In addition, electricity consumed for operation of the office through which the vehicle routes are developed and the collection workers are supervised is also included in the study. However, activities associated with the fabrication of capital equipment are *not* included.

Where a material is recycled, the resource and energy consumption and environmental releases associated with the manufacture of a new product are calculated, assuming closed-loop recycling processes, and included in the study. These parameters are then compared against those from manufacturing the product using virgin resources to estimate net resource and energy consumption and environmental releases. This procedure also applies to energy recovery from other unit processes including combustion, RDF, and landfill gas recovery projects.

Another system boundary is set at the waste treatment and disposal. Where liquid wastes are generated and require treatment (usually in a publicly owned treatment works), the resource and energy consumption and environmental releases associated with the treatment process is considered. For example, if biological oxidation demand (BOD) is treated in an aerobic biological wastewater treatment facility, then energy is consumed to supply adequate oxygen for waste treatment. If a solid waste is produced which requires burial, energy will be consumed in the transport of that waste to a landfill, during its burial (e.g., bulldozer) and after its burial (e.g., gas collection and leachate treatment systems) in the landfill. Also, if compost is applied to the land, volatile and leachate emissions are considered.

### 2.6.2 Boundaries for Cost Analysis

Costs have also included in this study because they play such a crucial role in making decisions about integrated MSW management strategies. Note that the system boundaries for cost analysis differ from that of the environmental analysis because they are designed to provide a relative comparison of annual cost among alternative MSW management strategies as incurred by the public sector. These costs are intended to provide a relative ranking of the different alternatives as part of a screening tool to narrow the range of options associated with integrated MSW management. No distinction is made between public and private sector costs. All MSW management activities are assumed to occur in the public sector and therefore costs are calculated as though they are accruing to the public sector. The cost analysis is intended to reflect the full costs associated with waste management alternatives based on U.S. EPA guidance from *Full Cost Accounting for Municipal Solid Waste Management: A Handbook* (U.S. EPA, 1997).

In focusing the cost analysis on publicly accrued costs, the costs associated with electricity production, for instance, are not included in the study because the public sector only pays the price for electricity consumed. In cases where recyclables are shipped from a MRF, the cost analysis ends where the public sector receives revenue (or incurs a cost) in exchange for the recyclables. The cost analysis does not include the costs associated with the remanufacturing processes for different materials (e.g., recycled office paper). These costs occur in the manufacturing are borne by the manufacturing sector and not to municipal or county governments. The same procedure is applied to the generation and sale of electricity derived from combustion facilities or landfills. Where waste is produced as part of a waste management facility, the cost of waste disposal or treatment is included in the cost analysis of that facility. For example, we include the cost of leachate treatment in our cost analysis of landfills. We also include the cost of training, educational, or other materials associated with source reduction or other aspects of MSW management.

Similar to environmental parameters, cost parameters are also allocated to individual MSW components. Thus, the result of the cost analysis can illustrate, for example, the additional capital and operating costs to a MRF for processing and storing glass. Similarly, the cost associated with the separate collection of residential yard waste can be analyzed.

# Chapter 3
# Technical Approach for Unit Processes

The detailed methodologies for cost and environmental analysis for each unit process (see Figure 3-1) for a representation of a generic process model) are implemented in process models. Process models include sets of equations that utilize the default (or user input) facility design information to calculate all cost and environmental parameters based on the quantity and composition of waste entering each MSW management unit process. The process models included in the system boundaries are as follows:

***Waste Management Processes***

- Collection
- Transfer Station
- Materials Recovery Facility
- Compost (mixed MSW and yard waste)
- Combustion
- Refuse Derived Fuel (conventional and process refuse fuel)
- Landfill (conventional, bioreactor, and ash)

***Other System Processes***

- Electrical Energy Production
- Inter-Unit Transportation (not including collection)
- Remanufacturing

The process models are linked in the DST through a set of mass flow equations. The cost and environmental results from process models are used in the DST to calculate the total system cost and environmental performance for alternative MSW management strategies. This Chapter includes summaries of the models developed for each unit process. These summaries are intended to provide the reader with a broad overview of the methodology employed for estimating cost and LCI coefficients. Key assumptions and issues for each process model are provided in Table 3-1. Full documentation for each process model drafted to date has been completed and is available as a series of Appendices to this report. Please contact EPA to obtain copies of the full process model documentation.

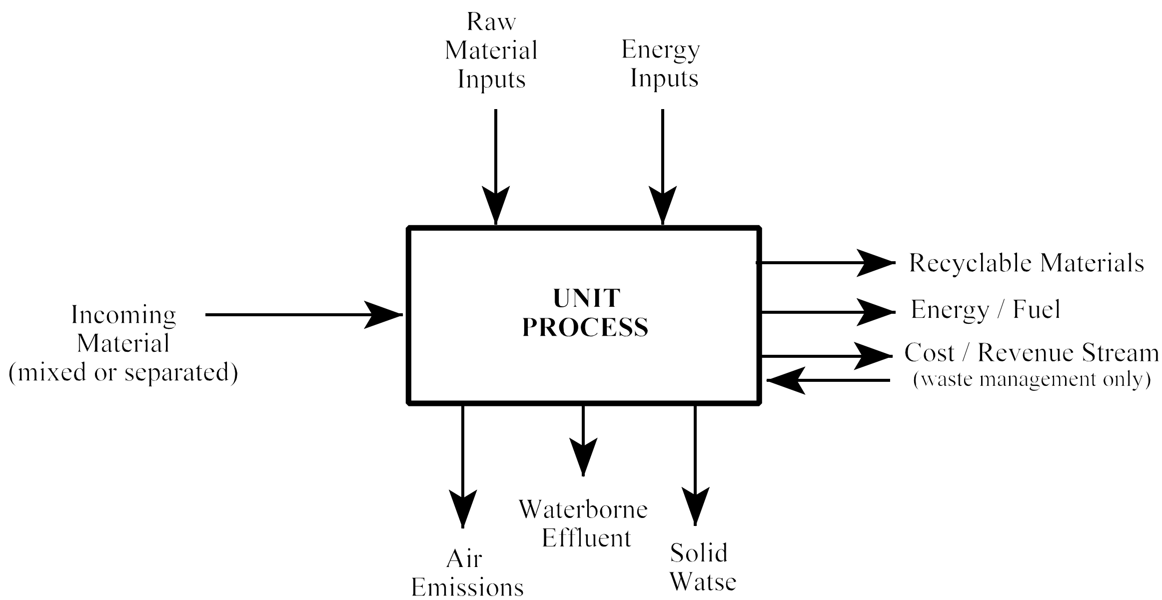



**Figure 3-1. Illustration of a Unit Process**

*A given quantity and composition of material flows into each unit process. Default facility designs and operating conditions are used to estimate the energy and resource use, environmental releases, and cost (or revenue) for each unit process. These values are then partitioned to individual MSW components.*

## 3.1 COLLECTION

There are a number of options for the collection of refuse generated in the residential, multifamily dwelling and commercial sectors. The manner in which refuse is collected will affect the cost, resource utilization, environmental releases, and design of both the collection operation and potential down stream processing facilities such as a MRF. The collection options included in the system are listed in Table 3-2. The design and generic cost and LCI methodologies for collection systems is presented in this section. There may be minor differences in the designs of the 20 collection systems included in Table 3-2. Please refer to full collection model documentation for addition details on the collection options.

The number of collection vehicles needed to collect the waste and recyclables generated in a community is calculated by determining the number of collection locations that a collection vehicle can stop at along a collection route before it is filled to capacity. This number is multiplied by the amount of time that a vehicle spends at each location and traveling between locations, to yield the length of time that a collection vehicle takes to travel from the beginning to

**Table 3-1. Process Model Assumptions and Allocation Procedures**

| | Key Assumptions/Design Properties | Allocation Procedures[a] |
|---|---|---|
| ***Waste Management Unit Processes*** | | |
| **Collection** | Location specific information (e.g., population, generation rate, capture rate) is provided by the user of the tool. | Environmental is based on mass. Cost is based on volume and mass. |
| **Transfer Station** | User selects between several default design options based on how the MSW is collected. | Environmental is based on mass. Cost is based on volume and mass. |
| **Materials Recovery Facility** | Design of the MRF depends on the collection type (mixed waste, commingled recyclables, etc.) and the recyclables mix. Eight different default designs are available. | Environmental is based on mass. Cost is based on volume and mass and includes revenue from the sale of recycables. |
| **Combustion** | The default design is a new facility assumed to meet the most recent U.S. regulations governing combustion of MSW. Designs to model older facilities are also available. | Environmental is based on mass and stoichiometry. Cost is based on mass and includes revenue from sale of metal scrap and electricity (based on Btu value of the waste and the heat rate of the facility). |
| **RDF and PRF** | Conventional RDF and Processed Refuse Fuel (PRF) design options are available. The facilities are assumed to meet the most recent U.S. regulations governing combustion of MSW. | Same as combustion. |
| **Composting** | A low and high quality mixed MSW and yard waste compost facilities are included. All use the aerated windrow composting process as the default design. | Environmental is based on mass. Cost is based on volume and mass and includes revenue from the sale of recyclables. |
| **Landfill** | The default design is a new facility that meets U.S. Subtitle D and Clean Air Act requirements. Enhanced bioreactor and ash designs are also available. | Cost and emissions for operations, closure, and post-closure are allocated equally over the mass of refuse buried. Landfill gas and leachate are allocated on a component specific basis. |
| ***Additional Unit Processes*** | | |
| **Electrical Energy** | Regional electrical energy grids are used for waste management processes; national grid for upstream processes. | Environmental is based on the fuel source used by regional or national electricity grids. Regional grids are used for waste management operations; National for manufacturing operations. Cost is not considered. |
| **Inter-Unit Transportation** | Distances between different unit operations are key input variables. | Environmental is based on mass. Cost is based on volume and mass, and is considered only for transportation necessary for waste management. |
| **Manufacturing** | Virgin and recycled (closed loop) processes are included. Electricity savings resulting from reprocessing displace regional base-loaded generation (mainly coal). | Environmental is based on mass. Cost is not considered. |

[A]Allocation of costs, resource and energy consumption, and environmental releases to individual MSW components

the end of its collection route. The length of time that a collection vehicle takes to make a complete collection trip includes the route travel time plus time spent traveling back and forth from the location where it unloads the material that it collects (landfill, MRF, composting facility, etc.) and the time spent unloading at that location.

Next, the number of daily collection vehicle trips is calculated. The number of fully loaded trips that a collection vehicle can make during one workday is calculated after time is deducted for travel to and from the vehicle garage at the beginning and end of each day, for the lunch break, and other break time.

The next step is to divide the total number of collection locations in the area served by a collection option by the number of collection locations that a vehicle stops at during one collection trip to determine the number of trips needed to collect all the MSW generated in that area during one collection cycle. A collection cycle may represent one or more visits to each collection site per week, with a default value of one visit per week.

Once the numbers of daily collection vehicle trips and total collection trips are known, the number of trucks is determined by dividing total trips by daily trips and by the number of days per week that collection vehicles operate. The number of trucks is used to calculate the annual cost and LCI of the collection system. Cost and LCI methodologies are discussed in the following sections.

### 3.1.1 Cost Methodology for Collection

Collection costs are divided into capital costs, operation & maintenance costs. Capital cost includes the cost of collection vehicles, backup vehicles, and an administrative rate that includes capital cost of the garage and maintenance facilities. Capital cost is expressed in annual terms using a capital recovery factor that is dependent upon the manufacturer estimated lifetime and discount rate.

The operation and maintenance (O&M) cost of the collection process includes the labor, overhead, taxes, administration, insurance, indirect costs, fuel cost, electricity cost, and maintenance cost.

The total annual collection cost is calculated by multiplying the number of trucks by economic factors including a vehicle's annualized capital cost based on the purchase price amortized over the service life, vehicle operating costs, labor costs, overhead costs, and costs for backup vehicles and collection crew personnel. Labor costs include the wages paid to drivers and collection workers. Overhead costs are calculated as a function of the labor costs and include administrative costs.

**Table 3-2. Collection Options for Waste Generating Sectors**

| Residential | Multi-Family | Commercial |
|---|---|---|
| **Mixed Refuse Collection**<br>• Collection of mixed refuse in a single compartment truck.<br><br>**Recyclables Collection**<br>• Collection of commingled recyclables sorted by the collection crew into a multi-compartment vehicle.<br><br>• Collection of recyclables presorted by the generator into a multi-compartment vehicle.<br><br>• Collection of commingled recyclables in a vehicle with two compartments.<br><br>**Co-Collection**<br>• Collection of mixed refuse and recyclables in different colored bags in a single compartment vehicle.<br><br>• Collection of mixed refuse, paper recyclables, and non-paper recyclables in three separate compartments of the same vehicle.<br><br>**Residuals Collection**<br>• If recyclables are collected in options 2, 3 or 4, then residual MSW is collected in a single compartment vehicle as in option 1.<br><br>**Recyclables Drop-Off**<br>• Generator brings recyclables to a centralized drop-off facility. This could also be a buy-back center.<br><br>**Yard Waste Collection**<br>• Collection of yard waste in a single compartment vehicle.<br><br>• Dedicated collection of leaves in a vacuum truck.<br><br>• Dropoff at a compost facility.<br><br>**Wet/Dry Collection**<br>• Wet/Dry collection with recyclables included with the dry portion.<br><br>• Wet/Dry collection with recyclables collected in a separate vehicle. | **Mixed Refuse Collection**<br>• Collection of mixed refuse from multifamily dwellings in a single compartment truck. The user will be required to specify the use of hauled or stationary containers.<br><br>**Recyclables Collection**<br>• Collection of pre-sorted recyclables into multiple stationary or hauled containers.<br><br>• Collection of commingled non-paper recyclables into a single compartment for containers and a second compartment for paper recyclables.<br><br>**Residuals Collection**<br>• If recyclables are collected in options 12 or 13, then residual MSW is collected in a single compartment vehicle as in option 11.<br><br>**Wet/Dry Collection**<br>• Wet/Dry collection with recyclables included with the dry portion. The user will be asked to specify whether various paper types are to be included in the wet or dry collection compartments.<br><br>• Wet/Dry collection with recyclables collected in a separate vehicle. The user will asked to specify whether various paper types are to be included in the wet or dry collection compartments. | **Recyclables Collection**<br>• Collection of presorted recyclables.<br><br>**Mixed Refuse Collection**<br>• Collection of mixed refuse before or after recycling. |

### 3.1.2 LCI Methodology for Collection

The number of collection vehicles and other parameters such as the miles traveled and fuel consumed by collection vehicles are used to calculate consumption rates and release rates for LCI parameters. Default or user override values for the speed that a vehicle travels while performing different tasks and its fuel consumption rate are used to determine how many miles it travels and how many gallons of fuel it consumes per day. These in turn are multiplied by pollutant emission factors to arrive at values for the amounts of air pollutants, water pollutants, and solid wastes generated per ton of waste collected. The LCI parameter calculations also include the consumption of electrical energy at the garage where the collection vehicles are stored and maintained when not in service. LCI parameters are allocated by weight to individual components of the waste stream.

The quantity of fuel consumed in the collection process is calculated based on the fuel consumption rate of vehicles and the quantity of waste or recyclables collected. Electrical energy is used by the garage facility for heating and lighting. The amount of electricity used is provided by standard consumption rates and is based on the size (square feet) of the garage.

Air emissions in the collection process are from combustion of fuel in vehicles, and from the production of energy used in the collection process. Air emissions data from fuel production and fuel combustion in collection vehicles are included in the LCI.

Water releases associated with the collection process are releases from the production of energy used in the collection process. There are no process related water releases.

Solid wastes due to collection include wastes released due to energy production (collection vehicle fuel and electricity). No other process related solid wastes are considered in the LCI.

## 3.2 TRANSFER STATIONS

The transfer station process model includes five types of roadway vehicle transfer stations and three types of rail transfer stations. The following general description applies to all types of transfer stations modeled. Transfer stations require a covered structure that houses collection vehicle unloading areas, trailer loading bays, refuse tipping floor space, and office space. Collection vehicles enter through a scale-house, then proceed to unloading areas. Therefore, the site is partially paved to accommodate maneuvering of both collection and transport vehicles and container storage. Facility staff operate waste handling equipment to load and distribute refuse in hauling containers and to move refuse on the tipping floor. Office space includes an employee rest area and an administrative work area. The loading bay area includes a trailer footprint and trailer maneuvering space. The cost of refuse drop-off areas open to the general public is included in the construction cost for each design.

The types of transfer stations modeled are:

**TR1:** **Processing mixed MSW**. For mixed waste transfer stations, the user selects from five design options. The major differences between these design options are single or multi-level design, the presence or absence of a compactor, and the type of rolling stock required.

**TR2:** **Processing commingled recyclables.** At a commingled recyclables transfer station, recyclables are loaded from collection vehicles into tractor trailers. As for TR1, the user can select from the same five transfer station designs. However, in all TR2 designs paper recyclables are processed separately.

**TR3:** **Processing separately bagged mixed waste, non-paper recyclables, and paper recyclables in a single compartment.** Single compartment co-collection vehicles have paper recyclables in one bag, non-paper recyclables in a second bag, and mixed refuse in a third bag in one compartment of the collection vehicle. Mixed waste is collected in black bags and recyclables are collected in blue bags. The facility area for TR3 consists of a tipping floor for mixed black and blue bags, a storage area for separated blue bags, and separate loading areas for blue and black bags.

**TR4:** **Processing separately bagged mixed waste, non-paper recyclables, and paper recyclables in separate compartments.** Three compartment collection vehicles deliver source-separated mixed refuse (in black bags), non-paper commingled recyclables (in blue bags), and paper recyclables (in blue bags) to TR4. Non-paper recyclables are unloaded onto a tipping floor and then loaded into a trailer with front-end loaders. Mixed refuse is directly tipped into a compactor via a hopper.

**TR5:** **Processing presorted recyclables.** A presorted recyclable transfer station is expected to operate at low capacities relative to other transfer stations. The facility is of a simpler design and includes a roof but no walls. Recyclables are unloaded into separate roll-on/roll-off containers with adequate collection vehicle maneuvering. A small backhoe is used for material handling. Full containers are removed from loading areas and stored on site until transported.

**RT1:** **Rail transfer of MSW from collection vehicles.** Mixed refuse is transferred from collection vehicles to a rail car at RT1. The user selects from two design options for RT1 transfer stations - the first is a one-level design and the second is a two-level design. For the one-level design, a crane is used to load containers. For the two-level design, refuse is pushed from the tipping floor into a compactor. The cost of rail spurs connecting the transfer station to existing local rail lines is included in the RT1 construction cost.

**RT2:** **Rail transfer of MSW from trains to landfill.** At the landfill rail haul transfer station, a crane unloads incoming containers of MSW into a storage area. Stored containers are loaded onto tractors, then hauled to the landfill working face. Tippers unload containers by inclining them greater than 60 degrees from horizontal.

**RT3: Rail transfer of MSW from trains to enhanced bioreactor landfill.** The design of rail transfer stations receiving containers at an enhanced bioreactor is the same as the design for RT2.

The five roadway vehicle transfer stations (TR1 to TR5) are categorized by the type of material processed. Rail transfer station nodes (RT1 to RT3) consist of a transfer station for unloading mixed refuse from collection vehicles onto rail cars and receiving transfer stations located at a conventional landfill and an enhanced bioreactor landfill. There are some differences in the process flows transfer stations. Not all these differences are mentioned here. Refer to the complete transfer stations documentation for process flows and details.

### 3.2.1 Cost Methodology for Transfer Stations

The cost of a transfer station depends on the type of transfer station, the quantity and type of materials processed, and user input data. Costs are divided into capital costs and O&M costs.

Capital cost consists of construction, land acquisition, engineering, and equipment cost that can be expressed in annual terms using a given capital recovery factor that is dependent upon a book lifetime and discount rate.

- Construction cost includes the cost of the structure, paving, access roads, fencing, landscaping, etc. For rail transfer stations, the paving and site work includes the cost of rail spurs that connect the facility to local rail lines. The cost of the structure includes support facilities such as office space and weigh stations. Construction cost is obtained by multiplying the floor area of the transfer station by the construction cost rate.

- Total area for a transfer station includes area for the structure, access roads, fencing, weigh station, landscaping, etc. Total area multiplied by a cost rate gives the land acquisition cost.

- Engineering cost consists of fees paid for consulting and technical services for the transfer station planning and construction, and is estimated to be a fraction of the construction cost.

- Equipment cost consists of the capital and installation cost of equipment such as rolling stock and compactors.

O&M costs of the transfer station include wages, overhead, equipment and building maintenance, and utilities.

- Labor required for the transfer station consists of management, drivers and equipment operators. In estimating the labor wages, it is assumed that part-time services can be hired. Management includes managers, supervisors, and secretaries. The wages paid for management are assumed to be a fraction of the wages paid to drivers and equipment operators.

- Overhead costs for labor are calculated as a fraction of labor wages. Overhead includes overtime, office supplies, insurance, social security, vacation, sick leave, and other services.

- The cost of utilities (power, fuel, oil, etc.) is proportional to the weight of material processed in the transfer station.

- The cost of maintenance of equipment and structure is assumed proportional to the weight of materials processed in the transfer station.

### 3.2.2 LCI Methodology for Transfer Stations

The LCI methodology calculates energy consumption or production, and environmental releases from a transfer station and allocates these LCI parameters to individual components of the waste stream.

The transfer station process model uses default or user-supplied data on <u>fuel consumed</u> by rolling stock, for heating and lighting purposes, and for processing equipment to calculate the total quantity of energy consumed per ton of material processed.

The transfer station process model accounts for <u>airborne releases</u> from two sources: (1) the pollutants released when fuel is combusted in a vehicle (combustion releases), and (2) the pollutants emitted when the fuel or electricity was produced. Data for fuel and electricity generation production are included in the electrical energy process model documentation.

The transfer station process model accounts for <u>waterborne pollutants</u> from the production of energy (electricity and fuel) consumed at the transfer station. There are no process related water releases. Default values for water releases from energy production are provided in the Electrical Energy process model documentation.

The transfer station process model uses the fuel consumed and energy consumed by equipment and for heating and lighting the transfer station building to calculate the <u>solid waste</u> generated. Solid waste generation is expressed in terms of pounds of pollutant per ton of material processed. Note that the solid waste referred to in this section pertains to the waste generated when energy is produced. Default values for solid wastes generated due to energy production are provided in the Electrical Energy process model.

## 3.3 MATERIALS RECOVERY FACILITY (MRF)

MRFs are used to recover recyclables from the municipal waste stream. The process flow in a MRF depends on the recyclables processed and the manner in which they are collected. Thus a critical element of the MRF design is to enable the flexibility to process any composition of recyclables. This is necessary to allow the model solution to specify which recyclables should be recovered for a given model objective (e.g., minimize cost, energy consumption, greenhouse gases, etc.).

Eight different MRF designs are included in the MSW management system:

**MRF 1:** **Mixed waste MRF.** Processes mixed municipal solid waste.

**MRF 2:** **Presorted recyclables MRF.** Processes recyclables collected either presorted by the resident or sorted at the curbside by the operator of the collection vehicle.

**MRF 3:** **Commingled recyclables MRF.** Receives recyclables from a commingled recyclables collection program. All fiber recyclables are collected in one compartment and non-fiber recyclables are collected in a separate compartment on the collection vehicle.

**MRF 4:** **Co-collection MRF.** Processes commingled recyclables and mixed waste collected in a **single compartment truck**. Recyclables are collected in a color-coded bag (blue) with mixed waste collected in a bag of a different color (black). All fiber recyclables are placed in one bag and all non-paper recyclables are placed in another bag. The colors of bags used in a city can be different, but blue and black are the two colors chosen for the discussions in this document and in the model.

**MRF 5:** **Co-collection MRF.** Processes commingled recyclables and mixed waste collected in a **three compartment truck**. All fiber recyclables are collected in bags that are placed in one compartment. Bags containing non-fiber recyclables are placed in the second compartment and bags with residual mixed waste are placed in a third compartment. Recyclables are collected in blue bags and mixed waste is collected in black bags.

**MRF 6:** **Front end MRF to a composting facility.** Material recovery operations precede composting operations. The MRF is similar to a mixed waste MRF, but includes provisions for additional sorting to remove contaminants from mixed waste as specified by the user based on product quality requirements.

**MRF 7: Front end MRF to an anaerobic digestion facility.** Material recovery operations precede anaerobic digestion operations. The MRF is similar to a mixed waste MRF, but includes additional sorting to remove contaminants as specified by the user based on product quality requirements.

**MRF 8: Front-end MRF to an RDF facility.** Material recovery operations precede RDF operations.

In the general MRF design, mixed waste or recyclables are collected at curbside. Waste or recyclables are collected in bags and pass through a debagging point in the MRF. The opening of bags can be done manually or mechanically, as specified by the user. Loose material from the bag opening operation is then conveyed into an elevated and enclosed sorting room where the recyclables are recovered. The elevation of the sort room provides for space underneath for placement of bunkers into which separated recyclables are dropped. In a presorted MRF, non-glass incoming material is baled without sorting, and glass recyclables are loaded into trailers. For recycling collection options, paper recyclables, collected in separate bags, are conveyed to a paper sorting line, and newsprint is recovered through a negative sort. Other paper types can be removed by pickers.

Note that there are some minor differences in the process flows of MRFs depending on the type of MRF and the material being processed. Refer to the complete MRF documentation describing the details of the alternative MRF designs.

### 3.3.1 Cost Methodology for MRFs

The cost of a MRF depends on the type of MRF, the quantity and type of recyclables processed, and user input data. Costs are divided into capital costs, O&M costs, and revenue from recyclables.

Capital cost consists of construction, land acquisition, engineering, and equipment cost that can be expressed in annual terms using a given capital recovery factor that is dependent upon a book lifetime and discount rate.

- Construction cost includes the cost of the structure, access roads, fencing, landscaping, etc. The cost of the structure includes support facilities such as office space, a weigh station, and the loading conveyer. Construction cost is obtained by multiplying the floor area of the MRF by the construction cost rate. Total area for a MRF includes area for the structure, access roads, fencing, weigh station, landscaping, etc. Total area multiplied by a cost rate gives the land acquisition cost.

- Engineering cost consists of fees paid for consulting and technical services for the MRF planning and construction, and is estimated to be a fraction of the construction cost.

- Equipment cost consists of the capital and installation cost of equipment.

O&M costs of the MRF include wages, overhead, equipment and building maintenance, and utilities.

- Labor required for the MRF consists of management, drivers and equipment operators, pickers, and bag openers. In estimating the labor wages, it is assumed that part-time services can be hired. Management includes managers, supervisors, and secretaries. The wages paid for management are assumed to be a fraction of the wages paid to pickers, drivers and equipment operators.

- Overhead costs for labor are calculated as a fraction of labor wages. Overhead includes overtime, office supplies, insurance, social security, vacation, sick leave, and other services.

- The cost of utilities, assumed to be electricity, fuel, oil, etc., is assumed to be proportional to the weight of recyclables recovered in the MRF.

- The cost of maintenance of equipment and structure is assumed to be proportional to the weight of recyclables recovered in the MRF.

Residue in the MRF is a result of the sorting efficiency being less than 100% and recovery of less than 100% of a recyclable. The cost of disposal of residue depends on the disposal facility used and will be accounted for at the downstream processing alternative.

Recyclables recovered in the MRF provide revenue to help offset the costs of the MRF. The user can enter the item-specific value of recyclables.

### 3.3.2 LCI Methodology for MRFs

The LCI methodology calculates energy consumption or production, and environmental releases from a MRF and allocates these LCI parameters to individual components of the waste stream.

The MRF process model accounts for two types of energy consumption: fuel and electricity. The energy calculations include:

1. Combustion energy: the energy used in rolling stock, lighting and heating, and equipment, and
2. Precombustion energy: the energy required to manufacture the fuel or electricity from feed stock.

Depending on the source of energy, the feedstock could be coal, petroleum, natural gas, nuclear fuel, etc. For electricity, the source of energy also depends on the regional energy grid used. Default data on the energy required to produce a unit of electricity, including its precombustion energy, are included in the electrical energy process model documentation. The MRF process model uses default or user-supplied data on fuel consumed by rolling stock, for heating and lighting purposes, and for processing equipment to calculate the total quantity of energy consumed per ton of material processed.

The MRF process model accounts for airborne releases from two sources: (1) the pollutants released when fuel is combusted in a vehicle (combustion releases), and (2) the pollutants emitted when the fuel or electricity was produced. Data for fuel production and electricity production are included in the common process model.

The MRF process model accounts for waterborne pollutants associated production of energy (electricity and fuel) consumed at the MRF. There are no process related water releases. Default values for water releases from energy production are provided in the common process model.

The MRF process model uses the fuel consumed and energy consumed by equipment and for heating and lighting the MRF building to calculate the solid waste generated. Solid waste generation is expressed in terms of pounds of pollutant per ton of material processed. Note that the solid waste referred to in this section pertains to the waste generated when energy is produced. Default values for solid wastes generated due to energy production are provided in the common process model. Solid waste remaining after recyclables are removed (residue) is routed to a treatment or disposal facility. The LCI of residue is accounted for in these treatment and disposal facilities.

## 3.4 COMBUSTION

The combustion process model calculates cost and LCI parameters on the basis of user input and default design information. The cost and LCI coefficients take into account the quantity and composition of the waste input to the combustion facility. The user can also model the following types of combustion facilities:

- newer combustion facility with state of the art air pollution control devices,
- older combustion facility with less advanced air pollution control devices,
- combustion with energy recovery, and
- combustion without energy recovery.

Default cost and emission factors for new and older combustion facilities are provided and are based on four basic designs of different capacities. The four designs include:

1. 100 ton per day (TPD) modular/starved air plant
2. 240 TPD modular/excess air plant
3. Mass burn/waterwall facilities handling 800 tons per day
4. Mass burn/waterwall facilities handling 2,250 tons per day

All designs assume that the facility will be operated to maintain compliance with all applicable regulations.  The default heat rate assumes energy recovery.  This can be changed for facilities that do not recover energy.  Cost assumptions for the four designs are based on a U.S. EPA study (U.S. EPA, 1989) to estimate the cost implications for proposed emission standards.  More recent cost data for $NO_x$ pollution control devices and carbon injectors was used from the U.S. EPA (1994).

The air pollution control equipment assumed to be present in a modern combustion facility include a spray dryer for acid gas control, injection of activated carbon for mercury control, ammonia or urea injection for $NO_x$ control (by conventional selective non-catalytic reduction) and a fabric filter for PM control.  After the air pollution control equipment, the flue gas is released to the atmosphere through the plant stack.  The fly ash is collected, mixed with the bottom ash, and sent to a landfill.  In addition, air pollution monitoring equipment is installed in the facility.

### 3.4.1 Cost Methodology for Combustion

Default cost values for new combustion facilities are based on a regression of the four model plants described above.  The regression was performed to arrive at linear cost functions.  The cost of the combustion facility is assumed to be proportional to the facility capacity, though the revenue from energy recovery is a function of the BTU input to the plant.   Costs are divided into capital costs, O&M costs, residue disposal costs, ferrous recovery revenue, and electricity generation revenue.

<u>Capital cost</u> includes the cost of combustors, ash handling system, turbine, and air pollution control and monitoring devices.  The capital cost of a combustion facility is calculated from a unit capital cost with units of dollars per ton feed rate.  It is adjusted with a capacity factor to account for the fact that the plant cannot operate at full capacity at all times.  In addition, it can be expressed in annual terms using a given capital recovery factor that is dependent upon a book lifetime and discount rate.

<u>O&M costs</u> of the combustion facility includes the labor, overhead, taxes, administration, insurance, indirect costs, auxiliary fuel cost, electricity cost and maintenance cost.  The O&M cost function depends upon the unit O&M cost, the rate at which waste enters the plant (expressed in energy per unit time), the capacity factor, and the cost of ash disposal.  Again, we developed default cost relationship by linear regression.

Combustion residue includes ash, unburned waste, and flue gas cleaning residue.  Combustion residue includes fly and bottom ash attributed to combustion of the waste.  The bottom ash includes combustible materials that do not combust due to inefficiencies of the combustors.  The cleaning residue includes the solid salts formed in the neutralization of the acid gases.  The cleaning residue is removed along with the fly ash by the fabric filter bags.

Electricity that is generated by recovery of heat from combustion of waste is sold to an end user. The recovery of the heat is not perfectly efficient.  This inefficiency is represented by the heat rate of the plant in BTU per kWh. This heat rate takes into account the house load of the combustor.

Ferrous metal can be recovered from the bottom ash and can provide some revenue to help offset the costs of the combustion facility. Based on calculations presented in the full model documentation, the cost of a magnet to separate the iron from the bottom ash is sufficiently small in comparison to the imprecise estimate of the ferrous scrap price that it can be ignored.

### 3.4.2 LCI Methodology for Combustion

The LCI methodology calculates energy consumption or production, and environmental releases from the combustion process and allocates these LCI parameters to individual components of the waste stream.

Energy recovered by a WTE facility is credited as an energy gain in the LCI inventory, and it is assumed to displace a similar amount of electricity produced from conventional fuels (e.g., coal, natural gas). The exact mix of the energy that is based on the regional energy grid or fuel mix specified by the user in the electrical energy process model.

Net emissions from a WTE facility are the post treatment emissions from the combustion facility minus the emissions that would have otherwise been produced by the avoided electricity production.

Different sets of default air emission factors for combustion of MSW are provided in the process model. These defaults are based on existing combustors in compliance with standards for existing facilities. The user may override these emission factors with site-specific factors based on performance tests. For existing facilities, default emission factors corresponding to the regulatory limits for existing combustion facilities may be selected. For newer facilities, default emission factors are provided based on U.S. EPA (Radian Corporation, 1995) performance testing for new facilities and corresponding regulatory limits for new combustion facilities. For unregulated pollutants, defaults emission factors based on actual performance tests are provided.

Although air emissions may be based on performance or regulatory limits, the composition of the waste still impacts emission levels. For example, while a pollutant may be controlled to a particular emission concentration, the volume of flue gas produced from the combustion of the waste components will dictate the mass emission rates of the pollutants. Since flue gas production per ton varies considerably from component to component, the mass emission rates per ton of aggregate waste will vary with composition based on this methodology. Importantly, the flue gas production per ton of waste component is based on a stoichiometric combustion equation for the MSW components and relies on ultimate analysis studies that provide the carbon, nitrogen, hydrogen, oxygen, sulfur and chlorine contents of the waste constituents.

Default air emission factors for metals are handled somewhat differently for the case where regulatory limits are not assumed and for unregulated metals. Metals content by waste component and the partitioning of metals to the flue gas as observed in the Burnaby study (Chandler & Associates Ltd., et al., 1993) is used in conjunction with metals removal efficiencies based on multiple modern combustion facilities to form the basis for the calculations of mass metals emission rates. For lack of sufficient theory and empirical studies relating metals volatilization to waste composition, an underlying, albeit crude, assumption is made that metals emissions vary in proportion to metals input to the combustor. This approach was deemed to be preferable to the simpler approach that would have metals emissions vary with mass input alone with no sensitivity to the metals content of the waste.

Water releases associated with the combustion process are post-treatment releases from publicly operated treatment works of water used in the process and those offset by generation of electricity. Net releases from the combustion facility are the releases from water use in the combustion facility minus the releases that would otherwise have been produced by the type of utility generation displaced.

Solid wastes from the combustion process include the ash residue from combustion of waste and the solid wastes offset by generation of electricity. Ash residue is transported to a dedicated ash landfill for disposal and is not counted as solid waste in the overall model.

## 3.5 REFUSE-DERIVED FUEL (RDF) AND PROCESSED REFUSE FUEL (PRF)

The objective of the Processed Refuse Fuel (PRF) and Refuse Derived Fuel (RDF) process model is to calculate the cost and LCI parameters for converting MSW into fuel that is combusted in on-site combustors. The user can choose to use either the PRF design or the RDF design in the design of their integrated solid waste management system. Costs and LCI parameters are calculated on the basis of user input and default design information. Based on the cost and LCI design information, coefficients are calculated in the process model to represent the cost and environmental burdens associated with a PRF or RDF facility. The coefficients take into account both the quantity and composition of the waste input to a PRF and RDF facility and are used in the solid waste management model to calculate the total system cost and LCI parameters for solid waste management alternatives that involve the PRF and RDF processes.

The mathematical equations used for model development are presented in the combustion model documentation. Mass balance equations used to estimate the quantity and composition waste moving through the PRF or RDF process designs are presented in this document. The cost and LCI allocation methodologies are identical to the combustion process model, and are not presented in this document.

Two designs for fuel processed from mixed waste are presented in this document. The differences between the PRF and RDF lie in steps in the process flow design preceding combustion of fuel. The following sections present descriptions of the processes involved in a Processed Refuse Fuel facility and a Refuse Derived Fuel facility.

### *Processed Refuse Fuel Facility*

For the PRF facility, MSW is conveyed directly into a shredder to provide a maximum particle size of 6 inches, with most of the materials being less than 2 inches in size. The shredded material is then passed under a magnet for removal of approximately 40% to 50% of the ferrous metal. The remaining shredded material now termed PRF, is blown into specifically designed boilers at a point approximately 2 meters above a traveling grate. Lighter materials burn in midair while heavier portions of the fuel including non-combustibles, drop to the rear of the grate. The grate moves from the back to the front of the furnace to allow for complete burnout of any combustible material at an ash bed depth of 12-20 centimeters. The heat liberated by the combustion of the PRF is recovered to produce superheated steam for the generation of electricity. By forcing most of the combustion air through the grate, grate temperatures are maintained below the melting point of glass and most metals, thereby eliminating slagging and producing a granular bottom ash from which marketable materials can be recovered. From the bottom ash, a substitute for natural aggregate can also be produced. Bottom ash and fly ash are collected separately in a dry state, allowing for recovery of ferrous and nonferrous metals and the production of aggregate from the bottom ash and isolation of the fly ash for conditioning and disposal by landfilling and for future beneficial reuse.

In the PRF process model design used in the DST, it is assumed that there is no revenue associated with the sale of building aggregate material or coins and other metals that may be recovered from the bottom ash. The combustion stoichiometry and emissions allocation are exactly the same as in the combustion process model. Refer to the combustion model documentation for more information about emission estimation and allocation procedures.

***Refuse Derived Fuel Facility***

In the RDF facility, refuse that is received either unconfined or in bags, is loaded onto a conveyor system and enters a flail mill. The flail mill opens any unopened bags and reduces the sizes of some of the breakable materials in the refuse. From the flail mill, the refuse passes under a magnet that recovers ferrous materials which are a source of revenue. The remainder then continues into a trommel for removal of material less than 2 inches in diameter. The trommel removes materials like broken glass, grit, sand, etc. From the trommel, the refuse is shredded in a shredder to reduce the size of components of the waste. The shredded waste then passes through an air classifier that separates the "lights," considered to have the high BTU content, from the "heavies," which have a relatively low BTU content. The "lights" then flow to an eddy current separator for aluminum removal. The material remaining after aluminum removal is combusted and the heat energy liberated is converted to electricity.

The combustion stoichiometry and emissions allocation in the RDF process model are exactly the same as in the combustion process model.

### 3.5.1 Cost Methodology for RDF and PRF

Costs for the PRF and RDF facility designs are divided into six components: capital cost, operation and maintenance cost, revenue from electricity generation and revenue from ferrous recovery, and revenue from aluminum recovery. The cost equations for the PRF and RDF facilities are exactly the same as those in the combustion process model. Refer to the combustion documentation for details of the cost methodology.

### 3.5.2 LCI Methodology for RDF and PRF

The LCI equations for the PRF and RDF facility are exactly the same as for the combustion process model. Refer to the combustion documentation for details of the LCI methodology.

## 3.6 MIXED MUNICIPAL AND YARD WASTE COMPOSTING

The composting process model captures both MSW and yard waste composting operations. Composting using the windrow turner method is used for both types of facilities, instead of aerated static pile designs and in-vessel systems. The windrow turner design was selected because it is used by a majority of compost facilities in the United States.

The three composting facility designs included in the system are summarized as follows:

**COMP 1:** **MSW compost facility, low quality compost.** Processes mixed MSW is collected and preprocessed at a MRF to remove any recyclable or non-compostable materials. This facility produces low quality compost that is used for landfill cover or is landfilled.

**COMP 2:** **MSW compost facility, high quality compost.** Processes mixed MSW is collected and preprocessed at a MRF to remove any recyclable or non-compostable materials. This facility produces high quality that is used for soil amendment.

**COMP 3:** **Yard waste compost facility.** Processes yard wastes (e.g., branches, grass, leaves) is collected and delivered to the compost facility by residents or a yard waste transfer station. Only one type of yard waste facility is designed; it is the same general design as the high quality MSW compost facility design.

In the general compost facility design, waste is collected at curbside and transported to a MRF where recyclables and non-compostable materials are removed. The residual mixed waste is transported to a compost facility. At the compost facility, waste is deposited onto a tipping floor, where large items (if any) are removed manually. A front-end loading introduces the waste to a preprocessing trommel screen. The finer fraction is directed to the composting pad or hammermill for shredding and then to the composting pad. The oversized fraction is sent to a landfill for disposal. Moisture is added to the compost to achieve an optimal moisture content. Turning, mixing, and aeration of the windrows takes place once or twice a week (a user input value) using self-propelled windrow turner. Curing takes place without any turning of the curing piles in an uncovered area, while cured compost is distributed for use as cover or sold as soil amendment. The compost facility is designed to handle MSW tonnage rates from 10 to 10,000 tons per day.

Note that there are some minor differences in the process flows of the different compost facility designs depending on the type of material being processed and desired quality of the final product. Refer to the full compost process model document for descriptions of the alternative compost facility designs.

### 3.6.1 Cost Methodology for Composting

The cost of a compost facility depends on the type of facility, the quantity and type of material processed, and user input data. Costs are divided into capital costs, O&M costs, and revenue from the sale of compost.

Capital cost consists of construction, land acquisition, engineering, and equipment cost that can be expressed in annual terms using a given capital recovery factor that is dependent upon a book lifetime and discount rate.

- Construction cost includes the cost of the structure, access roads, fencing, landscaping, etc. The cost of the structure includes support facilities such as office space, a weigh station, and the loading conveyer. Construction cost is obtained by multiplying the floor area of the compost facility by the construction cost rate. Total area for the facility includes area for the structure, access roads, fencing, weigh station, landscaping, etc. Total area multiplied by a cost rate gives the land acquisition cost.

- Engineering cost consists of fees paid for consulting and technical services for the compost facility planning and construction, and is estimated to be a fraction of the construction cost.

- Equipment cost consists of the capital and installation cost of equipment.

O&M costs of the compost facility includes wages, overhead, equipment and building maintenance, and utilities.

- Labor required for the compost facility consists of management, drivers and equipment operators. In estimating the labor wages, it is assumed that part-time services can be hired. Management includes managers, supervisors, and secretaries. The wages paid for management are assumed to be a fraction of the wages paid to drivers and equipment operators.

- Overhead costs for labor are calculated as a fraction of labor wages. Overhead includes overtime, office supplies, insurance, social security, vacation, sick leave, and other services.

- The cost of utilities, assumed to be electricity, fuel, oil, etc., is assumed to be proportional to the weight of incoming MSW or yard waste.

- The cost of maintenance of equipment and structure is assumed to be proportional to the weight of incoming MSW or yard waste.

High quality compost that is produced by the high quality MSW compost facility or yard waste compost facility may be sold as soil amendment and thus provide revenue to help offset the costs of the compost facility. The user can enter the value of compost.

### 3.6.2 LCI Methodology for Composting

The LCI methodology calculates energy consumption or production, and environmental releases from the compost facility and allocates these LCI parameters to individual components of the waste stream.

The composting process model accounts for two types of energy consumption: fuel and electricity. The energy calculations include:

1. Combustion energy: the energy used in rolling stock, lighting and heating, and equipment, and
2. Precombustion energy: the energy required to manufacture the fuel or electricity from feed stock.

For electricity, the source of energy depends on the regional energy grid used. Default data on the energy required to produce a unit of electricity, including its precombustion energy, are included in the electric energy process model documentation. The composting process model uses default or user-supplied data on fuel consumed by rolling stock, for heating and lighting purposes, and for processing equipment to calculate the total quantity of energy consumed per ton of material processed.

The composting process model accounts for airborne releases from two sources: (1) the pollutants released when fuel is combusted in a vehicle (combustion releases), and (2) the pollutants emitted from the biodegradation of organic material. Data for fuel production and electricity generation, and associated air emissions, are included in the common process model. Data for air emissions resulting from the biodegradation of organic material are being developed through a laboratory experiment being conduct at the University of Wisconsin-Madison. In this experiment, food, mixed paper, yard waste, and inorganics are biodegraded in lab-scale vessels. Emissions from the vessels are captured and analyzed and will ultimately be used to develop air emission factors for all waste components.

The compost process model accounts for waterborne pollutants associated production of energy (electricity and fuel) consumed at the compost facility. There are no process related water releases. Default values for water releases from energy production are provided in the common process model.

The compost process model uses the fuel consumed and energy consumed by equipment and for heating and lighting the compost facility to calculate the solid waste generated. Solid waste generation is expressed in terms of pounds of pollutant per ton of material processed. Note that the solid waste referred to in this section pertains to the waste generated when energy is produced. Default values for solid wastes generated due to energy production are provided in the common process model. Solid waste remaining after non-compostables are removed (residue) is routed to a treatment or disposal facility. The LCI of residue is accounted for in these treatment and disposal facilities.

## 3.7 LANDFILL

The objective of the landfill process model is to calculate the cost and life-cycle inventory (LCI) for the burial of one ton of municipal solid waste (MSW) or combustion ash in a landfill. The model is designed to calculate the cost and LCI for one ton of waste in consideration of user-input and default values for a conventional, bioreactor, and/or ash landfill and can also to specify whether the landfill includes liner, landfill gas collection, and leachate collection systems. The formats for the three types of landfills are similar and areas of divergence are addressed in the following section.

Three types of landfill designs are considered in the decision support tool:

1) conventional landfill operated to minimize moisture infiltration,
2) bioreactor landfill operated to enhance decomposition, and
3) ash landfill.

These landfills are primarily defined by their physical characteristics and by the waste that they receive. All landfills are designed and operated in compliance with RCRA Subtitle D regulations. Bioreactor landfills use leachate recycling to enhance waste decomposition, leachate stabilization, and gas production. Ash landfills accept MSW incinerator ash.

All three landfill process models contain five different phases in the landfill lifecycle:

- Operations: considers fuel use and equipment emissions associated with landfill operation.
- Closure: considers fuel use and equipment emissions associated with landfill closure.
- Post-closure: This section details the post-closure phase of a modern MSW landfill including cover maintenance and monitoring.
- Landfill Gas: This section describes gas generation, treatment, and utilization.
- Landfill Leachate: This section describes leachate generation and treatment.

Contrary to other waste management options, which generally have instantaneous, landfill emissions occur over time.  The emissions associated with disposal of a ton of waste in a landfill are reported for one of three user selected time horizons beginning from when the waste is placed in the site:

- A short-term time frame (20 years) corresponding roughly to the landfill's period of active decomposition.
- An intermediate-term time frame (100 years) corresponding roughly to the life span of a given generation.
- A long-term time frame (500 years) corresponding to an indefinite time reference, at which point the emission of any given environmental flow will have likely reached its theoretical yield.

Emissions are estimated for one time horizon which the user selects.

### 3.7.1 Cost Methodology for Landfills

The methodology used to estimate the costs associated with the three landfill options are described in the following sections.  Landfill costs fall into four main categories: initial construction, cell construction, operations, and closure.  To calculate the cost for each of these categories, the size of the landfill is needed.  In order to size the landfill, the waste flowing to the landfill must be known.  However, the waste flow to the landfill is specified by the decision support tool solution.  Thus, to use the landfill process model, the size is based on user input values for the facility life and daily waste flow.  As input by the user, these parameters are used to provide a rough estimate of landfill size which is used to calculate costs.
Landfills represent a unique problem relative to other MSW management unit operations in that all other operations have a useful life and assumed replacement cost equal to its original cost. The same assumption is made for replacing a landfill.

#### *Initial Construction Cost*

Included in the initial construction cost are land acquisition; site fencing; building and structures required to support operation of the landfill and for a flare required for landfill gas treatment; platform scales; site utilities installation; site access roads; monitoring wells; initial landscaping; leachate pump and storage (in accordance with 40CFR258.40); site suitability study, planning and licensing.  A multiplier is applied to the overall initial construction cost to account for engineering costs.  The total cost is then amortized over the operating period of the facility and normalized to the annual volume of waste received.

#### *Cell Construction Cost*

The section summarizes the costs applicable to the development and preparation of each individual cell of the landfill.  Cell construction costs include site clearing and excavation; site berm construction; liner systems (if specified and in accordance with 40CFR258.40); leachate control materials for conventional and ash landfills; leachate collection and recirculation materials for bioreactor landfills; and any cell pre-operational costs (e.g., engineering design, hydrogeologic studies). The total cell construction cost is amortized over the operating period of the facility and normalized to the annual volume of waste received.

***Operation and Maintenance Cost***

The operation and maintenance (O&M) costs of a landfill include labor, equipment procurement, leachate treatment, daily cover overhead, taxes, administration, insurance, indirect costs, auxiliary fuel cost, utilities, and maintenance. The O&M cost function depends upon the unit O&M cost, the rate at which waste enters the landfill. There is no amortization of the annual operation and maintenance because they are annual, recurring costs.

***Closure and Postclosure Cost***

Closure costs for the landfill model include costs associated with the installation of the final landfill gas extraction system (in accordance with 40CFR258.23); final cover (can include soil, geotextile, sand, HDPE, and clay as specified by the user); cost of replacing final cover; and perpetual care. The total closure cost is amortized over the operating period of the facility and normalized to the annual volume of waste received.

***Revenue from Landfill Gas***

If a turbine, boiler, or internal combustion engine is used to treat landfill gas, it may result in a revenue stream for the landfill. Three gas collection periods are defined in the model. Within each of the gas collection periods, the user has five options for landfill gas treatment: vent, flare, turbine, direct use, and internal combustion engine.. The electricity that is generated is assumed to be sold to an end user. The default value for revenue from electricity generation is set at the national average per kWh. The yearly revenue generated during each landfill gas treatment period is converted to the present value and then annualized over the operating life of the landfill. The amortized revenues are for each period are then summed to obtain the total revenue from landfill gas treatment. This total revenue offsets the cost of landfill construction, operation, and closure.

### 3.7.2 LCI Methodology for Landfills

The LCI methodology calculates the net energy consumption and environmental releases (air, water, and solid waste) from the landfill construction, operation, closure and post closure and allocates these LCI parameters to individual components of the waste stream.

***Energy***

Energy is consumed during the operation, closure and post-closure phases of the landfill. Energy that is recovered is credited as an energy gain in the LCI, and it is assumed to displace a similar amount of electricity produced from conventional fuels (e.g., coal and natural gas). However, the exact mix of the energy that is offset can be specified by the user if it is known. In addition, the user can specify whether or not energy is actually recovered.

***Air Emissions***

Air emissions are associated with equipment use during each phase of the landfill as well as with decomposition of the buried waste and emissions during leachate treatment. Where energy is recovered, some air emissions associated with electrical energy production from fossil fuel is avoided.

***Water Releases***

Water releases associated with the landfill are post-treatment releases from publicly operated treatment works (POTW) of leachate. Net releases from the landfill are the releases from the POTW plus uncontrolled leachate. If energy if recovered from the landfill, then water releases would net out the releases that would otherwise have been produced by the type of utility generation displaced.

***Solid Waste Releases***

Solid wastes from the landfill processes include the solid wastes associated with energy utilization, treatment of landfill leachate, and production of landfill materials. If energy is captured at the landfill, then total solid waste is calculated by netting out the solid waste that would have otherwise been produced by the type of utility generation being displaced.

## 3.8 ELECTRICAL ENERGY

The electric energy process model provides an accounting of the total energy consumption and emissions resulting from the generation and use of electric energy. Pre-combustion and combustion energy consumption and emissions on a per unit fuel basis are used in conjunction with unit efficiencies, transmission and distribution line losses, and electric generation fuel types to allocate energy consumption and emissions to the use of a kilo-watt hour (kWh). Emissions and energy consumption per kWh are calculated for the national grid fuel mix as well as for the nine major electrical generating regions in the United States (see Tables 3-3 and 3-4). The user may input a site-specific fuel mix.

The user may also change the default values for fuel mix by region, power generation efficiency, and other defaults.

The electrical energy process model results are used by spreadsheet models for other unit operations to obtain the total energy consumption and emissions related to electric energy usage in those unit operations. For example, energy is consumed and emissions result for each kWh of electricity used to operate a baler in a MRF. For each kWh consumed, the electrical energy process model provides the total energy consumed and the resulting emissions (pre-combustion and combustion).

### 3.8.1 Energy Conversion Processes

The vast majority of electrical energy in the United Sates is derived from seven major sources: coal, natural gas, residual oil, distillate oil, uranium, hydroelectric and wood. Therefore, these seven major fuel types are addressed by the electric energy process model with provision for the model user to include one "other" fuel type. Key points associated with each of the major fuel types are as follows:

- **Coal:** Pre-combustion energy and emissions for coal are associated with surface and underground mining operations, size reduction, cleaning and transportation. Use of coal as a fuel consists of burning it in a boiler to produce steam that is then used to generate electricity or is used for other process operations.

- **Natural Gas**: Pre-combustion energy and emissions for natural gas are associated with oil well operations, pipeline pumping, transportation, and fugitive emissions from pumping and production facilities. Use of natural gas as a fuel consists of combusting it in several types of facilities including gas turbines and combined cycle units to produce steam that is then used to generate electricity or is used for other processes.

- **Residual and Distillate Oils:** Pre-combustion energy and emissions for residual and distillate oils are associated with oil well operations, refining (process and fugitive emissions), and transportation. Use of residual and distillate oils as fuels consists of combusting them in boilers to produce steam that is then used to generate electricity or is used for other process operations.

- **Nuclear:** Pre-combustion energy and emissions for nuclear fuel are associated with surface and underground mining operations, refining (process and fugitive emissions), and transportation. Use of nuclear fuel consists of reacting it in a nuclear reactor to produce steam that is then used to generate electricity.

- **Hydroelectric:** There are no pre-combustion energy and emissions associated with hydroelectric power generation, as a default. Use of hydraulic fuel usually consists of damming a river and using the potential energy of the entrained water to generate electricity by passing it through a water turbine-generator.

- **Wood:** Since wood fuel is usually a by-product of other wood processing operations and is usually burned on site for self-generated electricity, there are no pre-combustion emissions associated with wood fuel, as a default. Use of wood as a fuel consists of combusting it in a boiler to produce steam that is then used to generate electricity or is used for other process operations.

Insignificant contributions are made by sources such as solar, wind, geothermal, and other emerging technologies.

To provide the appropriate emissions and energy usage values to the various model components, it was necessary to define fuel usage by type for national and regional grids. Table 3-3 shows the regional grid definitions that have been adopted. The geographic locations of these grids are defined in Table 3-4**.** These grid definitions were adopted since they represent the vast majority of the United States, the area to which the model will most likely be applied. However, a "user-defined" region has been included to allow the model user to define a region with unique characteristics not available in the Table 3-3 default regions.

### 3.8.1 Cost Methodology for Electrical Energy

Cost for electrical energy generation is *not* included in the boundaries for cost analysis. The cost that waste management operations accrue for electricity consumption is accounted for in the individual waste management process models.

**Table 3-3. Electric Region Definitions**

| Control Area Name | Control Area Description |
|---|---|
| ECAR | East Central Area Reliability Coordination Agreement |
| ERCOT | Electric Reliability Council of Texas |
| MAAC | Mid-Atlantic Area Council |
| MAIN | Mid-America Interconnected Network |
| MAAP | Mid-Continent Area Power Pool |
| NPCC | Northeast Power Coordinating Council |
| SERC | Southeasterm Electric reliability Council |
| SPP | Southwest Power Pool |
| WSCC | Western Systems Coordinating Council |
| User Defined | User Defined Electric Region |

**Table 3-4. Electric Region Locations**

| Control Area Name | Location |
|---|---|
| ECAR | Michigan, Indiana, Ohio, Kentucky, West Virginia |
| ERCOT | Texas |
| MAAC | Pennsylvania, New Jersey, Maryland, Delaware |
| MAIN | Illinois, Missouri (east) Wisconsin (excluding north west) |
| MAAP | North Dakota, South Dakota, Nebraska, Minnesota, Wisconsin (east) |
| NPCC | New York, Vermont, Connecticut, Maine, Rhode Island, New Hampshire |
| SERC | North Carolina, South Carolina, Georgia, Florida, Alabama, Tennessee, Mississippi |
| SPP | Kansas, Oklahoma, Arkansas, Louisiana, Mississippi (west) Missouri (west) |
| WSCC | Washington, Oregon, Colorado, California, Nevada, Montana, Idaho, Wyoming, Utah, Arizona, New Mexico |

### 3.8.2 LCI Methodology for Electrical Energy

Wherever electricity is consumed in the waste management portion of the system, the cost for electricity accrues to the local government. However, environmental burdens association with the production and consumption of that electricity affects society as a whole. Therefore, the global environmental burdens associated with electrical energy production (termed precombustion emissions) are considered in this research. This section summarizes the approach used to determine precombustion emissions for different locales.

#### *Electric Generation Fuel Usage*

The national generation weighted usage for each fuel type was calculated from North American Electric Reliability Council (NERC) regional databases submitted to the Energy Information Administration (EIA) for 1994. These databases include several thousand generating units from the nine NERC regions in the continental United States and represent the vast majority of the U.S. generating capacity. The regional generation weighted usage for each generating region and fuel type were also calculated using EIA data.

#### *Total Fuel Emissions*

Pre-combustion and combustion emissions generated per 1000 fuel units combusted (pounds of coal, cubic feet of natural gas, etc.) on a national and regional basis are included in the appendices of the electric energy process model documentation. The default emissions data for all regions have been set to the values for national generation since data for fuel-related emissions for each of the nine generating regions were not available.

#### *Energy and Emissions Offsets*

To account for the energy and emissions savings associated with utility generation that is not required as a result of generating electricity from combusting MSW, RDF, or gases recovered from landfill or anaerobic digestion, it is necessary for the model user to specify the type of utility generation that is being displaced. This would typically be the type of generating unit being constructed in the region by the utility. The majority of units currently being constructed are coal and natural gas fueled. However, the type of fuel that would be displaced depends on the regional base-loaded fuel mix. For example, oil units are often base-loaded in Northeast states. If a base-loaded MSW combustor with energy recovery came on line in the northeast, the utility might back down an expensive oil-fired unit. Therefore, the definition of displaced fuel types is user definable with the default being coal and natural gas.

The default values and calculation methodology discussed in the preceding sections have been implemented in the electrical energy portion of the overall LCI model to ensure that the LCI implications of electrical energy consumption in various unit processes are accounted for. The intent of this implementation is to provide the best available default information. It is also to provide a model that is responsive to macro-level user input values such as electric generating region and generating efficiency by fuel type while allowing for user override of micro-level inputs such as emissions associated with coal combustion should region-specific data become available.

## 3.9 INTER-UNIT TRANSPORTATION

The inter-unit transportation process model includes transportation by rail, heavy-duty diesel (tractor trailers), light-duty diesel vehicles, and light-duty gasoline vehicles. The type of roadway transportation utilized between any two given nodes is site specific. However, typically tractor trailers are utilized for long distance hauling to economize on transportation costs, while light-duty vehicles are utilized for shorter distances and more frequent trips.

Cost and LCI factors for transport of mixed refuse, fuel, and compost are calculated per ton of aggregate mass flow between nodes. In contrast, recyclable materials are often shipped separately and have item-specific densities. For example, loose glass has a density nine to ten times that of plastic. For this reason, item-specific cost and LCI factors are calculated for recyclables transport. Connections for which item-specific factors are determined for recyclables include transport from transfer stations to separation facilities and from separation facilities to remanufacturing.

For each nodal connection, unique cost and LCI factors are calculated based on user input values pertaining to transportation modes and connections between facilities. The governing equations presented in this section fall into three categories:

1. Rail transport of mixed refuse.
2. Roadway transport of non-recyclables (mixed refuse, refuse recovered for fuel, and compost).
3. Roadway transportation of recyclables.

Refer to the full process model documentation for complete descriptions of the alternative inter-unit process transportation categories.

### 3.9.1 Cost Methodology for Inter-Unit Process Transportation

The cost methodology for mixed refuse rail transport, non-recyclables roadway transport, and recyclables roadway transport are discussed in this section. Unique factors for each nodal connection are calculated based on input values specific to each nodal connection. Cost factors are based on the rate charged for hauling MSW. Rail transportation costs also include fees for the use of existing local rail lines between a community and a landfill. The cost for spurs built to connect existing rail lines to a transfer station and rail lines within transfer station sites are included in transfer station cost factors. Costs and LCI factors associated with moving MSW from the landfill rail transfer stations to the working face of the landfill are accounted for in the transfer station cost.

<u>Rail transportation</u> costs are calculated on a per ton basis from the user input hauling rate in units of dollars per ton per mile and the distances between nodes.

Cost factors for roadway transportation of non-recyclable are calculated on a per ton basis from the user input hauling rate in units of dollars per mile, vehicle weight capacity and the distances between nodes. Item-specific factors are determined for recyclables because recyclable item densities vary. To calculate weight based factors, volume based costs for each transportation connection between nodes are first calculated. Volume based costs are divided by item-specific densities to give weight based factors. Costs per ton are then calculated for each recyclable item.

### 3.9.2 LCI Methodology for Inter-Unit Process Transportation

LCI factors account for production and combustion of fuel utilized by transportation vehicles. If the user selects a two-way trip as input for roadway transport connections, then calculated factors will account for empty vehicles returning to the origin. The transportation process model accounts for fuel energy used in vehicles to transport materials. The fuel energy calculations include:

1. Combustion energy: the energy used by rail engines and hauling vehicles, and
2. Precombustion energy: the energy required to manufacture the fuel from feed stock.

The process model uses default or user-supplied data on fuel consumed (e.g., diesel) for rail haul and roadway transport to calculate the total quantity of energy consumed per ton of material processed.

The transportation process model accounts for airborne releases from two sources: (1) the pollutants released when fuel is combusted in a vehicle (combustion releases), and (2) the pollutants emitted when the fuel was produced. Data for fuel production are included in a common process model, which contains data and conversion factors for common processes throughout the system.

The transportation process model accounts for waterborne pollutants associated production of energy (fuel) consumed during transportation of recyclables and waste. There are no process related water releases. Default values for water releases from fuel production are provided in the common process model.

Solid waste generation associated with the transportation process model are from production of fuel consumed by vehicles. Solid waste generation is expressed in terms of pounds of pollutant per ton of material transported. Default values for solid wastes generated due to energy production are provided in the common process model.

## 3.10 REMANUFACTURING

The remanufacturing process model was developed so that the net environmental benefit of recycling various materials could be captured. Whenever a material is recovered from the MSW stream it is assumed to be sold and recycled into a “new” product. The use of recycled materials means that there is an offset of the use of virgin materials, which presumably would result in some environmental benefit.

The remanufacturing process model provides estimates of net energy usage and emissions estimates on a per ton basis for products produced using virgin and/or recycled materials. The approach that has been taken in the remanufacturing process model is “cradle to product” in which the LCI parameters are compared up to some point in each manufacturing process where a common product can be identified. For aluminum, this is the point at which aluminum ingots are produced. For newsprint and corrugated containers, this is the point at which newsprint and corrugated liner and medium are produced.

Beyond these common points in the manufacturing process, the LCI parameters for each product are assumed to be identical regardless of what product is ultimately manufactured. Therefore, downstream items such as staples for corrugated containers and emissions from transporting the product to the user are not included in the LCI since these items are assumed to be unchanged regardless of whether the product is made from predominately virgin or recycled resources. This distinction is important in that it captures the difference between recycled and virgin manufacturing processes and not the absolute environmental burden.

### 3.10.1 Cost Methodology for Remanufacturing

The costs associated with remanufacturing any given material accrue to the private sector and not to the public sector waste management entity. Therefore, remanufacturing costs are not included in this research.

### 3.10.2 LCI Methodology for Remanufacturing

In MSW management strategies where some portion of the MSW is recycled, the recyclables will ultimately be delivered to a facility for remanufacturing. Separation will occur during collection, at a MRF, or at another waste management facility.

Energy and resources will be expended to deliver recyclables to a remanufacturing facility. At the facility, additional energy and resources will be expended to convert the recyclables to a new product. The total amount of energy required to recover the recyclable from the waste stream and convert it to a new product will be included in the inventory analysis. This energy is termed ($E_r$). In addition, the amount of energy required to produce a similar amount of product from virgin material will be calculated. This energy is termed ($E_v$). The net amount of energy ($E_n$) expended (or saved) to recycle a material is then be calculated as the difference between ($E_r$)and ($E_v$), where ($E_n = E_r - E_v$).

While energy has been used here as an example, a similar calculation is performed for all LCI parameters involved in the remanufacturing process such as carbon dioxide and other air emissions, wastewater pollutants, and solid waste, etc. This calculation assumes that a product manufactured using recycled materials is indistinguishable from the same product manufactured with virgin materials. The calculation described above is illustrated conceptually for ONP in

Figure 3-2. Figure 3-2 shows the flow diagram which accounts for the total energy required to produce and deliver to consumers 1000 tons of newsprint (as newspapers). As can be seen in the Figure, newsprint is not produced from 100% recycled material; some virgin material is mixed with the recycled fiber.

To develop the LCI, an assumption must be made with respect to which remanufacturing process is utilized for a recyclable. In the case of ONP, the major use is the production of new newsprint. However, some ONP is used in other applications (containerboard, cellulose insulation, animal bedding, etc.). For each recyclable, it will be necessary to collect data on remanufacturing processes to complete the LCI. Data collection efforts will focus initially on the major remanufacturing process for each recyclable. Additional remanufacturing processes will be included to the extent that resources are available to collect data on more than one remanufacturing process. The system is designed with the capacity to incorporate more that one remanufacturing process into the analysis.

The remanufacturing process model includes LCI parameters for the following categories:

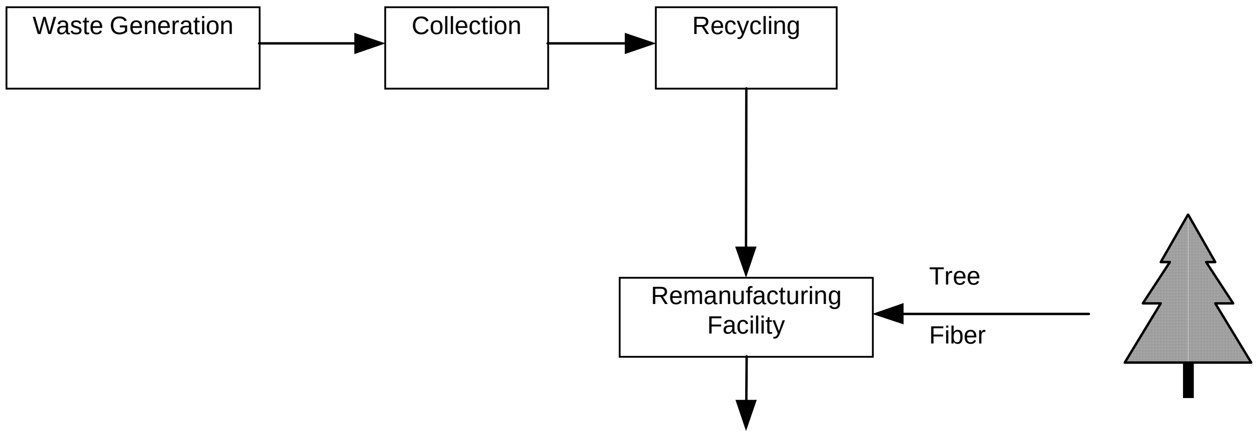
- **Material resource energy:** the fuel used in manufacturing that is physically integrated into the product rather that used to produce steam or electricity. Examples of this type of fuel usage are the use of coal to produce coke, which is then used to produce aluminum, or the use of petroleum to product plastics.

- **Combustion process energy:** the electricity consumed in producing the product and the energy associated with the amount of fuel combusted in the production process. An example of this type of fuel combustion is the use of coal in process boilers to produce process steam.

- **Pre-combustion process energy:** the energy consumed in mining and transportation steps required to produce fuels used in the manufacturing process. Examples of this type of energy are the use of energy to extract petroleum, transport it to a refinery, and produce natural gas that is combusted at a manufacturing facility for process steam.

- **Combustion transportation energy:** the energy consumed to transport the various intermediate products or materials to the next unit process in the system. This information is estimated by Franklin Associates, Ltd. using national average transportation distances and modes (truck, ocean freighter, etc.).

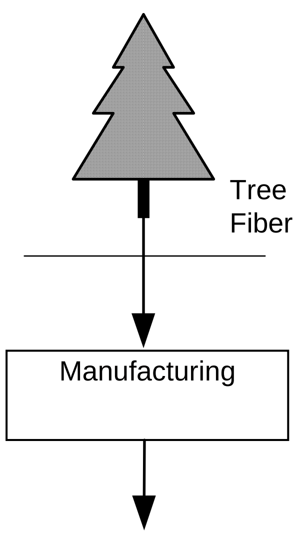
**A. Calculation of $E_r$**




1,000 Tons Secondary Newsprint

$E_r$ = Total energy required to produce 1000 tons of newsprint using secondary material, from collection through new material production.

**B. Calculation of $E_v$**




$E_v$ = Total energy required to produce 1,000 tons of newsprint from primary material. Includes energy from growth of trees through final production.

1,000 Tons of Primary Newsprint

**Figure 3-2. Illustration of Framework For Calculating Remanufacturing Offsets for Newsprint.**

- **Pre-combustion transportation energy:** the energy consumed in mining and transportation steps required to produce fuels for transportation. Examples of this type of energy are the use of energy to extract petroleum, transport it to a refinery, and produce diesel fuel for truck, ocean freighters, locomotives, etc.

- **Manufacturing emissions:** the total air, water, and solid waste emissions associated with both the production process and transportation energy consumption. This includes emissions from process, transportation, and pre-combustion activities.

- **Manufacturing energy consumption:** the total energy consumed in the manufacturing process, including combustion and precombustion, as well as process and transportation related energy consumption.

The LCI data for the virgin and recycled systems were compiled for this project by Franklin Associates, Ltd. and Roy F. Weston using a combination of their in-house LCI databases and publicly available LCI data.

# Chapter 4
# Research Products

The objective of this research effort has been to develop information and tool to assist solid waste planners in evaluating the relative cost and environmental performance of integrated MSW management strategies. The project is providing this information and tools through two main research products: a life cycle database and decision support tool. Each of these products is summarized in the following sections.

## 4.1 DATABASE

The database was developed to provide cost and LCI type information for all unit processes included in the system. The approach used to build this database is as follows. First, data from publicly available and private MSW and LCA studies, and other relevant sources, were collected and reviewed against the data quality goals and data quality indicators established for this project. The data quality assessment is based on guidance from the ISO 14040 Standards (ISO, 1996). These data were compiled into a database management system using commonly available software (Microsoft Access™). The format of the database is made as consistent as possible with other LCA data efforts in the U.S. and Europe.

The database management system was established to enable users to view and manipulate information through predefined forms, as shown in Figure 4-1. In these forms, the main categories of data are predefined, and the user's options are limited to narrowing the focus of the predefined search criteria. For example, the predefined PROCESS-ENERGY form displays information about energy consumption in a waste management operation. Similarly, to see air emissions data for a waste management operation, the PROCESS-AIR RELEASES form would be used. Many such predefined forms will be made available for "common" searches. In addition, forms will be provided to allow for maintaining and updating information in the database.

The database will be used to support the DST, but it is not linked to the tool. Rather, the database will be made available as a stand-alone application that may be used as input data to other studies or models. If solid waste practitioners possess higher quality or more site-specific data than those provided in the database, users may add data to the database.

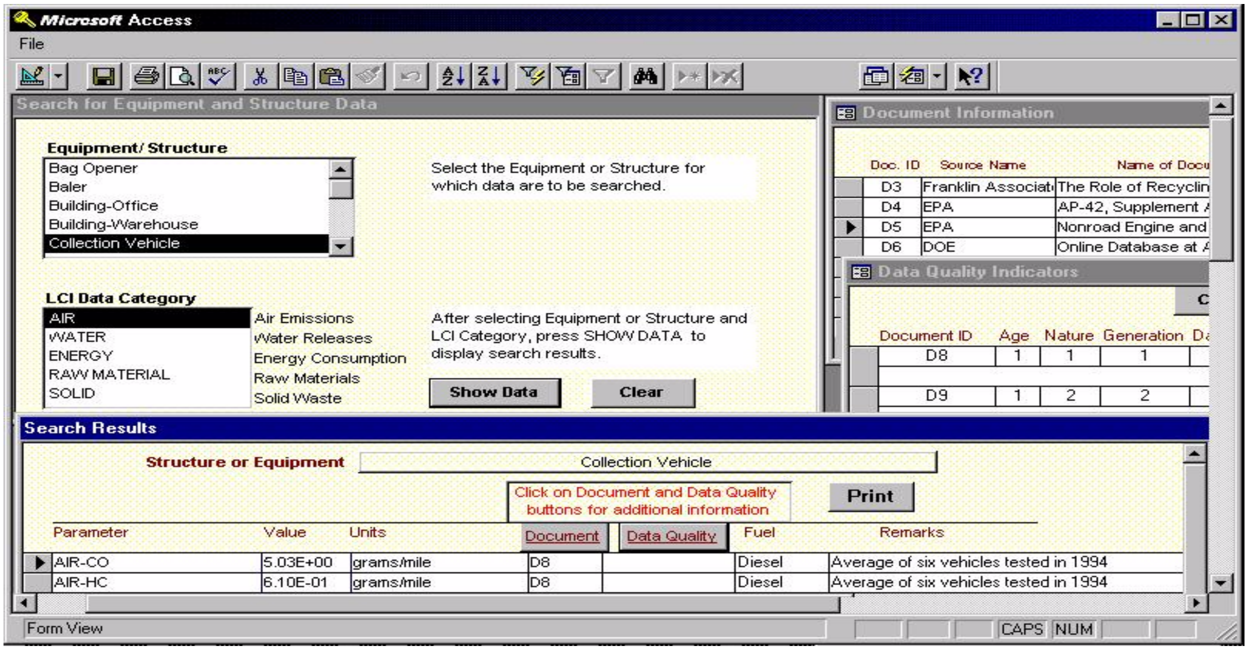



**Figure 4-1. Screen Capture from the Life Cycle Database**

### 4.1.1 Appropriate Uses of the Database

The goal for the overall project is to develop information and tools to evaluate the relative cost and environmental burdens of integrated MSW management strategies. For instance, how does the cost and environmental burdens of a MSW management system change if a specific material (e.g., glass, metal, paper, plastic) is added to or removed from a community's recycling program? And, what are the tradeoffs in cost and environmental burden if paper is recycled versus combusted or landfilled with energy recovery?

The database was designed to enable users to perform such analyses, either through the use of the DST developed in this project or through some other tool. The database can be used to perform such screening-level type analyses of MSW management options.

### 4.1.2 Limitations of the Database

See Chapter 1 of this document for a discussion of the limitations associated with the database. Appropriate uses and limitations of the database are also detailed in the database Users Manual, which is available as a stand-alone document.

## 4.2 DECISION SUPPORT TOOL (DST)

The DST provides a user-friendly interface that allows users to evaluate the cost and environmental burdens of existing solid waste management systems, entirely new systems, or some combination of both based on user-specified data on MSW generation, constraints, etc. The processes that can be modeled include waste generation, collection, transfer, separation (MRF and drop-off facilities), composting, combustion, RDF, and disposal in a landfill. Existing facilities and/or equipment can be incorporated as model constraints to ensure that previous capital expenditures are not negated by the model solution.

As illustrated in Figure 4-2, the DST consists of several components including process models, waste flow equations, an optimization module, and a graphic user interface. The process models consist of a set of spreadsheets developed in Microsoft Excel. These spreadsheets use a combination of default and user supplied data to calculate the cost and environmental coefficients on a per unit mass (ton) basis for each MSW component modeled and for each MSW management unit process (collection, transfer, etc.). For example, in the electric energy process model, the user may specify the fuel mix used to generate electricity in the geographic region of interest, or select a default grid. Based on this information, and the emissions associated with generating electricity from each fuel type, the model calculates coefficients for emissions related to the use of 1 kWh of electricity. These emissions are then assigned to MSW components for each unit process that uses electricity and through which the mass flows. MRFs, for instance, use electricity for running conveyor belts. The emissions associated with electricity generation would be assigned to the mass of materials that flowed through that facility. The user will also have the ability to override the default data if more site-specific data are available.

Optimization modeling is relatively new in life cycle studies and in this case allows DST users to search for MSW management strategies that minimize an objective function. For example, the DST currently enables users to optimize on annual cost, electricity consumption, greenhouse gas equivalents, or emissions of carbon monoxide, carbon dioxide (fossil or biomass), nitrogen oxides, particulate matter, and sulfur dioxide. The optimization module is implemented using a commercial linear programming solver called CPLEX and is governed by mass flow equations that are based on the quantity and composition of waste entering each unit process, and that intricately link the different unit processes in the MSW management system. Constraints in the mass flow equations preclude impossible or nonsensical model solutions. For example, the mass flow constraints will exclude the possibility of removing aluminum from the waste stream via a mixed waste MRF and then sending the aluminum to a landfill. Users may also specify constraints. Examples of user-specified constraints are the use of existing equipment/facilities and a minimum recycling percentage requirement.

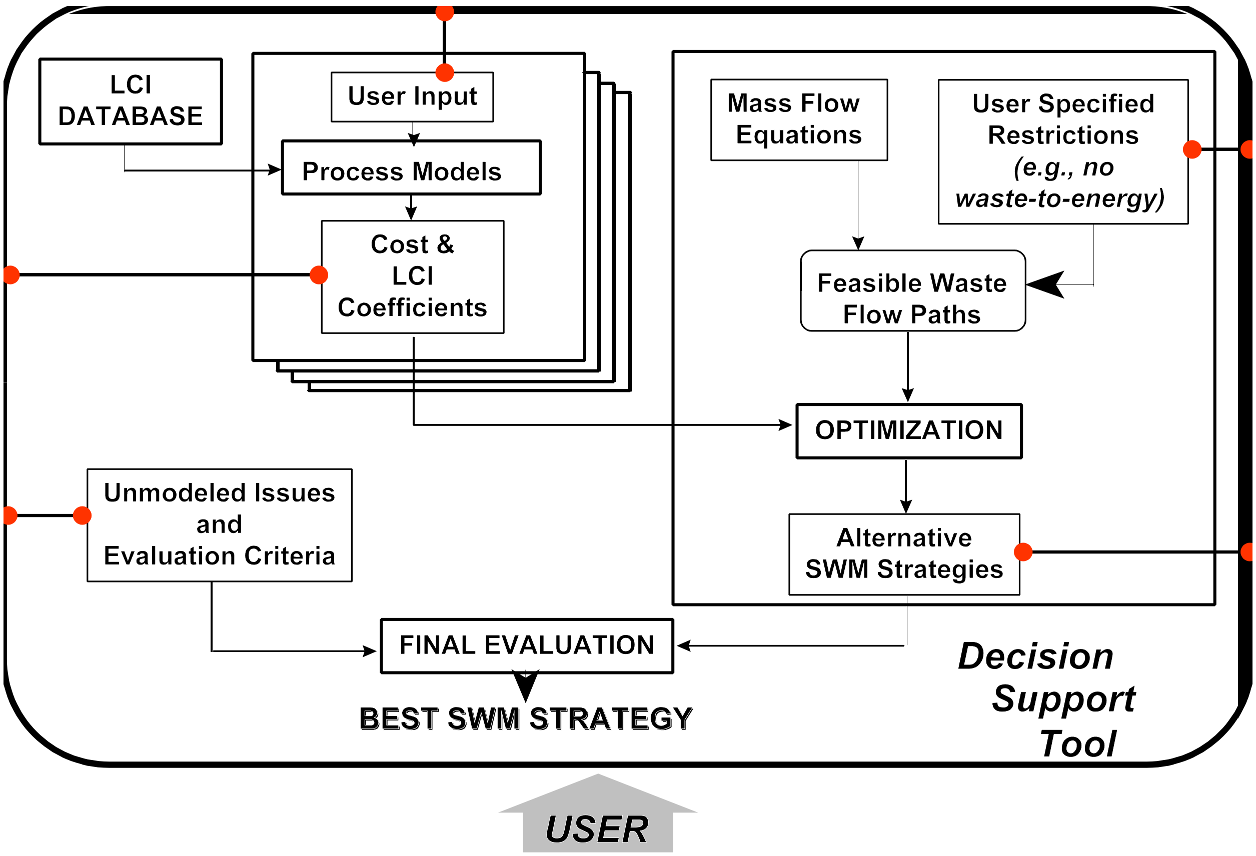



**Figure 4-2. Framework for Decision Support Tool**

The graphic user interface consists of a Microsoft Visual Basic routine that integrates the different components of the tool together to allow easy user manipulation of the spreadsheet models and the optimization module. It allows additional user constraints to be specified and provides a graphical representation of the solid waste management alternatives resulting from the optimization. Currently, results are presented on a dollar cost per ton or pounds of emission per ton basis and can be viewed at the system level, process model level, or MSW component level.

### 4.2.1 Appropriate Uses of the DST

The DST is a screening level tool designed for use in evaluating community level MSW management strategies. It allows you to conduct scenario analyses of strategies with the objective of optimizing cost or environmental performance of the system. The MSW management system modeled may be an existing system, entirely new systems, or some combination of both based on user-specified data on MSW generation, requirements, etc. The processes that can be modeled include waste generation, collection, transfer, separation (material recovery and drop-off facilities), composting, combustion, refuse-derived fuel, and disposal in a landfill. Existing facilities and equipment can be incorporated as model constraints to ensure that previous capital expenditures are not negated by the model solution.

Local governments and solid waste planners can use the tool, for example, to evaluate the affects of changes in the existing MSW management on cost and environmental burdens, identify least cost ways to manage recycling and waste diversion, evaluate options for reducing greenhouse gases or air toxics, or estimate the environmental benefit of recycling. The tool will also be of value to other user groups such as Federal agencies, environmental and solid waste consultants, industry, LCA practitioners, and environmental advocacy organizations. These users can use the tool, for example, to evaluate recycling policies and programs, policies and technologies for reducing environmental burdens, and strategies for optimizing energy recovery from MSW.

The tool is not a cash flow model and therefore should not be used to set prices for any specific waste management service. The cost results provided by the tool represent screening level engineering costs. A more detailed cash flow analysis would be need to determine the appropriate prices for services and materials.

The tool also should not be used to conduct life cycle comparisons of specific products or materials. The LCI results for recycling are based on generic process designs for product manufacturing and remanufacturing operations. To properly compare the preferability of packaging materials, you would need to do a more in-depth analysis of the production, use, and pre-consumer recycling of the products or materials.

Screen captures from a prototype of the DST are presented in Figures 4-3 to 4-5 to illustrate the functionality and the ease of use of the DST. The ability to perform detailed economic and environmental analysis with ease, multiple scenario “runs,” and sensitivity analyses makes the DST a unique and powerful software tool.

### 4.2.2 Limitations of the DST

See Chapter 1 of this document for a discussion of the limitations associated with the DST. Appropriate uses and limitations of the DST are also detailed in the DST Users Manual, which is available as a stand-alone document.

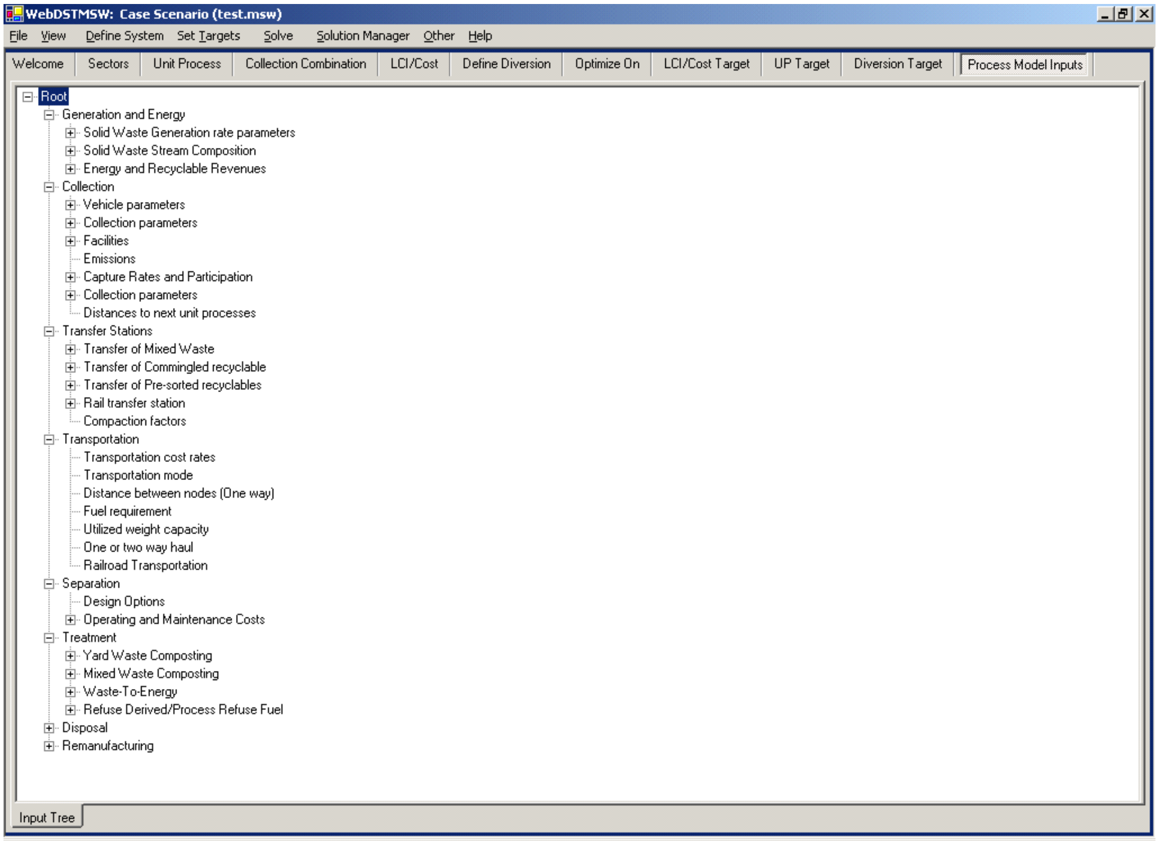



**Figure 4-3. Decision Support Tool User Interface.**

*The decision support tool interface allows users to enter data to simulate site or region-specific conditions, set targets and constraints for the analysis, and run and view results.*

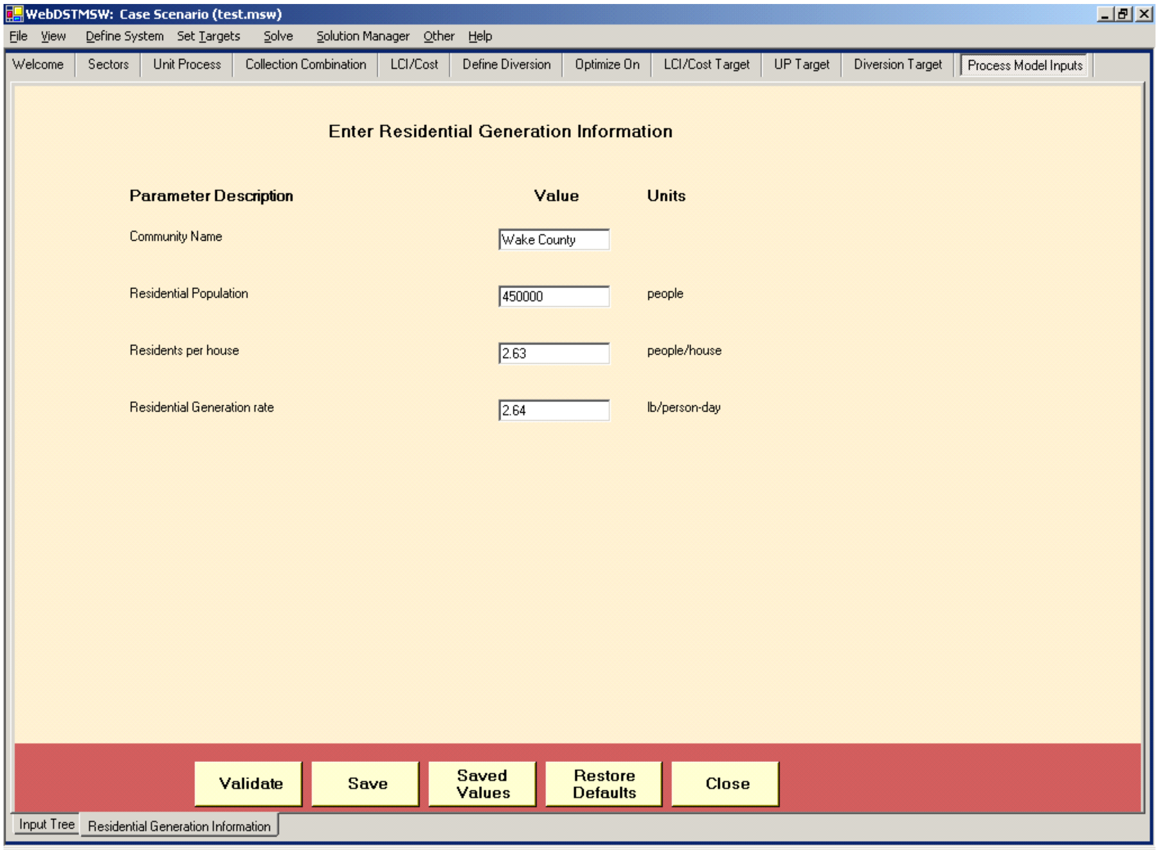



**Figure 4-4. Data Entry Through the User Interface.**

*User's can enter site- or region-specific data (e.g., waste generation and composition)*

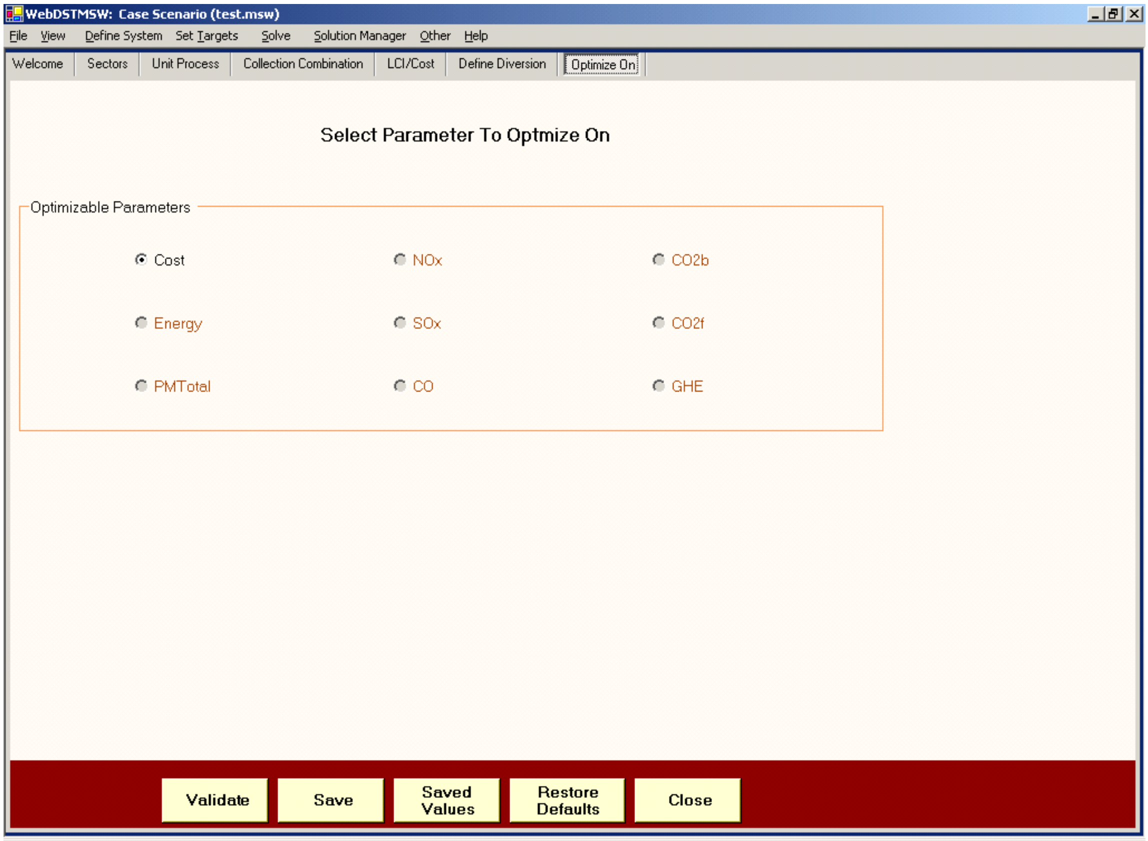



**Figure 4-5. Setting Targets for Analysis.**
*After the user enters data to model a specific (or generic/hypothetical) site or region, cost and/or environmental objectives for the analysis can be selected.*

# Chapter 5
# Sample User Applications of the Decision Support Tool

Through this project, the decision support tool has proven to be the primary product used to develop information to assist solid waste planners in evaluating the relative cost and environmental performance of integrated MSW management strategies. This chapter contains a selected sample of user applications that range in scope from national-level assessments to analysis of specific local issues. The sample applications illustrate the flexibility of the decision support tool to analyze a wide variety of MSW management issues and include the following:

**Section 5.1 – U.S. Greenhouse Gas Emissions Analysis (National Level):** Climate change and greenhouse gas (GHG) emissions have become a focal environmental issue around the globe. Landfills represent the largest anthropogenic source of methane emissions (a potent greenhouse gas) in the U.S. The purpose of this study was to identify and assess the trends in GHG emissions associated with MSW management in the U.S. since the 1970's when the majority of waste was disposed in landfill without gas collection and control. The decision support tool helped to quantify GHG emisions and illustrated the amount of GHG emissions avoided in time through the employment of new MSW management techniques and technologies such as landfill gas collection and flaring, landfill gas-to-energy systems, recycling, composting, and WTE.

**Section 5.2 – Island of Honolulu, Hawaii (Regional Level):** Many States and island communities are facing challenges as their MSW management needs grow and landfills reach capacity. This study focused on the island an Honolulu, HI and options for meeting the future MSW management needs of the Island. Four management options for the management of an additional 120,000 tons per year of MSW were investigated. These options included: (1) expanding the existing WTE facility for post-recycled MSW; (2) expanding the current recycling program; (3) disposing of wastes at a new landfill on Oahu; or (4) diverting post-recycled MSW from local landfill disposal to long-haul (West Coast U.S.) landfill operations. The goal of this study was to better understand the range of potential environmental burdens and tradeoffs of the four options using a life-cycle approach as provided by the decision support tool.

**Section 5.3 – State of Minnesota (State Level):** In recent years, bioreactor landfills have gained prominence as an emerging technology in the management of MSW. Bioreactor technology differs from the conventional "dry tomb" landfill technology primarily through this addition of extra liquid. The desired effect of the bioreactor is that it produces landfill gas (LFG) at an earlier stage in the landfill's life and at a higher rate as compared to a conventional landfill.Bioreactor landfills were studied by the State of Minnesota to better understand their environmental significance as compared to more traditional MSW management options and technologies. The goal of this study was to apply the decision support tool better understand the range of potential environmental burdens and tradeoffs of using bioreactor versus conventional landfill technologies in the State.

**Section 5.4 – City of Edmonton (Local Level):** With the growing focus on climate change and greenhouse gas (GHG) emissions, carbon trading markets have begun to develop. Kyoto-ratified countries can participate in the world-wide carbon trading market. In the U.S., groups of States in the northeast U.S. have started their own carbon market. In this study, the City of Edmonton sought to obtain accreditation for GHG emission reductions associated with the use of its compost facility as compared to the alternative of landfill disposal. The decision support tool was used to analyze the GHG emissions and emission reductions associated with Edmonton Compost Facility (ECF) as compared to baseline landfill options on a life cycle basis. The results of this analysis are intended for use in the verification of GHG emission offsets by a third-party verifier.

**Section 5.5 – City of Tacoma (Local Level):** The City of Tacoma, Washington was interested in analyzing proposed upgrades to their waste-to-energy system and evaluating the environmental aspects of implementing these upgrades versus disposal of the waste in a landfill. Specifically, Tacoma was interested in comparing the conversion of 75% of their waste stream to refuse-derived fuel (RDF) and then burning the RDF in a WTE facility for energy versus landfill disposal of the waste. The data and results generated through this project were used to evaluate the cost and life-cycle environmental tradeoffs of the RDF versus disposal options for Tacoma, with the overall goal of identifying waste management strategies that are cost efficient and environmentally protective.

Summary write-ups for each of these applications is provide in the following sections. Note that the sample applications included in this Chapter are intended as illustrative example of the use of the decision support tool. They are not intended for use in making MSW management decisions or establishing policy outside their intended scope.

## 5.1 Greenhouse Gas Emissions from Municipal Solid Waste Management in the United States

The U.S. EPA, OSW estimated that the U.S. generated and managed 236,200,000 tons of MSW in the year 2003. EPA estimates that of the total amount of MSW generated, approximately 23.5% is recycled, 7.1% is composted, 14.0% is combusted, and the remaining 55.4% is land disposed. The historical trend in MSW management from 1960 to 2003 is shown in Table 1.

**Table 1. MSW Management Trend in the U.S. from 1960 – 2003.**

| | Millions of tons | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **1960** | **1970** | **1980** | **1990** | **1995** | **2000** | **2001** | **2002** | **2003** |
| **Total Generated** | 88.1 | 121.1 | 151.6 | 205.2 | 213.7 | 234.0 | 231.2 | 235.5 | 236.2 |
| **Recovery*** | 5.6 | 8.0 | 14.5 | 33.2 | 55.8 | 68.9 | 69.3 | 70.5 | 72.3 |
| **Combustion** | 27.0 | 25.1 | 13.7 | 31.9 | 35.5 | 33.7 | 33.6 | 33.4 | 33.1 |
| **Land Disposal** | 55.5 | 87.8 | 123.4 | 140.1 | 122.4 | 131.4 | 128.3 | 131.7 | 130.8 |

*Includes materials recycling and composting.

In 2002, RTI International worked in cooperation with the Integrated Waste Services Association (IWSA) and the U.S. EPA to conduct a study of GHG emissions from MSW management in the U.S. from the mid-1970's to present time. The objective of that study was to quantify the reduction in GHG emissions that resulted from improved waste management practices and technologies over time. The mid-1970's was selected as the baseline because that represented a time when most of the MSW in the U.S. was managed by disposal in landfills that did not collect or manage landfill gas. At the time of the 2002 study, the most recent data available was for the year 1997. Results of this study were published in a journal article titled "The Impact of Municipal Solid Waste Management on Greenhouse Gas Emissions in the United States" (2002, *Journal of the Air & Waste Management Association*, Vol. 52).

Since the time of the original study, new data (year 2003) for waste generation, composition, and management has been released by EPA OSW (EPA, 2005 – MSW Facts and Figures). RTI was contracted by the Shaw Group, Inc. to prepare an update of the original study. The goal of this study is to further identify, quantify, and understand trends in GHG emissions from MSW management over time in the U.S. and how MSW management practices and technologies release and/or reduce GHG emissions.

RTI employed its MSW DST to complete this study. The MSW DST is a computer-based model developed by RTI in cooperation with the U.S. EPA's Office of Research and Development. The MSW DST has been developed with an emphasis on objectivity and scientific credibility and has undergone extensive stakeholder input and peer review, as well as a separate EPA peer review.  The tool is regarded as a cutting-edge software tool to assist solid waste planners make more informed decisions.

The methods used in the MSW DST to calculate the energy and environmental results are built on the principles of Life-Cycle Assessment (LCA).  LCA is a type of systems analysis that accounts for the complete set of upstream and downstream (cradle-to-grave) energy and environmental impacts associated with industrial systems.  The technique examines the inputs and outputs from every stage of the life cycle from the extraction of raw materials, through manufacturing, distribution, use/reuse, and then final disposal.  In the context of integrated waste management systems, an LCA tracks the energy and environmental burdens associated with all stages of waste management from waste collection, transfer, materials recovery, treatment, and final disposal.  For each of the waste management operations, energy and material inputs and emissions and energy and/or material outputs are calculated (see Figure 1).  In addition, the energy and emissions associated with the production of fuels, electrical energy, and material inputs for each operation are captured.  For energy and/or material outputs, the potential benefits associated with displacing energy and/or materials production from virgin resources are captured.

Taking a life-cycle perspective encourages waste planners to consider the environmental aspects of the entire system, including activities that occur outside the traditional framework of activities from the point of waste collection to final disposal.  For example, when evaluating options for recycling, it is important to consider the net environmental benefits (or additional burdens), including any potential displacement of raw materials or energy.  Similarly, when electricity is recovered through the combustion of waste or landfill gas, emissions associated with the generation of electricity from the utility sector are displaced.

**Project Goals**

The primary goal of this study is to update the results of the original 2002 GHG study and generate results for 2003 based on more recent MSW data released by the U.S. EPA's OSW.  This update will further work to identify, quantify, and understand trends in GHG emissions from MSW management over time in the U.S. and how MSW management practices and technologies release and/or reduce GHG emissions.

The MSW DST was used to generate estimates of GHG emissions for selected model years included in the study (1970, 1980, 1990, 1995, and 2003).  Two primary activities were required to update the results:

1) Re-run the scenarios from the original study.
2) Run a new "current" 2003 scenario using the most recent data.

The reason we re-ran the scenarios from the original study is that changes have been model to the MSW DST since the original study was performed.  In particular, changes were made to the landfill module and how landfill gas generation is calculated.  The changes will modify the results for the model years from the original study.

The methodology used for this study is intended to illustrate GHG emissions and reduction potentials for the integrated waste management system (i.e., all aspects from collection, transportation, remanufacturing into a new product, and/or disposal are accounted for). This study was not designed to compare GHG reduction potential between specific MSW management technologies (e.g., recycling versus combustion). The MSW DST was used to calculate the net GHG emissions resulting from waste collection, transport, recycling, composting, combustion, and land disposal option (i.e., offsets for displacement of fossil fuel). Both direct GHG emissions from each waste management activity were included as well as the GHG emissions associated with the production and consumption of fuels.

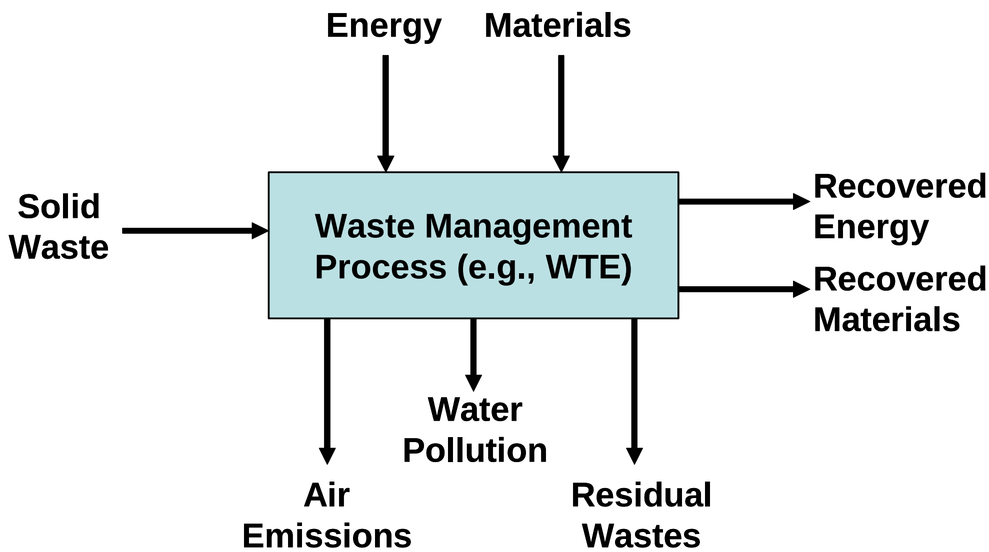



**Figure 1. Life-Cycle Inputs and Outputs of a Waste Management Operation.**

*All waste management processes that comprise an integrated waste management system consume energy and materials and produce emissions. Some processes, such as WTE, recover energy and materials. The benefits associated with any energy or materials recovered are captured in the life-cycle study.*

**Analysis of Scenarios**

For estimate the GHG emissions and potential emissions savings over time for this study, two basic sets of scenarios were analyzed:

1) The actual MSW management practices for the years 1970, 1980, 1990, 1995, and 2003.

2) Hypothetical MSW management practices for the years 1980, 1990, 1995, and 2003 using the same practice as employed in 1970.

Analyzing the set of hypothetical scenarios using 1970s technology enables us to estimate the affect of MSW management practice and technology advancements on GHG emissions over time. In effect, the hypothetical scenarios serve as the baseline for GHG emissions.

Each of the scenarios modeled for each model year include the following MSW management operations.

- Recycling
- Composting
- Combustion (with and without energy recovery)
- Landfill (with varied landfill gas management)

The specific mass of MSW input to each of the operations is shown in Table 2 (in both mass and percent mass terms).

**Table 2. Annual MSW Managed by Different Operations.**

| | **Million Metric Tons** | | | | |
|---|---|---|---|---|---|
| | **1970** | **1980** | **1990** | **1995** | **2003** |
| Recycling | 8.0 | 14.5 | 33.2 | 55.8 | 55.5 |
| Composting | 0 | 0 | 4.2 | 9.6 | 16.8 |
| Combustion | 25.1 | 13.7 | 31.9 | 35.5 | 33.1 |
| Landfill | 87.8 | 123.4 | 140.1 | 122.4 | 130.8 |
| Total | 121 | 152 | 205 | 232 | 236 |

| | **Percent (by Mass)** | | | | |
|---|---|---|---|---|---|
| | **1970** | **1980** | **1990** | **1995** | **2003** |
| Recycling | 6.6% | 9.6% | 14.2% | 21.6% | 23.5% |
| Composting | 0% | 0% | 2% | 4.5% | 7.1% |
| Combustion | 20.7% | 9.0% | 15.5% | 16.6 | 14.0 |
| Landfill | 72.6% | 81.4% | 68.3% | 57.3% | 55.4% |
| Total | 100% | 100% | 100% | 100% | 100% |

Note: Columns may not add up to the totals due to rounding

As shown in Table 2, in the 1970s, waste management primarily involved the collection and landfilling of MSW. Approximately 6.6% of waste was recycled as commingled material and 20.7% of the waste was combusted (without energy recovery). The remaining 72.6% of the waste was disposed in landfills without landfill gas collection or control. During the next 25 years, recycling steadily increased from 6.6% in the 1970s to 9.6% in 1980, 14.2% in 1990, 21.6% in 1995 and 23.5% by 2003. Composting of yard wastes wasn't a wide-spread practice until the 1990's. Composting increased from 2% in 1990 to 4.5% in 1995, and 7.1% by 2003. In 1980, waste combustion without energy recovery declined and was replaced by more modern waste-to-energy (WTE) plants. Data indicated that by 2003, 14% of the MSW generated in the U.S. was used to produce electricity at approximately 102 waste-to-energy facilities nationwide. Also in 2003, 55.4% of the waste that is landfilled is going to about 1,200 sites with liners, leachate collection and control. Some of these sites, primarily the larger ones, also have landfill gas control. All of these considerations were taken into account in the calculations.

Table 3 lists the key assumptions for each unit operation in this study.

Using the data in Table 2 and key assumptions in Table 3, the MSW DST was run and GHG emissions calculated for the years 1970, 1980, 1990, 1995 and 2003. GHG emissions are calculated as metric tons of carbon equivalent (MTCE) in the MSW DST. Carbon emissions can result from the combustion of fossil fuels and the biodegradation of organic materials (e.g., methane gas from landfills). Offsets of carbon emissions can result from the displacement of fossil fuels, materials recycling, and the diversion of organic wastes from landfills. The equation for the derivation of MTCE in the MSW DST is as follows:

$$\mathbf{MTCE = [(Fossil\ CO2*1 + CH4*21)*12/44] / 2200}$$

**Results**

Figure 2 illustrates the overall trend in GHG emissions from a 1970 to 2003. Two technology pathways are shown. One pathway represents GHG emissions from the actual integrated MSW management technologies employed in each study year. The other pathway represents GHG emissions if the same 1970s technologies and MSW management practices were used in all study years (i.e., 1980, 1990, 1995 and 2003). As illustrated in this figure, by adopting new technologies and MSW management practices, GHG emissions have decreased from 1970 to 2003, despite an almost two-fold increase in the quantity of waste generated. Net GHG emissions in 2003 were about 2.5 MMTCE versus 16.5 MMTCE in 1970. If the same technology and MSW management practices were used today as in the 1970s, then net GHG emissions would be approximately 34.0 MMTCE. Thus, it could be concluded that the employment of new MSW management technologies are currently saving approximately 31.5 MMTCE per year.

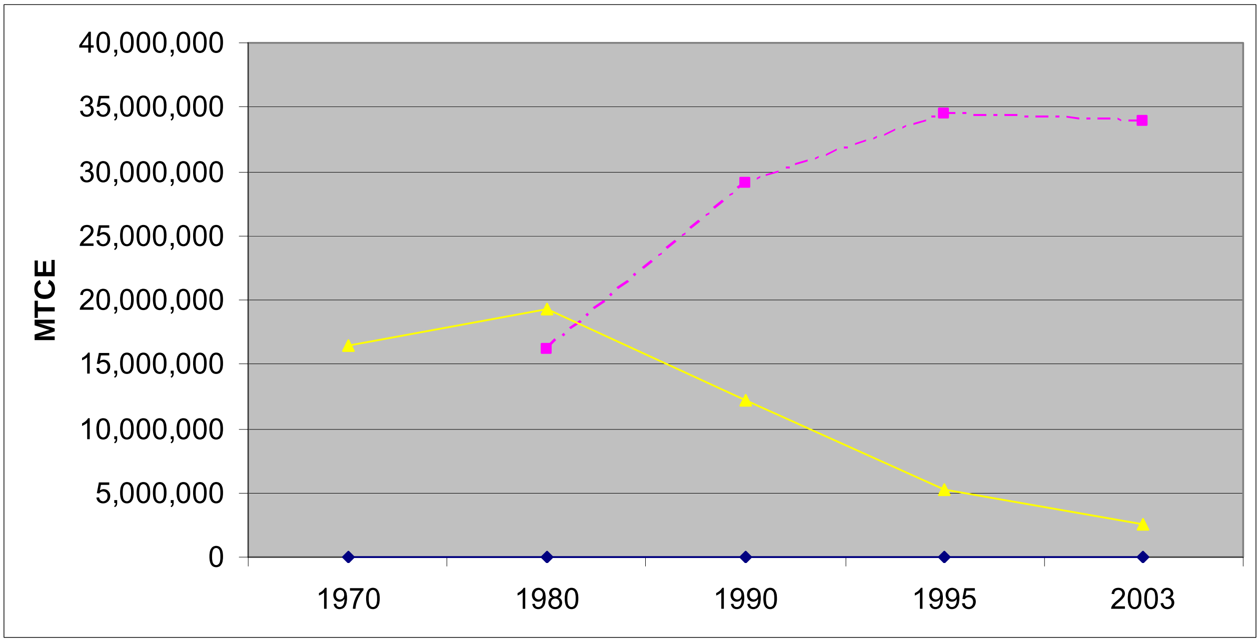
The following sections discuss the net contributions of GHGs from recycling and composting, combustion, landfills, and collection and transportation practices.

**Table 3. Key Assumptions Used in This Study**

| Parameter | Assumption |
|---|---|

| | |
|---|---|
| Waste Generation | 236,200,000 TPY |
| Waste Composition | U.S. National Average* |
| *Collection* | |
| MSW Collection | Single compartment collection vehicle |
| Recyclables Collection | Commingled collection vehicle; sorted at MRF |
| Yardwaste Collection | Separate collection; single compartment vehicle |
| Waste Collection Frequency | 1 time per week |
| *Transportation Distances* | |
| Collection to Transfer Station | 10 miles one way |
| Collection to MRF | 10 miles one way |
| Collection to WTE Facility | 10 miles one way |
| Collection to Landfill | 10 miles one way |
| *Recycling* | |
| Basic Design | Semi-Automated Commingled MRF |
| *Composting* | |
| Basic Design | Windrow |
| *Combustion* | |
| Basic Design | Mass burn of mixed MSW |
| Heat Rate | 18,000 BTU/kWh |
| Waste Input Heating Value | Varies by waste constituent |
| Metals Recovery Rate | 90% ferrous recovery from ash |
| Utility Sector Offset | Offset is baseload coal, oil, and natural gas power production based on the U.S. National grid mix. |
| *Landfill* | |
| Basic Design | Subtitle D |
| Time Period for Calculating Emissions | 100 years |
| Landfill Gas Management | Varies by year (see Table 4) |
| Utility Sector Offset | Offset is baseload coal, oil, and natural gas power production based on the U.S. National grid mix. |

Note: MRF = Materials Recovery Facility; WTE = Waste to Energy.




Solid Line = actual practice/technology; Dashed Line = using 1970 practice/technology

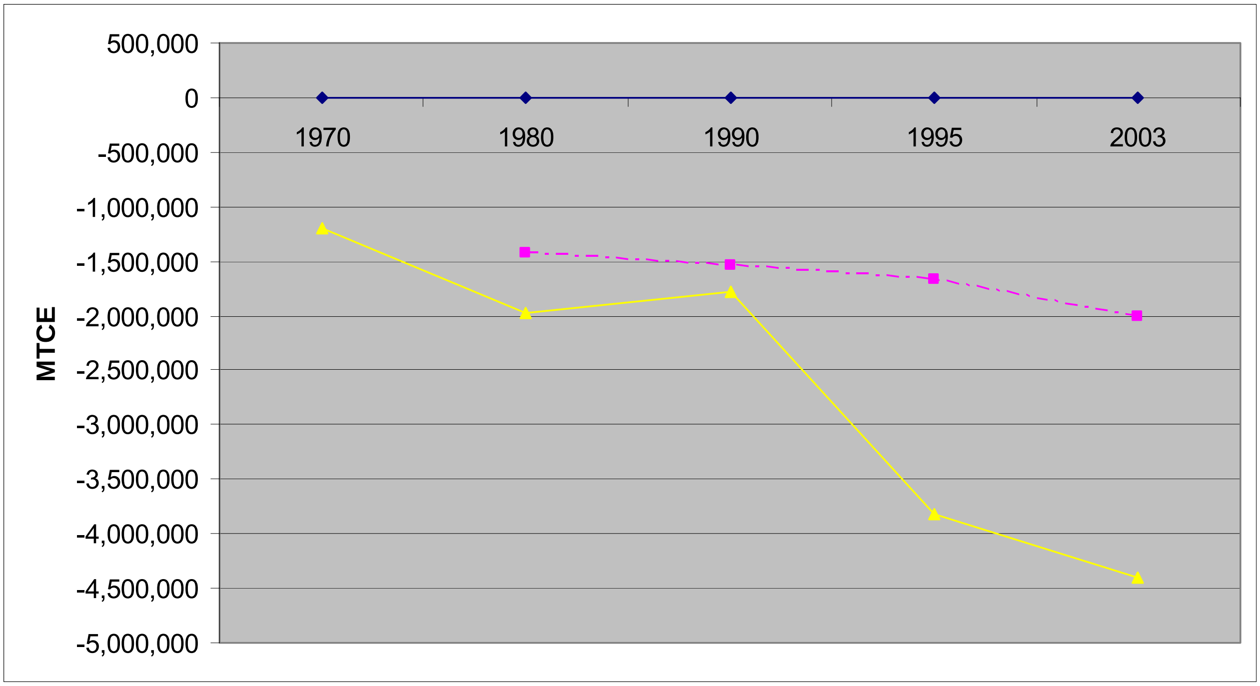
**Figure 2. Overall Trend in GHG Emissions from MSW Management in the U.S.**

### Recycling and Composting

Recycling contributes to the reduction of GHG emissions by displacing the use of virgin raw materials and thereby avoiding environmental releases associated with raw materials extraction and materials processing/production. In addition, recycling and composting avoids GHG emissions by diverting the disposal of materials from landfills that produce methane and other GHGs. As shown in Figure 3, increasing recycling and composting from about 8 million metric tons, or 6.6% in 1970, to more than 72 million metric tons, or 30.6% in 2003, is currently avoiding the release of more than 2.4 MMTCE annually. These results include GHG emissions from materials collection, separation, treatment (in the case of composting), and transportation to a remanufacturing facility. For recycled materials, GHG emissions avoided by displacing virgin raw materials production are netted out of the results. Additional emissions are also avoided as the result of diversion from landfills and from source reduction.

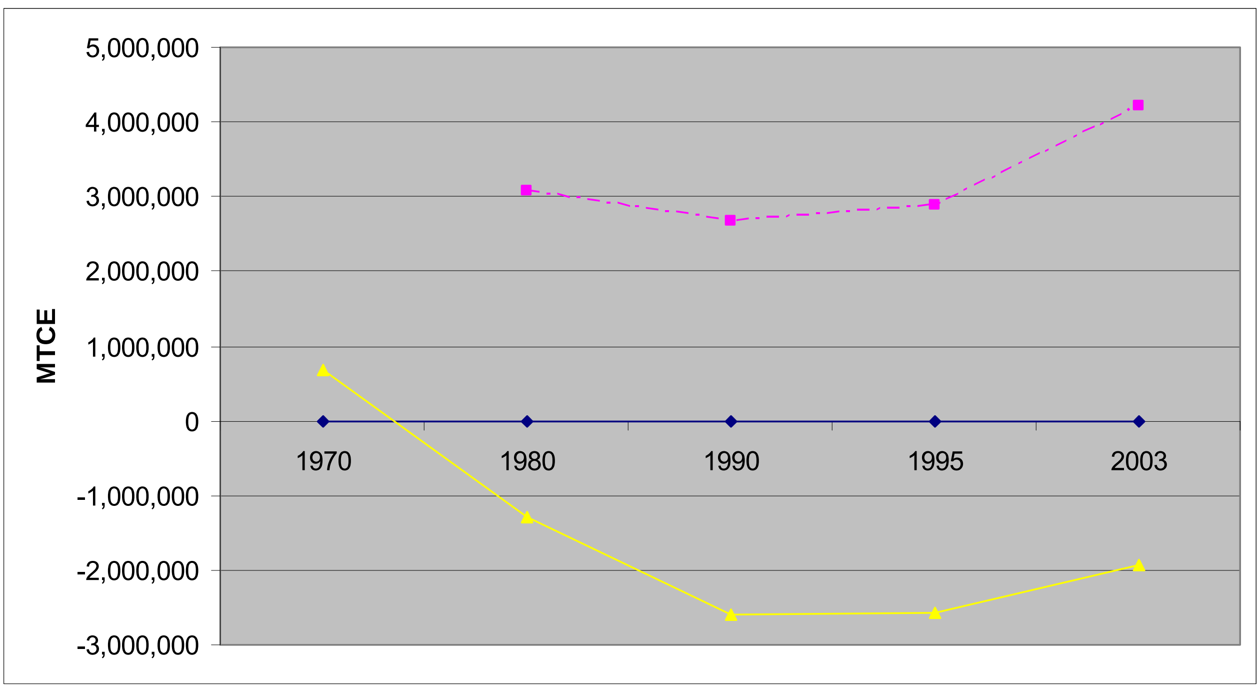
### Combustion

For nearly one hundred years, the U.S. has used combustion as a means of waste disposal. Similar to landfill technology of twenty-five years ago, the benefit of early combustion technologies was solely its disposal ability, as well as its ability to destroy pathogens in waste. Energy recovery through the combustion of waste was not seriously considered in the U.S. until the 1970's. At that time, waste combustion technology developed from a realization that waste had an inherent energy content and could be




Solid Line = actual practice/technology; Dashed Line = using 1970 practice/technology

**Figure 3. Comparison of Net GHG Emissions for Recovery (Recycling and Composting). Avoided emissions reflect offsets from resource conservation.**




Solid Line = actual practice/technology; Dashed Line = using 1970 practice/technology

**Figure 4. Comparison of Net GHG Emissions for MSW Combustion. Avoided emissions reflect offsets for fossil fuel conservation from energy that is produced.**

harnessed to generate electricity.  For the past 25 years, combustion technology has grown to include an added benefit of energy recovery.  Combustion facilities have been successful in recovering materials from the waste stream that can be recycled and recovering energy from the residual waste to generate electricity.  All present MSW combustion facilities in the U.S. include recycling programs and energy production.  Electricity generated from waste combustion has become so reliable that the power is "base load" for utilities that buy it, thus allowing those utilities to avoid construction of new power plants or the purchase of fossil fuel generated electricity.

In 1970, about 25 million metric tons of MSW, representing about 21% of U.S. MSW was managed in combustion units without energy recovery.  As shown in Figure 4, this technology was a net generator of GHG emissions.  By 2003, about 33 million metric tons of MSW, representing about 14% of U.S. MSW was managed by MSW combustion.  This resulted in avoiding the release of about 6.2 MMTCE of GHG emissions annually, as compared to GHG emissions if 1970 combustion technology was still employed.  The GHG emissions from combustion facilities were based on emission test results provided to the U.S. EPA and state environmental agencies.

Similar to recycling, waste combustion can reduce GHG emissions in two ways.  First, combustion diverts MSW from landfills where it would otherwise produce methane as it decomposes.  Second, the electrical energy produced from waste combustion displaces electricity generated by fossil fuel-fired power generators (and associated GHG emissions).  Both Figures 3 and 4 reflect the net decrease in emissions that are attributed to displacement of virgin resources and fossil fuel.  They do not reflect added reductions from methane emissions that are avoided if waste were landfilled.

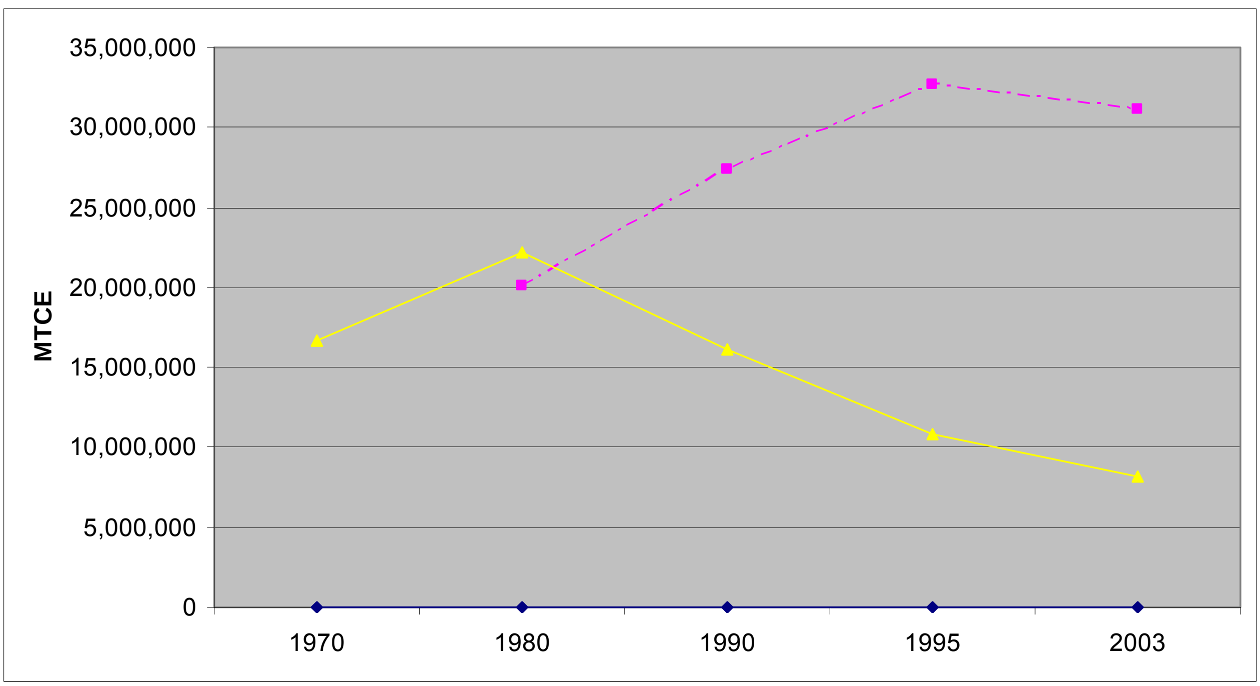
### Landfills

In 1970, 87.8 million metric tons of MSW was landfilled in the U.S.  In 2003, about 130.8 million metric tons of MSW were landfilled, representing 55.3% of MSW generated.  As of 2000, there were 2,526 MSW landfills in the U.S.[30]  Landfills with gas collection systems reduce the release of GHG emissions associated with the decomposition of waste.  Figure 6 illustrates the landfill gas generation rate during a 100-year time period.  Since GHG emissions are reported for a specific time period, the cumulative methane yield as opposed to an annual emission rate is needed to account for the total emissions for the management (i.e., landfilling) of the MSW for each year of the study.  Energy can be recovered from the utilization of the methane in landfill gas (which is typically about 50% of the landfill gas) to produce energy.   Offsets for fossil fuel conservation were included in the analysis as was done for recycling and combustion.  Due to diversion of waste from landfills, the growth of landfill gas to energy projects from zero in 1970 to over 325 in 2002 (EPA, OAR, LMOP Brochure, EPA-430-F-02-013), Clean Air Act requirements, and improvements in landfill design and management, there has been a substantial reduction of GHG emissions associated with MSW landfills.

For the baseline year of 1970, there was no gas control or energy recovery.  For 2003, using recent data, GHG emissions were calculated based on 70% of MSW being landfilled at sites with landfill gas collection and control. Of this 70%, half of the gas was assumed to be flared and half was used for energy recovery using recent statistics of the distribution of energy recovery projects (internal combustion engines, direct gas use, gas turbines, etc.). Specific assumptions for landfill gas parameters in each study year are included in Table 4. These assumptions were verified through communication with national experts. The GHG emissions associated with fossil-fuel-based electrical energy that was displaced by the use of landfill gas was also included in the calculations using the national electrical energy grid mix.

**Table 4. Key Landfill Design and Gas Management Assumptions.**

| | Study Year | | | | |
|---|---|---|---|---|---|
| **Parameter** | **1970** | **1980** | **1990** | **1995** | **2003** |
| Waste managed in landfills with gas control | 0% | 10% | 30% | 50% | 70% |
| Landfill gas collection efficiency | 0% | 75% | 75% | 75% | 75% |
| $CH_4$ Oxidation rate | 20% | 20% | 20% | 20% | 20% |
| Collected landfill gas utilized for energy recovery projects | 0% | 0% | 31% | 50% | 50% |



Solid Line = actual practice/technology; Dashed Line = using 1970 practice/technology

**Figure 5. Comparison of Net GHG Emissions for Landfills.**

The results, as illustrated in Figure 5, indicated that modern landfills in 2003 avoided the release of 23 MMTCE of GHG emissions annually. This level of avoided GHG emissions was achieved through the use of gas collection and control systems as well as the diversion of MSW from landfills by using of recycling, composting, and combustion technologies. The key factors in determining GHG emissions produced from landfills are the amount of waste managed, level of gas collection and control, effectiveness and timing of these controls, and level and type of energy recovery. We also accounted for gas that would be oxidized and not emitted as methane. The gas collection efficiency that was used was obtained from EPA's guidance for estimating landfill gas emissions and is considered environmentally conservative.

### Collection and Transportation

Collection and transportation of MSW and recyclables accounted for about 0.2 and .5 MMTCE in 1970 and 2003, respectively, and are a relatively insignificant source of GHG emissions from MSW management. More GHG emissions are emitted in 2003 from collection and transportation due to the doubling of the amount of MSW generated and collected since 1970. In addition to increases in GHG emissions from collection and transportation, increases in other local pollutants (such as sulfur oxides, nitrogen oxides, carbon monoxide, ozone, and particulate) should also be considered, particularly in regions that are classified as nonattainment areas with respect to the National Ambient Air Quality Standards. Table 5 includes estimates of these other, non GHG pollutants associated with waste collection and transportation.

**Table 5. Non-GHG Pollutant Releases from Waste Collection and Transportation.**

| | Pollutant (lb/year) | | | |
|---|---|---|---|---|
| **Scenario** | **SOx** | **NOx** | **CO** | **Particulate** |
| 1970 | 7,404,934 | 71,054,613 | 16,716,280 | 1,707,520 |
| 1980a | 8,961,163 | 86,487,661 | 20,582,590 | 2,112,453 |
| 1980b | 9,054,720 | 86,817,326 | 20,907,562 | 2,159,925 |
| 1990a | 12,622,833 | 121,366,886 | 41,382,969 | 4,592,891 |
| 1990b | 11,528,113 | 112,157,781 | 27,216,238 | 2,816,074 |
| 1995a | 17,260,950 | 149,443,941 | 41,382,969 | 4,592,891 |
| 1995b | 12,789,351 | 124,944,778 | 30,409,094 | 3,149,042 |
| 2003a | 18,248,753 | 158,791,960 | 42,288,179 | 4,621,385 |
| 2003b | 13,483,165 | 130,023,476 | 31,979,040 | 3,333,531 |

a-actual practice and technologies

b-using 1970 practice and technologies

## Conclusions

The U.S. is avoiding the annual release of about 31.5 MMTCE of GHG emissions each year through the use of modern MSW management practices. The total quantity of GHG emissions from MSW management in 2003 was reduced 31.5 MMTCE from what it otherwise would have been if 1970s MSW management practices and technologies were still employed, despite an almost doubling in the rate of MSW generation. This reduction is a result of several key factors:

- Increasing recycling and composting efforts from 6.6A% to 30.6% resulted in savings of 2.4 MMTCE from avoiding use of virgin materials.
- Producing electricity in waste combustion facilities avoids 6.2 MMTCE that would otherwise have been produced by fossil fuel electrical energy generation and metals production.
- Increasing diversion of MSW from landfills by using recycling, composting, and waste combustion.
- Increasing landfill gas collection and energy recovery technology avoids 23 MMTCE that would otherwise have been produced by older landfills (without landfill gas control), by displacing fossil fuel consumption for that portion of sites utilizing landfill methane (rather than flaring the gas), and through diversion to other technologies and source reduction.

This study illustrates that there has been a positive impact on GHG emissions as a result of technology advancements in managing MSW and more integrated management strategies. It can be concluded that the greatest reductions in GHG emissions during the past 25 years have come from technology advancements to recover energy and recycle materials. The large reductions in GHG emissions from energy recovery and recycling result from displacing the need to produce energy from fossil sources and to produce new raw materials from virgin sources. There are additional opportunities for decreases in GHG emissions as well as improvement in other environmental co-benefits through improved materials and energy recovery from MSW management.

Because this study is an overview of the entire U.S., the design and assumptions used for modeling the MSW management operations are generic national averages and not representative of any specific facility. There may be significant site and regional differences in facilities and operations that will result in different GHG emission profiles from those presented in this study.

## 5.2 Life-Cycle Study of Municipal Solid Waste Management Alternatives for Honolulu, Hawaii

RTI was contracted by Covanta Projects, Inc., to conduct a detailed life-cycle study of municipal solid waste (MSW) management options for Honolulu, HI. This study focused on four management options for the disposal of 120,000 TPY (tons per year) of MSW. These options included: (1) expanding the existing HPOWER waste-to-energy (WTE) facility for postrecycled MSW; (2) expanding the current recycling program; (3) disposing of wastes at a new landfill on Oahu; or (4) diverting postrecycled MSW from local landfill disposal to long-haul (West Coast U.S.) landfill operations. The goal of this study was to better understand the range of potential environmental burdens and tradeoffs of the four options through a life-cycle analysis.

The life-cycle study was completed using a computer-based MSW decision support tool developed by RTI over a period of 10 years in cooperation with the U.S. EPA's Office of Research and Development. The MSW DST has undergone extensive stakeholder input and peer review (as well as a separate peer review by EPA) and is regarded as a cutting-edge software tool that can help solid waste planners make more informed decisions.

The results from this study demonstrate that the WTE facility expansion option has the lowest energy consumption and also the lowest environmental impact when considering air emissions, solid waste, and waste water. Recycling typically has the second lowest energy consumption and environmental impact, with the two landfill options using the most energy and having the greatest impact on the environment.

### Introduction

Honolulu currently manages 1,600,000 TPY (tons per year) of municipal solid waste (MSW) through an integrated management system that combines a waste-to-energy (WTE) facility (HPOWER), recycling, and local landfill disposal. This annual rate is expected to increase due to growth in both residential and commercial development. The City and County of Honolulu have proposed to expand the existing HPOWER WTE facility to include a third municipal waste combustor (MWC) identical in size to the existing two units, both of which have a nominal rating of 854 TPD (tons per day). The turbine generator is not rated for steam from three MWC units operating at full load. Therefore, the two primary operating scenarios are two units at 100% load or three units at 70% load. It is anticipated that the third unit would increase the annual average capacity of the HPOWER WTE facility by approximately 120,000 TPY based on waste generation projections.

The goal of this study was to better understand the range of potential environmental burdens and tradeoffs of four alternatives for managing 120,000 TPY of MSW: (1) expansion of the existing HPOWER WTE facility with a MWC; (2) addition of a new landfill on Oahu; (3) diversion of local landfill disposal to long-haul, west coast U.S. landfill disposal; and (4) expansion of the current recycling program.

RTI International (RTI) was contracted by Covanta Projects, Inc., on behalf of the City and County of Honolulu, to conduct a detailed life-cycle study to quantify and compare the energy and environmental aspects of these alternative waste management options for Honolulu, using RTI's MSW decision support tool (DST). The MSW DST is a computer-based model developed by RTI over a period of 10 years in cooperation with the U.S. Environmental Protection Agency's (EPA's) Office of Research and Development. The MSW DST computer model has been developed with an emphasis on objectivity and scientific credibility and has undergone extensive stakeholder input and peer review, as well as a separate EPA peer review. The tool is regarded as a cutting-edge software tool that can help solid waste planners make more informed decisions.

The methods used in the MSW DST to calculate the energy and environmental results are built on the principles of Life-Cycle Assessment (LCA). LCA is a type of systems analysis that accounts for the complete set of upstream and downstream (cradle-to-grave) energy and environmental impacts associated with industrial systems. The technique examines the inputs and outputs from every stage of the life cycle from the extraction of raw materials, through manufacturing, distribution, use/reuse, and then final disposal. In the context of integrated waste management systems, an LCA tracks the energy and environmental burdens associated with all stages of waste management from waste collection, transfer, materials recovery, treatment, and final disposal. For each of the waste management operations, energy and material inputs and emissions and energy/material outputs are calculated (see Figure 1). In addition, the energy and emissions associated with fuels, electrical energy, and material inputs are captured. Likewise, the potential benefits associated with energy and/or materials recovery displacing energy and/or materials production from virgin resources are captured.

Taking a life-cycle perspective encourages waste planners to consider the environmental aspects of the entire system, including activities that occur outside the traditional framework of activities from the point of waste collection to final disposal. For example, when evaluating options for recycling, it is important to consider the net environmental benefits (or additional burdens), including any potential displacement of raw materials or energy. Similarly, when electricity is recovered through the combustion of waste or landfill gas, the production of fuels and generation of electricity from the utility sector are displaced.

The system considered in this study was an integrated MSW management system for Honolulu. This integrated system is comprised of multiple waste management activities, such as waste collection, transfer, treatment (i.e., WTE), materials recovery and recycling, and disposal. The analysis took into account all of the numerous upstream and downstream impacts and benefits associated with the management of 120,000 TPY of MSW for the four alternative operating scenarios. As illustrated in Figure 1, each waste management process consumes energy and materials, and creates air and water emissions. Some waste management activities also recover materials (e.g., recyclable metals) and/or energy. The benefits associated with the recovery of energy and materials are captured in this study. For example, when electrical energy is recovered through a WTE facility, the generation of electricity from the utility sector is displaced. The environmental burdens associated with the production of that electricity from the utility sector is captured in the WTE life-cycle results. Similarly, when materials are recovered for recycling, the environmental burdens associated with the production of virgin materials are avoided. This burden reduction also is accounted for in the life-cycle results. The results from this study make it possible to evaluate the life-cycle environmental burdens and tradeoffs involved in an expansion of the HPOWER WTE facility versus the long-haul landfill disposal or increased recycling program options. They thus further the overall goal of identifying the waste management strategies that are environmentally protective. In this respect, an LCA can be a valuable tool to ensure that a given technology creates actual environmental improvements rather than simply transferring environmental burdens from one life-cycle stage to another or from one environmental medium to another. This study is also useful for screening waste management strategies to identify the key drivers behind their environmental performance.

**Project Goals**

The primary goal of this study was to better understand the energy and environmental tradeoffs and implications of expanding the HPOWER WTE facility versus other MSW management alternatives for the City of Honolulu. As described in the previous section, the alternatives to expanding the WTE facility included landfill disposal (in Oahu or a landfill in Washington State) or expansion of the recycling program.

Figure 1 illustrates the general mass and energy balance for each of the four waste management options. The specific goals were to estimate energy and environmental impacts for each of the four options when considering

- Transportation
- Raw materials
- Energy requirements or energy generated.

The following assumed basic conditions were applied to all four scenarios evaluated:

- 120,000 TPY of MSW is managed under each scenario considered.
- Waste composition is based on local waste characterization data for Honolulu.
- A 20-year life of the project.

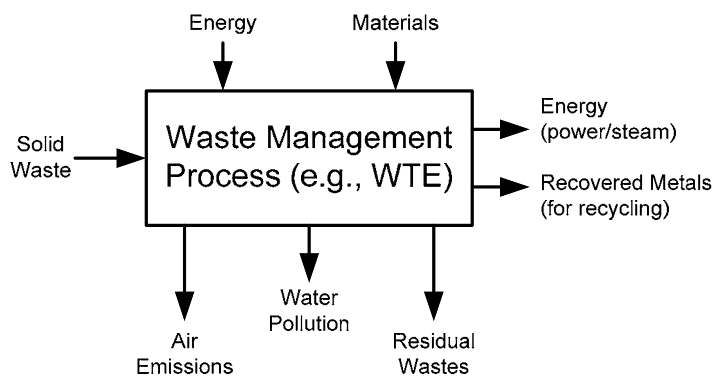



**Figure 1. Life-Cycle Inputs and Outputs of a Waste Management Process.**

Note: All waste management processes that comprise an integrated waste management system consume energy and materials and produce emissions. Some processes, such as WTE, recover energy and materials. The benefits associated with any energy or materials recovered are captured in the life-cycle study.

Table 1 provides additional details regarding each scenario.

**Table 1. Key Assumptions Used in This Study**

| Parameter | Assumption |
|---|---|
| Waste Generation | 120,000 TPY |
| Waste Composition | Honolulu* |
| Waste Collection Frequency | 1 time per week |
| | |
| Transportation Distances | |
| Collection to Transfer Station | 15 miles one way |
| Collection to MRF | 15 miles one way |
| Collection to WTE Facility | 15 miles one way |
| Collection to Landfill | 15 miles one way |
| MRF/Transfer Station to Port Terminal | 7.5 miles one way |
| Transfer Station to Landfill | 25 miles one way |
| Transfer Station to WTE Facility | 25 miles one way |
| WTE Facility to Ash Landfill | 5 miles one way |
| Port Terminal to Portland, OR, or China | 5,800 miles one way |
| Portland Port Terminal to Washington Landfill | 90 miles one way |
| China/U.S. Port Terminal to Remanufacturing Plant | 100 miles one way |
| | |
| WTE Facility | |
| Basic Design | Mass burn of preprocessed waste |
| Heat Rate | 18,000 BTU/kWh |
| Waste Input Heating Value | Varies by waste constituent |
| Metals Recovery Rate | 95% ferrous and nonferrous |
| Utility Sector Offset | Offset is baseload coal, oil, and natural gas power production based on the Honolulu grid mix. |
| | |
| Landfill | |
| Basic Design | Subtitle D |
| Time Period for Calculating Emissions | 100 years |
| Landfill Gas-Collection Efficiency | 75% |
| Landfill Gas Management | None for Honolulu; gas collection and energy recovery for Washington State |
| Utility Sector Offset | Offset is baseload coal, oil, and natural gas power production based on the Honolulu grid mix. |

* From *Solid Waste Integrated Management Plan*, for Honolulu Hawaii. Prepared by Pacific Waste Consulting Group. November 2004.

Note: MRF = Materials Recovery Facility; WTE = Waste to Energy.

## Analysis of Alternatives for Managing 120,000 TPY of MSW

Four alternative waste management options have been individually analyzed, with the expansion of the HPOWER WTE facility being the base case.

### Expansion of the HPOWER WTE Facility

The expansion of the HPOWER WTE facility to process an additional 120,000 TPY of MSW is illustrated in Figure 2 and includes the activities of waste collection, transfer by truck, combustion in the HPOWER WTE facility, recovery of ferrous and nonferrous metals for recycling, and transport and disposal of combustion ash in a local landfill.

Assumptions related to this scenario are as follows:

- 120,000 TPY of postrecycled MSW is processed in the HPOWER WTE facility.
- 15% of waste is hauled to the transfer station and then to the WTE facility via truck.
- 83% of the MSW delivered to the HPOWER WTE facility is combusted as refuse-derived fuel (RDF) with the other 17% being process residuals that are landfilled.
- Air emissions for the HPOWER WTE facility are based on the Maximum Achievable Control Technology (MACT) as are promulgated as the subpart Eb standards.

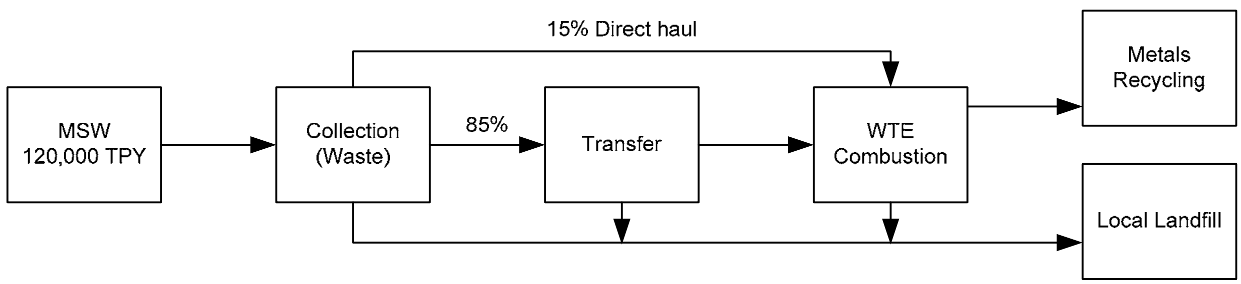



**Figure 2. Illustration of the WTE Facility Expansion Alternative.**

(Note: For the WTE box, 83% is processed as RDF and the remaining 17% is process residuals disposed of in the local landfill).

- Ferrous and nonferrous materials are separated at the HPOWER WTE facility and transported for recycling.
- The electrical energy generated offsets baseload fossil (coal, oil, and natural gas) electrical energy production based on the Honolulu grid mix of fuels.

Landfill is a Subtitle D landfill with a liner system and no gas collection.

**Local (Honolulu) Landfill**

This scenario models the creation of a new landfill on the Island of Oahu in the general vicinity of the existing landfill located at Waimanulo Gulch. This landfill would be designed and constructed to meet current EPA requirements for a new landfill, which means there would be a leachate-collection system but no gas-collection and flaring or combustion system.

The local landfill alternative is illustrated in Figure 3 and includes the activities of waste collection, transfer by truck, and disposal in a local (Honolulu) landfill. As with the previous scenarios, it was assumed that 85% of the waste is hauled directly to the landfill and 15 percent of the waste is hauled to the transfer station and then to the landfill by trailer truck. Also, it was assumed that the Honolulu landfill does not have a gas- collection and management system.

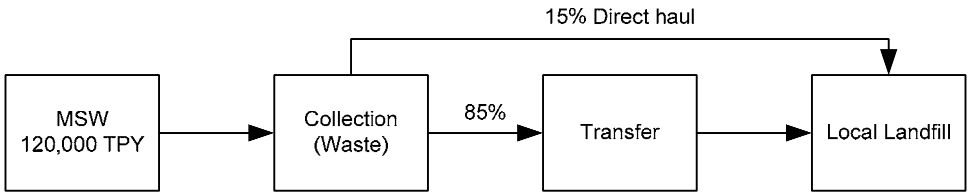



**Figure 3. Illustration of the Local Landfill Alternative.**

**West Coast U.S. Landfill**

This scenario models diversion of a portion of the local landfill disposal to an out-of-state landfill. The landfill waste transfer includes the following steps:

- MSW is delivered to a hypothetical marine transfer station located on Sand Island, Oahu.
- The MSW is shredded, compacted, and wrapped in plastic.
- The plastic wrapped logs are loaded on a barge for delivery to a marine transfer station at the mouth of the Columbia River, where it is off-loaded and then trucked to a landfill in Washington State.
- We are not aware of how the MSW is to be unwrapped to facilitate decomposition and generation of landfill gas. However, for the purpose of this calculation, this MSW is assumed to react the same way as other MSW.

The mainland U.S. landfill alternative is illustrated in Figure 4 and includes the activities of waste collection, transfer by ocean freighter to Portland, OR, and transfer by trailer truck to a landfill in Washington State. It was assumed that 100% of the waste is shipped by ocean freighter to the landfill in Washington State. Also, it was assumed that the landfill in Washington State includes a gas-collection and gas-to-energy recovery system.

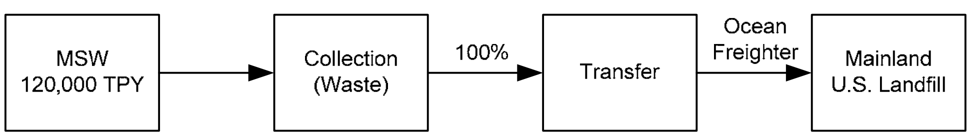



**Figure 4. Illustration of the Mainland U.S. Landfill Alternative.**

**Recycling**

The recycling alternative is illustrated in Figure 5 and includes the activities of drop-off recyclables collection, residual waste collection, transfer, local landfill disposal of the residual waste, and shipping of the recyclables to China and the mainland United States by ocean freighter. It was calculated that 1 ton of Honolulu waste contains approximately 31% recyclable material. Therefore, it was assumed that 31% of the total 120,000 TPY of MSW is managed by the drop-off recycling centers and the remaining 69% is residual waste that is landfilled.

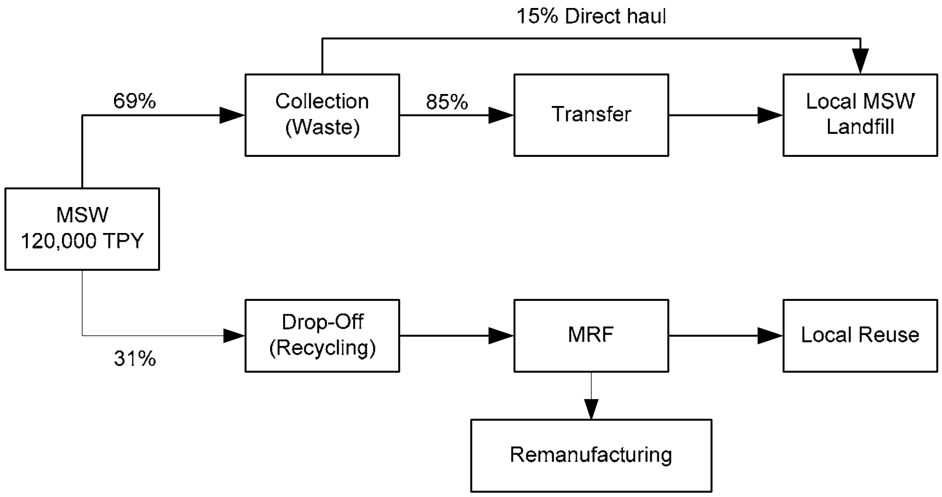



**Figure 5. Illustration of the West Coast U.S. Landfill Alternative.**

## Results of the Incremental Analysis of Alternatives for Managing 120,000 TPY of MSW

Summary-level results for the management of 120,000 TPY of MSW via each management alternative are shown in Table 2. These results are presented as *net* life-cycle totals for each scenario. Therefore, a positive value represents a net life-cycle burden, whereas a negative value represents a net life-cycle savings or avoidance. For example, a negative value for energy consumption for the WTE facility expansion alternative means that the WTE system generates more energy than it consumes by virtue of energy generation as well as significant energy offsets created through the recovery and recycling of metals.

### Net Energy Consumption

Energy is consumed by all waste management activities (e.g., collection, transportation, treatment, disposal), as well as by the processes to produce energy and material inputs (e.g., liners for landfills) that are included in the analysis. Energy is also produced by some waste management activities (e.g., WTE) and can be offset or avoided by others (e.g., recycling). If the energy produced/offset by the waste management system is greater than the energy consumed, then energy is saved. The benefit of this savings is that fossil fuels are saved. Energy use (or savings) is an important parameter in life-cycle studies, because it often drives the results of the study due to the significant amounts of air and water emissions associated with energy production.

As shown in Figure 6, only the WTE facility expansion and recycling alternatives result in a net energy savings. The landfill alternatives are net energy consumers, even with energy recovery (i.e., Washington State landfill alternative).

**Table 2. Summary Level Results Comparing Management Alternatives for 120,000 TPY of MSW**

| Parameter | Units | WTE System with Metals Recovery | Honolulu Landfill | Washington State Landfill | Drop-off Recycling |
|---|---|---|---|---|---|
| | | | | | |
| **Energy Consumption** | MBTU | -1,327,300 | 104,528 | 62,211 | -802,940 |
| | | | | | |
| **Air Emissions** | | | | | |
| Total Particulate Matter | lb | -155,861 | 10,997 | 26,067 | -72,050 |
| Nitrogen Oxides | lb | -146,730 | 101,450 | 167,205 | -180,979 |
| Sulfur Oxides | lb | -1,235,480 | 14,081 | -266,405 | -817,995 |
| Carbon Monoxide | lb | -182,768 | 49,647 | 263,637 | -328,960 |
| Carbon Dioxide Biomass | lb | 187,273,789 | 459,705,388 | 482,052,331 | 368,771,079 |
| Carbon Dioxide Fossil | lb | -152,095,114 | 3,538,398 | -35,210,577 | -62,173,996 |
| Carbon Equivalents | MTCE* | -21,147 | 330,478 | 67,566 | 226,560 |
| Hydrocarbons (non-$CH_4$) | lb | -201,370 | 21,643 | -26,937 | -88,404 |
| Lead | lb | -19 | 0 | -7 | -13 |
| Ammonia | lb | -5,240 | 17 | -1,619 | -757 |
| Methane | lb | -142,022 | 115,236,491 | 25,271,071 | 82,076,928 |
| Hydrochloric Acid | lb | 22,288 | 419 | 3,148 | -10,611 |
| | | | | | |
| **Ancillary Solid Waste** | lb | -24,421,687 | 304,328 | -1,284,511 | -24,219,280 |
| | | | | | |
| **Water Emissions** | | | | | |
| Dissolved Solids | lb | -355,999 | 13,027 | -28,090 | -405,116 |
| Suspended Solids | lb | -47,706 | 427 | -7,843 | 22,997 |
| Biochemical Oxygen Demand | lb | -839 | 56,585 | 56,433 | 85,241 |
| Chemical Oxygen Demand | lb | -7,963 | 157,621 | 156,593 | 53,646 |
| Oil | lb | -5,957 | 19,187 | 18,224 | 6,663 |
| Sulfuric Acid | lb | -840 | 4 | -183 | -309 |
| Iron | lb | -2,663 | 11 | -405 | -107 |
| Ammonia | lb | -146 | 1,809 | 1,793 | 625 |
| Copper | lb | 0 | 0 | 0 | 0 |
| Cadmium | lb | -15 | 0 | -1 | -19 |
| Arsenic | lb | 0 | 0 | 0 | 0 |
| Mercury | lb | 0 | 0 | 0 | 0 |
| Phosphate | lb | -418 | 14 | -80 | -154 |
| Selenium | lb | 0 | 0 | 0 | 0 |
| Chromium | lb | -15 | 1 | -1 | -19 |
| Lead | lb | 0 | 0 | 0 | 0 |
| Zinc | lb | -6 | 0 | -1 | 19 |

* MTCE is based on carbon dioxide fossil and methane emissions. Carbon dioxide biomass is not included because it is considered to be part of the natural short-term carbon cycle.

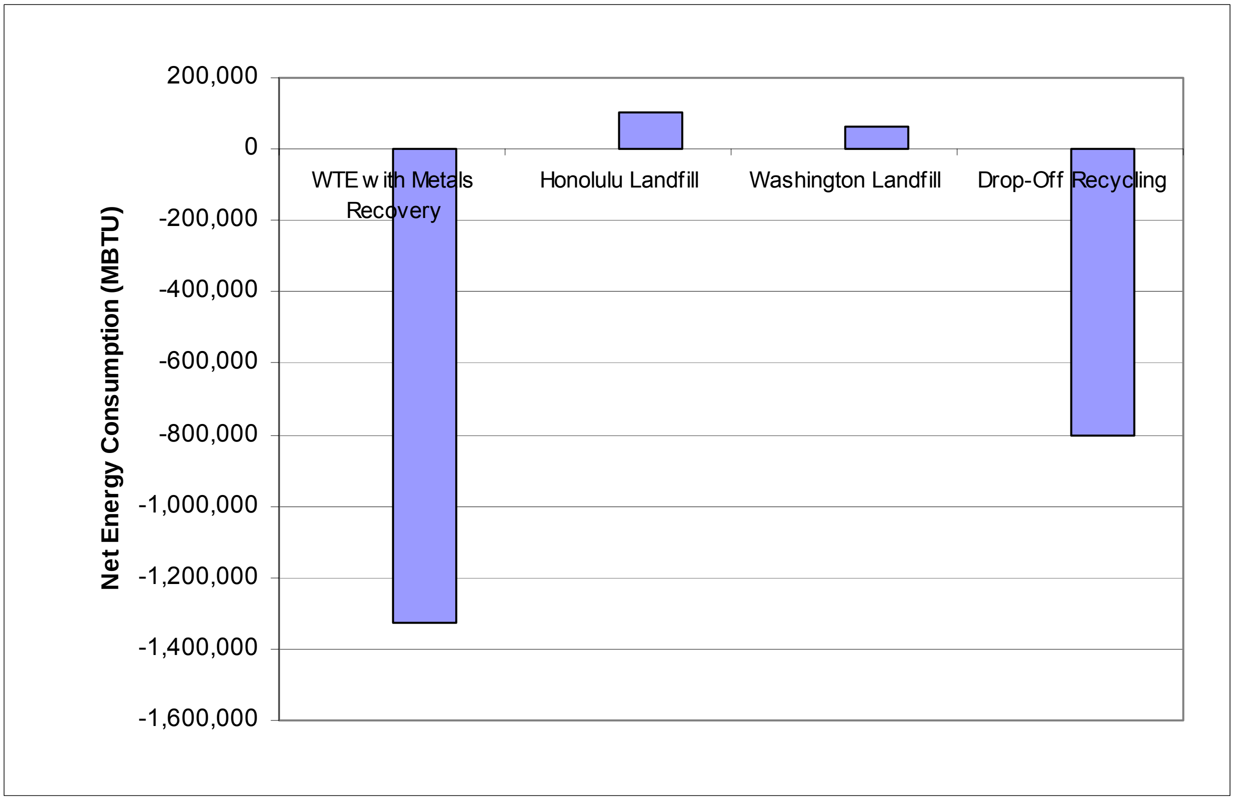



**Figure 6. Net Energy Consumption by Management Alternative Per 120,000 TPY of MSW.**

The net energy savings attributed to the WTE facility expansion and recycling alternatives can be summarized as resulting from the following key aspects:

- Electrical energy produced by the WTE process offsets electrical energy produced in the utility sector.
- Ferrous and nonferrous metals recovery from the WTE process (in which these metals are shipped for recycling) offsets the extraction of virgin resources and the production of virgin materials.

The recovery and recycling of materials by recycling drop-off centers in Honolulu offsets the extraction of virgin resources and the production of virgin materials.

### Criteria Pollutants

Figure 7 illustrates the results of the different management alternatives with respect to emissions of criteria air pollutants, including particulate matter (PM), sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), carbon monoxide (CO), and lead. Because criteria pollutants are highly correlated to energy production, we would expect the differences in criteria pollutants to generally track with the differences in net energy between the alternatives.

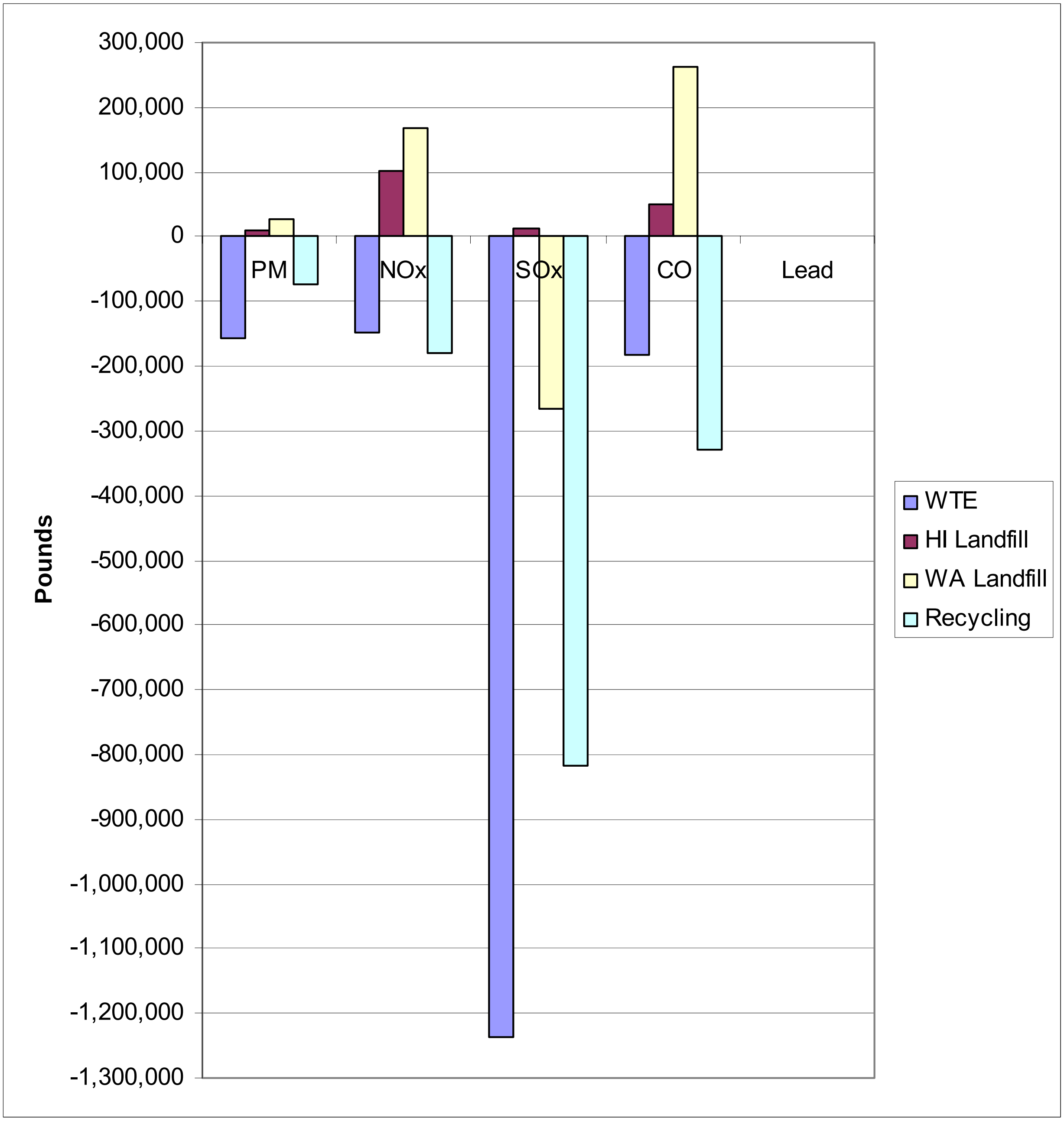



**Figure 7. Net Pounds of Criteria Air Emissions by Management Alternative Per 120,000 TPY of MSW.**

***Particulate Emissions***

Particulate matter, or PM, is the term for particles found in the air, including dust, dirt, soot, smoke, and liquid droplets. Particles can be suspended in the air for long periods of time. They come from a variety of sources and, in the case of waste management and this study, result largely from fuels combustion in vehicles, combustion of waste, and combustion of fuels for the production of electrical energy. PM is a major source of haze that reduces visibility, can cause erosion of structures, and can lead to health effects associated with lung and heart disease.

As shown in Figure 7, the WTE facility expansion and recycling alternatives result in the lowest levels of particulate emissions, while the landfill alternatives result in higher levels. Both the WTE facility expansion and recycling alternative result in net particulate offsets, which means they avoid more particulate emissions than they create by virtue of energy and materials recovery. The WTE alternative generates over twice the particulate offset as the recycling scenario.

***Nitrogen Oxide Emissions***

NOx emissions can lead to such environmental impacts as smog production, acid deposition, and decreased visibility. NOx emissions are largely the result of fuel combustion processes. Likewise, NOx emission offsets can result from the displacement of combustion activities, mainly fuels and electrical energy production.

Figure 7 illustrates that NOx emissions follow a similar pattern as the particulate emissions. The WTE facility expansion and recycling alternatives result in net offsets of NOx, and the landfill alternatives are net NOx producers. For NOx, the recycling alternative appears to be slightly better than the WTE facility expansion alternative, likely because of the NOx that is produced by the combustion process.

***Sulfur Oxide Emissions***

$SO_x$ emissions can lead to such environmental impacts as acid deposition, corrosion, and decreased visibility. Similar to $NO_x$ emissions, $SO_x$ emissions are largely the result of fuel combustion processes. Likewise, $SO_x$ emission offsets can result from the displacement of combustion activities, mainly fuels and electrical energy production, as well as the use of lower sulfur-containing fuels.

Figure 7 shows that the WTE facility expansion and recycling alternatives result in large $SO_x$ offsets (savings). The Washington State landfill alternative, which has a landfill gas-to-energy system, also creates a significant $SO_x$ offset. These offsets largely are the result of the displacement of fossil fuel electrical energy generation in the utility sector, which produces significant levels of $SO_x$. The local landfill alternative is a net $SO_x$ producer because it does not have any energy or materials recovery component. Instead fossil fuels are combusted in vehicles and equipment, leading to $SO_x$ emissions.

***Carbon Monoxide Emissions***

CO is a colorless, odorless gas that is formed when carbon in fuel is not burned completely. It is a component of motor vehicle exhaust, which contributes about 56% of all CO emissions nationwide. Other sources of CO emissions include industrial processes (such as metals processing and chemical manufacturing) and power production. CO contributes to the formation of smog, which can trigger serious respiratory problems.

Figure 7 illustrates that CO follows the same trend as seen with particulate and $NO_x$ emissions; that is, the WTE facility expansion and recycling alternatives generate net CO offsets and the landfill alternatives are net CO producers.

### *Lead Emissions*

The major sources of lead emissions have historically been motor vehicles (such as cars and trucks) and industrial sources. Due to the phaseout of leaded gasoline, metals processing is the major source of lead emissions to the air today. The highest levels of lead in air are generally found near lead smelters. Other stationary sources are waste incinerators, utilities, and lead-acid battery manufacturers. People, animals, and fish are mainly exposed to lead by breathing and ingesting it in food, water, soil, or dust. Lead accumulates in the blood, bones, muscles, and fat, leading to a variety of health effects. Infants and young children are especially sensitive to even low levels of lead.

Lead emissions from each scenario are negligible (these emissions are not shown in Figure 7, but can be seen in Table 2). As shown in Table 2, lead emissions for the WTE facility expansion, recycling, and Washington State landfill alternatives are all negative, constituting a net lead offset. As with the other criteria pollutants, this offset is due to the displacement of electrical energy production by virtue of energy and materials recovery. The local landfill alternative has no (or likely very small) lead emissions..

### Carbon Emissions

Carbon emissions contribute to the greenhouse effect; thus, these emissions can lead to climate change and its associated impacts. Carbon emissions can result from the combustion of fossil fuels and the biodegradation of organic materials (e.g., methane gas from landfills). Offsets of carbon emissions can result from the displacement of fossil fuels, materials recycling, and the diversion of organic wastes from landfills. We report carbon emissions in units of MTCE, derived as follows:

$$\mathbf{[(Fossil\ CO_2*1 + CH_4*21)*12/44] / 2200}$$

As shown in Figure 8, the WTE facility expansion alternative is the only alternative that results in a net offset of carbon emissions. This offset is directly related to the following aspects:

- Electrical energy production offsets carbon emissions from the generation of electrical energy using fossil fuels in the utility sector.
- Metals recovery and recycling offsets carbon emissions by avoiding the consumption of electrical energy generated by fossil fuels.
- Landfill disposal, which creates methane gas, a potent GHG, is avoided.

The local (Honolulu) landfill and recycling alternatives exhibit the highest level of carbon emissions. This is a direct result of the Honolulu landfill’s not having a gas-collection and gas-flaring or energy-recovery system. In the Honolulu landfill alternative, all of the waste is going to the landfill. In the recycling alternative, 69% of the waste is going to the Honolulu landfill. The Washington State landfill alternative shows considerably lower levels of carbon emissions due to its gas-collection and energy-recovery system.

The gas-collection system for the Washington State landfill was assumed to have had a gas-collection system efficiency of 75% (i.e., 25% of the gas generated vented to the atmosphere). Without gas

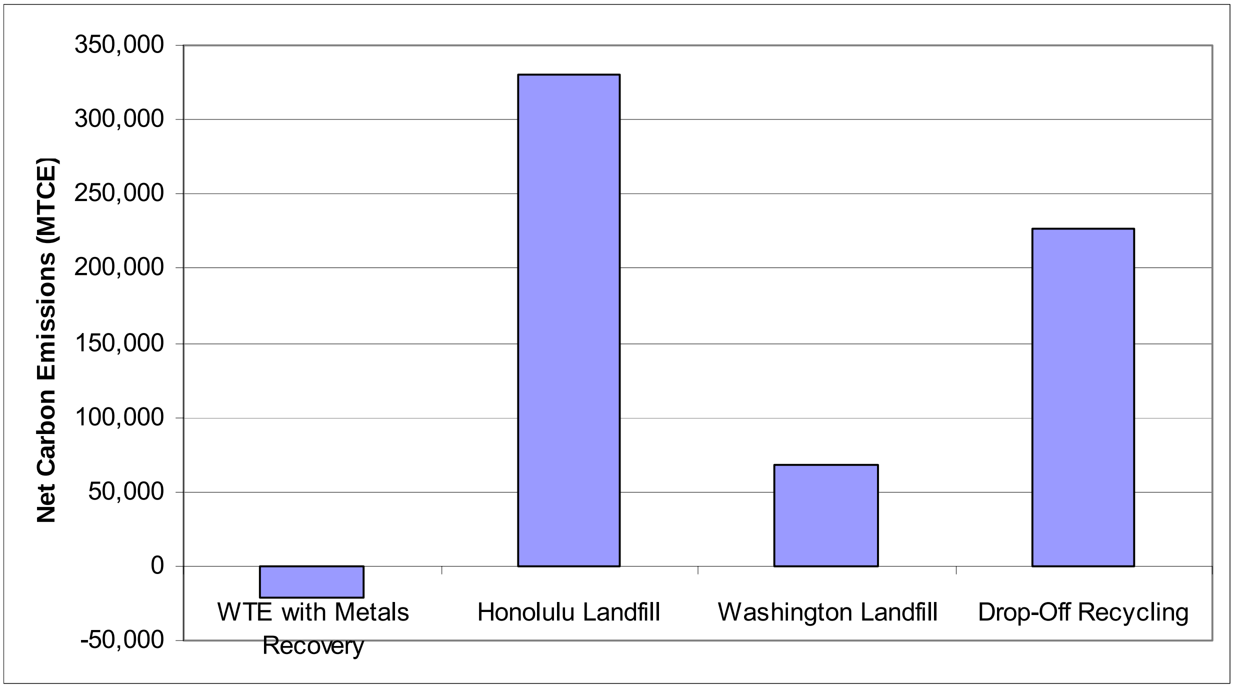



**Figure 8. Net Carbon Emissions by Management Alternative Per 120,000 TPY of MSW.**

collection and energy recovery, the Washington State landfill alternative would produce similar levels of carbon emissions as shown for the Honolulu landfill alternative.

**Summary of the Incremental Analysis Findings**

The incremental analysis was useful for identifying the impacts of the individual waste management alternatives. As compared to the comprehensive analysis, the results of the incremental analysis showed discernible differences between the alternatives. The WTE facility expansion option provides a significant advantage relative to net energy production and lower environmental impacts. The advantage of WTE facility expansion is directly related to offsets associated with its electrical energy production and metals recovery for recycling. In addition, this option avoids a significant amount of waste disposal in landfills and their associated impacts. The landfill alternatives show the worst energy and environmental performance. The local landfill alternative was particularly bad for carbon emissions. Although recycling creates significant offsets of energy and environmental impacts by displacing the use of virgin materials, the benefits of the recycling alternative are somewhat negated by the burdens associated with the considerable amount of non-recoverable waste disposed of in the local landfill.

## 5.3 Analysis of Bioreactor Landfills for Managing Municipal Solid Waste in the State of Minnesota

In recent years, bioreactor landfills have gained prominence as an emerging technology in the management of municipal solid waste (MSW). A bioreactor landfill is one that is designed to rapidly transform and degrade organic waste through the addition of liquid and air to enhance microbial processes. Bioreactor technology differs from the conventional "dry tomb" landfill technology primarily through this addition of extra liquid and relies on maintaining optimal moisture content near field capacity (approximately 35 to 65%). The desired effect of the bioreactor is that it produces landfill gas (LFG) at an earlier stage in the landfill's life and at a higher rate as compared to a conventional landfill.

Bioreactor landfills are being studied by the State of Minnesota to better understand their environmental significance as compared to more traditional MSW management options and technologies. RTI International (RTI) is pleased to provide support to the State of Minnesota Pollution Control Agency to assist in the analysis of bioreactor landfills. The goal of this analysis is to better understand the range of potential environmental burdens and tradeoffs of using bioreactor versus conventional landfill technologies as well as alternatives for managing organic wastes. The results of this analysis will be used to inform a Legislative Group working on developing state policy on Solid Waste Issues.

The study was performed using RTI's in-house MSW DST that was developed in cooperation with the U.S. EPA, Office of Research and Development and RTI. The MSW DST computer model has been developed with an emphasis on objectivity and scientific credibility and has undergone extensive stakeholder input and peer review, as well as a separate EPA peer review.

The methods used in the MSW DST to calculate the energy and environmental results are built on the principles of Life Cycle Assessment (LCA). LCA is a type of systems analysis that accounts for the complete set of upstream and downstream (cradle-to-grave) energy and environmental aspects associated with industrial systems. The technique examines the inputs and outputs from every stage of the life cycle from the extraction of raw materials, through manufacturing, distribution, use/reuse, and waste management. In the context of integrated waste management systems, an LCA tracks the energy and environmental aspects associated with all stages of waste management from waste collection, transfer, materials recovery, treatment, and final disposal. For each of the waste management operations, energy and material inputs and emissions and energy/material outputs are calculated (see Figure 1). In addition, the energy and emissions associated with fuels, electrical energy, and material inputs are captured. Likewise, the potential benefits associated with energy and/or materials recovery displacing energy and/or materials production from virgin resources are captured.

Taking a life-cycle perspective encourages waste planners to consider the environmental aspects of the entire system including activities that occur outside of the traditional framework of activities from the point of waste collection to final disposal. For example, when evaluating options for recycling, it is important to consider the net environmental

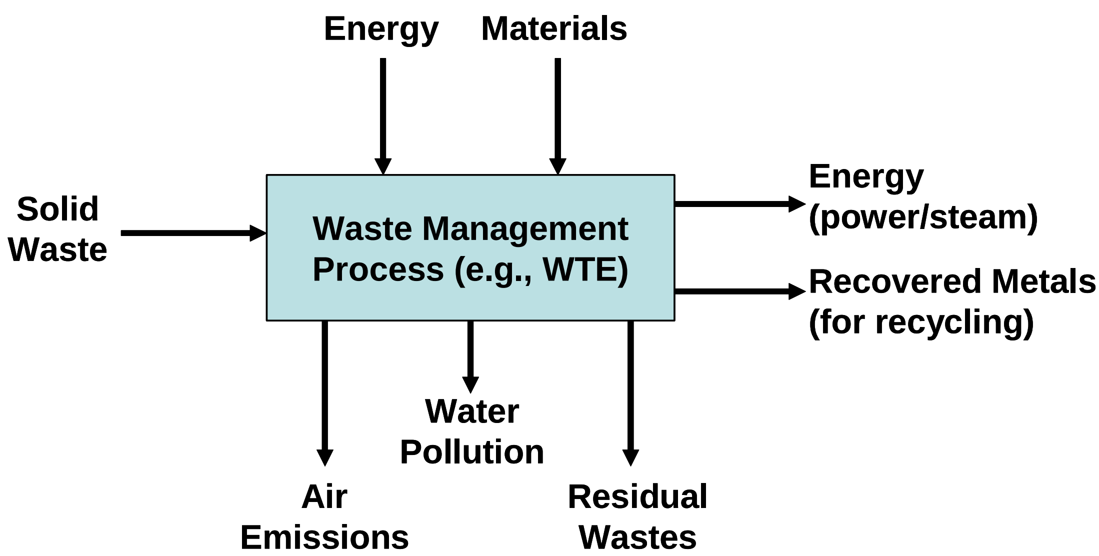



**Figure 1. Life Cycle Inputs and Outputs of a Waste Management Process.**
All waste management processes that comprise an integrated waste management system consume energy and materials and produce emissions. Some processes, such as WTE, recover energy and materials. The benefits associated with any energy or materials recovered are captured in the life cycle study.

benefits (or additional burdens) including any potential displacement of raw materials or energy. Similarly, when electricity is recovered through the combustion of waste or landfill gas, the production of fuels and generation of electricity from the utility sector is displaced.

In this study, our system is an integrated waste management system is looking at the State of Minnesota's MSW stream. The two main waste management options included in the analysis are the bioreactor and conventional landfill disposal. The analysis of these options includes waste collection, management, and transportation and management of recovered materials and residuals. The analysis took into account all of the upstream and downstream impacts and benefits associated with the management of 1,370,082 tons per year of MSW. As illustrated in Figure 1, each of these activities consumes energy and materials, and creates air and water emissions. Some waste management activities also recover energy and materials (e.g., recyclable metals). The benefits associated with the recovery of energy and materials are captured in this study. For example, when energy is recovered through LFG-to-energy, the generation of electricity from the utility sector is displaced. The benefit associated with the displaced production of that electricity from the utility sector is captured in the landfill results.

Similarly, when a material (e.g., steel) is recovered from an operation (e.g., recycling), the emissions associated with the production and use of virgin materials are avoided and accounted for in the life cycle results. In this analysis, no processes that recover materials will be analyzed. However, composting of organics will be analyzed however it is difficult to determine what exactly would be displaced by using compost product and how much. Therefore no offset was included for the compost product.

**Project Goals**

The overall goal of this analysis is to quantify and analyze the cost, energy consumption, and environmental releases associated with the management of MSW using bioreactor versus conventional landfill technologies as well as alternatives for managing organic wastes. The results of this analysis will be used to inform a Legislative Group working on developing state policy on Solid Waste Issues.

**Waste Management Scenarios Analyzed**

To meet the goals of this project, the following alternative MSW strategies were analyzed and compared:

1) Collection of mixed MSW, transfer and disposal in a conventional landfill.
2) Collection of mixed MSW, transfer and disposal in a bioreactor landfill.
3) Separate collection of organics and residual MSW, transfer, composting of organics and disposal of residuals in a conventional landfill.

LFG management specifications were split between venting, flaring, and energy recovery to simulate current practices in Minnesota. Table 1 lists the mass flow and LFG management assumptions associated with each of the scenarios.

**Table 1. Overall Mass Flow and Landfill Gas Management of Scenarios Analyzed.**

| Scenario | Annual Tonnage Managed (tons) | | | | |
|---|---|---|---|---|---|
| | Compost | Landfill with Gas Venting | Landfill with Gas Flaring | Landfill with Gas-to-Energy | Bioreactor with Gas-to-Energy |
| **1** | 0 | 438,426 | 150,709 | 780,947 | 0 |
| **2** | 0 | 438,426 | 150,709 | 0 | 780,947 |
| **3** | 9,213 | 435,478 | 149,696 | 775,695 | 0 |

The following basic conditions were applied to all four scenarios evaluated:

- 1,370,082 tons of MSW per year is managed in each scenario based on data from the Minnesota Office of Environmental Assistance (2004).
- Waste composition is based on data developed for the State of Minnesota (RW Beck, 2000)
- 100-year time frame was used for estimating landfill emissions.

- For landfill energy recovery, it was assumed to offset base loaded coal-fired electrical energy production.

The analysis was conducted using RTI's MSW DST. As mentioned above, this tool was developed through a cooperative research agreement between RTI and the U.S. EPA and has undergone stakeholder, peer, and EPA review.

Additional details and a summary of key assumptions employed in the analysis of the scenarios are included in Table 2.

**Table 2. Summary of Key Assumptions Used in This Study.**

| **Parameter** | **Assumption** |
|---|---|
| *General* | |
| Waste Generation disposed in MN | 1,370,082 tons/year |
| Waste Composition | MN Statewide Average (see Table 3) |
| Waste Collection Frequency | 1 time per week |
| | |
| *Transportation Distances* | |
| Collection to Transfer Station | 30miles one way |
| Transfer to Bioreactor Landfill | 30 miles one way |
| Transfer to Conventional Landfill | 30 miles one way |
| Collection to Composting | 30 miles one way |
| | |
| *Conventional Landfill* | |
| Basic Design | Conventional Subtitle D |
| Time Period for Calculating Emissions | 100 years |
| Landfill Gas Collection Efficiency | 60% |
| Landfill Gas Management | Based on current mix of practices |
| Utility Sector Offset | na |
| | |
| *Bioreactor Landfill* | |
| Basic Design | Bioreactor with leachate recirculation |
| Time Period for Calculating Emissions | 100 years |
| Landfill Gas Collection Efficiency | 90% |
| Landfill Gas Management | Energy recovery using ICE gen-set |
| Utility Sector Offset | Baseload coal-fired power |
| | |
| *Organics Composting* | |
| Basic Design | Windrow |
| Compost Residence Time | 168 days |
| Compost Turning Frequency | 5000 lb/week |
| Compost Curing Residence Time | 90 days |

**Table 3. Statewide Average Waste Composition.**

| Constituent | Percent by Mass* |
|---|---|
| Yard Waste | 12.2 |
| Food Waste | 12.4 |
| Paper and Cardboard | 28.9 |
| Plastics | 12.0 |
| Metals | 5.0 |
| Glass | 2.7 |
| Misc Wastes | 26.7 |

*values may not sum to 100 due to rounding.

## Results

The summary level results for each scenario analyzed are shown in Table 4. These results are presented as net totals for the entire mass (1,370,082 tons) of waste managed in each scenario. In Table 5, results are presented on a per ton basis. Note that a positive value in Table 4 and/or 5 represents a net burden (cost, energy consumption, or emission) whereas a negative value represents a net savings or avoidance (revenue, energy savings, emissions avoidance). For example, the negative value for MTCE means that the operation or system offsets (or avoids) more carbon emissions than it produces by virtue of energy or materials recovery.

It should be noted that for scenario 3 that includes organics composting, there is no product (e.g., fertilizer) that the compost product is assumed to displace because it is difficult to determine what exactly the compost product displaces, if anything. If the compost product can be shown to reduce the consumption of another product, then there would be an added environmental benefit to the compost scenario (scenario 3). In this study, any environmental savings/benefits not captured are likely to be insignificant due to the small amount of composting assumed (less than 1 percent of the MSW stream).

### Cost

As shown in Table 4a and Figure 2a, the net annual cost for the scenarios range from $88-90 million per year, or $64-65 on a per ton basis (see Table 4b and Figure 2b). This is only about a 1-2 percent difference and not considered significant. The lack of a significant difference in cost is due to the scenarios analyzed being very similar. In all scenarios, almost half of the total waste is managed in landfills with gas venting or gas flaring. The key difference between the scenarios is that a bioreactor landfill is used in scenario 2, whereas a conventional landfill with LFG-to-energy recovery is used in scenarios 1 and 3. In scenario 3, organics composting is also added but at a relatively insignificant amount compared to the amount landfilled. Scenario 2 shows the lowest annual cost due to the increase in LFG-to-energy recovery as compared to scenarios 1 and 3. Revenue from the sale of electricity (in all scenarios) is netted out of the total cost.

### Energy Consumption

As shown in Table 4a and Figure 3a, for net annual energy consumption scenarios 1 and 3 are very similar at approximately 260,000 MBTU and scenario 2 (bioreactor) shows a net negative energy consumption of approximately -114,000 MBTU, a difference of 374,000 MBTU. On a per ton basis (see Table 4b and Figure 3b), the difference between scenarios 1 and 3, and 2 is approximately 273,000 BTU. To provide context, an average U.S. household consumes approximately 105,000,000 BTU per year. The negative value for scenario 2 means that the total energy recovered from the bioreactor LFG-to-energy system is greater than the total energy required to manage the waste from collection through disposal and thus results in a net energy savings.

It is important to note that the LFG collection efficiency for the bioreactor landfill was assumed to be 90 percent and 60 percent for the conventional landfill. If higher LFG collection efficiency was used for the conventional landfill, the difference between scenarios 1, 3 and 2 would be smaller. However, since bioreactors are designed to promote gas production for energy recovery they will likely outperform conventional landfills on an energy basis if designed and operated efficiently.

In Attachment A, a sensitivity analysis on gas collection efficiency for conventional and bioreactor landfills was performed. For conventional landfills a low, medium, and high LFG collection efficiency of 60, 70, and 80 percent was used, respectively. For bioreactor landfills, 80, 85, and 90 percent LFG collection efficiency was used. As illustrated in the Attachment, and as one would expect, an increase in the LFG collection efficiency increases the amount of energy that can be generated at both the conventional and bioreactor landfill. For the conventional landfill, an incremental 10 percent increase in the LFG collection efficiency resulted in a corresponding 129,000 MBTU decrease in total net energy consumption. For the bioreactor landfill, an incremental 5 percent increase in the LFG collection efficiency resulted in 62,000 MBTU decrease in total net energy consumption.

### Environmental Releases

The results for all environmental releases reported by the MSW DST are shown in Table 4a for an annual basis and in Table 4b on a per ton basis. Additional releases are tracked for different operations (e.g., dioxin for waste combustion) but not reported since comparable data is not available for all operations. Figures 4a and 4b illustrate the results for criteria air pollutants and Figures 5a and 5b illustrate the results for greenhouse gas emissions.

For criteria pollutants, the life cycle environmental results comparing the conventional to bioreactor are mixed. For total particulate matter (PM) and carbon monoxide (CO), the convention landfill performs better. For nitrogen oxides (NOx) and sulfur oxides (SOx), the bioreactor landfill performs better. Scenarios 1 and 3 are virtually identical. Again this is due to the scenarios being identical except for a small fraction of the organic waste being managed via composting. The key difference between scenarios 1, 3 and scenario 2 is that in 1 and 3, conventional landfill designs are assumed whereas in scenario 2, a large portion of the waste is managed via a bioreactor landfill. Although the bioreactor landfill produces and collects more gas that in turn is used to produce more electricity than a conventional landfill, it also has increased fuel and material needs for the enhanced leachate recirculation system.

For PM and CO, it appears that the life cycle burdens associated with the increased fuel and materials needs outweigh the benefit of increased gas recovery and energy production. However, for NOx and SOx, the opposite appears. Thus there appears to be a tradeoff between the benefits of increased LFG recovery and electricity production and the burdens associated with the construction and operation of the enhanced leachate collection and recirculation system required for a bioreactor.

For lead air emissions, there does not appear to be a significant difference in the results between the scenarios.

For greenhouse gas emissions, the MSW DST calculates a net total carbon equivalent value (in units of metric tons of carbon equivalent) as follows:

$$\mathbf{[(Fossil\ CO_2*1 + CH_4*23)*12/44] / 2200}$$

As shown in Tables 4a and 4b and Figures 5a and 5b, scenario 2 produces about 30 percent less carbon emissions. This is a direct result of the bioreactor having a higher gas collection efficiency that the conventional landfills as well as the associated increase in electricity production and offsets to the utility sector. If higher gas collection efficiency was used for the conventional landfill in scenarios 1 and 3, the net results would be much closer.

**Table 4a. Summary-Level Annual Net Total Results by Scenario.**

| Parameter | Units | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| | | | | |
| **Cost** | $US | 90,065,260 | 88,166,772 | 89,834,659 |
| | | | | |
| **Energy Consumption** | MBTU | 259,333 | -113,758 | 260,363 |
| | | | | |
| **Air Emissions** | | | | |
| Total Particulate Matter | lb | -40,925 | 350,561 | -40,461 |
| Nitrogen Oxides | lb | 852,051 | 790,881 | 852,035 |
| Sulfur Oxides | lb | -896,425 | -1,347,110 | -889,788 |
| Carbon Monoxide | lb | 1,629,066 | 1,865,964 | 1,619,562 |
| Carbon Dioxide Biomass | lb | 952,449,153 | 918,200,914 | 946,044,581 |
| Carbon Dioxide Fossil | lb | -106,478,039 | -168,961,083 | -105,570,945 |
| Carbon Equivalents | MTCE | 140,343 | 96,504 | 139,426 |
| Hydrocarbons (non CH4) | lb | 123,362 | 161,998 | 123,633 |
| Lead | lb | -6 | -9 | -6 |
| Ammonia | lb | -610 | -872 | -606 |
| Methane | lb | 54,079,224 | 41,745,570 | 53,715,651 |
| Hydrochloric Acid | lb | 13,028 | 13,776 | 12,941 |
| | | | | |
| **Ancillary Solid Waste** | lb | -21,706,919 | -35,637,048 | -21,558,510 |
| | | | | |
| **Water Releases** | | | | |
| Dissolved Solids | lb | -230,112 | -345,960 | -227,954 |
| Suspended Solids | lb | -91,985 | -138,042 | -91,352 |
| BOD | lb | 691,155 | 298,749 | 686,510 |
| COD | lb | 1,920,675 | 826,704 | 1,907,774 |
| Oil | lb | 227,026 | 435,331 | 225,514 |
| Sulfuric Acid | lb | -1,272 | -1,903 | -1,263 |
| Iron | lb | -6,843 | -10,265 | -6,796 |
| Ammonia | lb | 22,081 | 9,612 | 21,933 |
| Copper | lb | 0 | 0 | 0 |
| Cadmium | lb | -11 | -17 | -11 |
| Arsenic | lb | 0 | 0 | 0 |
| Mercury | lb | 0 | 0 | 0 |
| Phosphate | lb | -494 | -890 | -490 |
| Selenium | lb | 0 | 0 | 0 |
| Chromium | lb | -10 | -16 | -10 |
| Lead | lb | 0 | 0 | 0 |
| Zinc | lb | -3 | -5 | -3 |

**Table 4b. Summary-Level Net Per Ton Results by Scenario.**

| Parameter | Units | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| | | | | |
| **Cost** | $US | 65.74 | 64.35 | 65.57 |
| | | | | |
| **Energy Consumption** | MBTU | 0.19 | -0.08 | 0.19 |
| | | | | |
| **Air Emissions** | | | | |
| Total Particulate Matter | lb | -0.03 | 0.26 | -0.03 |
| Nitrogen Oxides | lb | 0.62 | 0.58 | 0.62 |
| Sulfur Oxides | lb | -0.65 | -0.98 | -0.65 |
| Carbon Monoxide | lb | 1.19 | 1.36 | 1.18 |
| Carbon Dioxide Biomass | lb | 695.18 | 670.18 | 690.50 |
| Carbon Dioxide Fossil | lb | -77.72 | -123.32 | -77.05 |
| Carbon Equivalents | MTCE | 0.10 | 0.07 | 0.10 |
| Hydrocarbons (non CH4) | lb | 0.09 | 0.12 | 0.09 |
| Lead | lb | 0.00 | 0.00 | 0.00 |
| Ammonia | lb | 0.00 | 0.00 | 0.00 |
| Methane | lb | 39.47 | 30.47 | 39.21 |
| Hydrochloric Acid | lb | 0.01 | 0.01 | 0.01 |
| | | | | |
| **Ancillary Solid Waste** | lb | -15.84 | -26.01 | -15.74 |
| | | | | |
| **Water Releases** | | | | |
| Dissolved Solids | lb | -0.17 | -0.25 | -0.17 |
| Suspended Solids | lb | -0.07 | -0.10 | -0.07 |
| BOD | lb | 0.50 | 0.22 | 0.50 |
| COD | lb | 1.40 | 0.60 | 1.39 |
| Oil | lb | 0.17 | 0.32 | 0.16 |
| Sulfuric Acid | lb | 0.00 | 0.00 | 0.00 |
| Iron | lb | 0.00 | -0.01 | 0.00 |
| Ammonia | lb | 0.02 | 0.01 | 0.02 |
| Copper | lb | 0.00 | 0.00 | 0.00 |
| Cadmium | lb | 0.00 | 0.00 | 0.00 |
| Arsenic | lb | 0.00 | 0.00 | 0.00 |
| Mercury | lb | 0.00 | 0.00 | 0.00 |
| Phosphate | lb | 0.00 | 0.00 | 0.00 |
| Selenium | lb | 0.00 | 0.00 | 0.00 |
| Chromium | lb | 0.00 | 0.00 | 0.00 |
| Lead | lb | 0.00 | 0.00 | 0.00 |
| Zinc | lb | 0.00 | 0.00 | 0.00 |

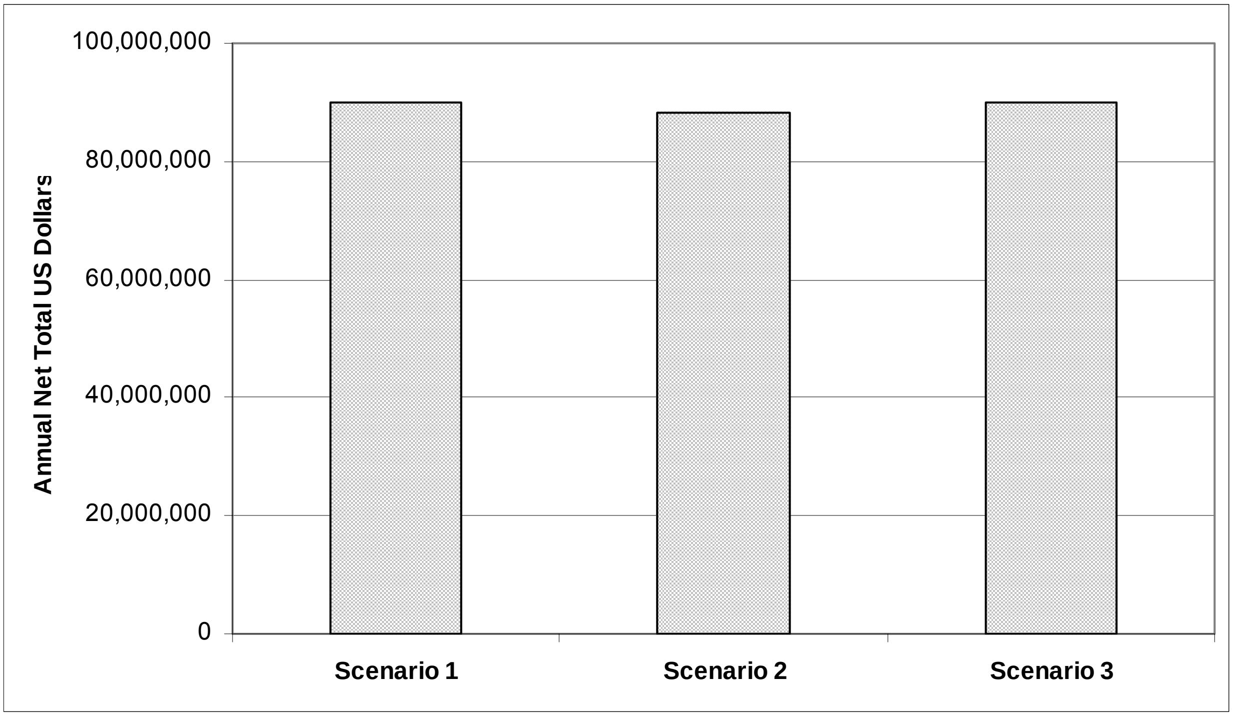



**Figure 2a. Annual Net Total Cost by Scenario.**

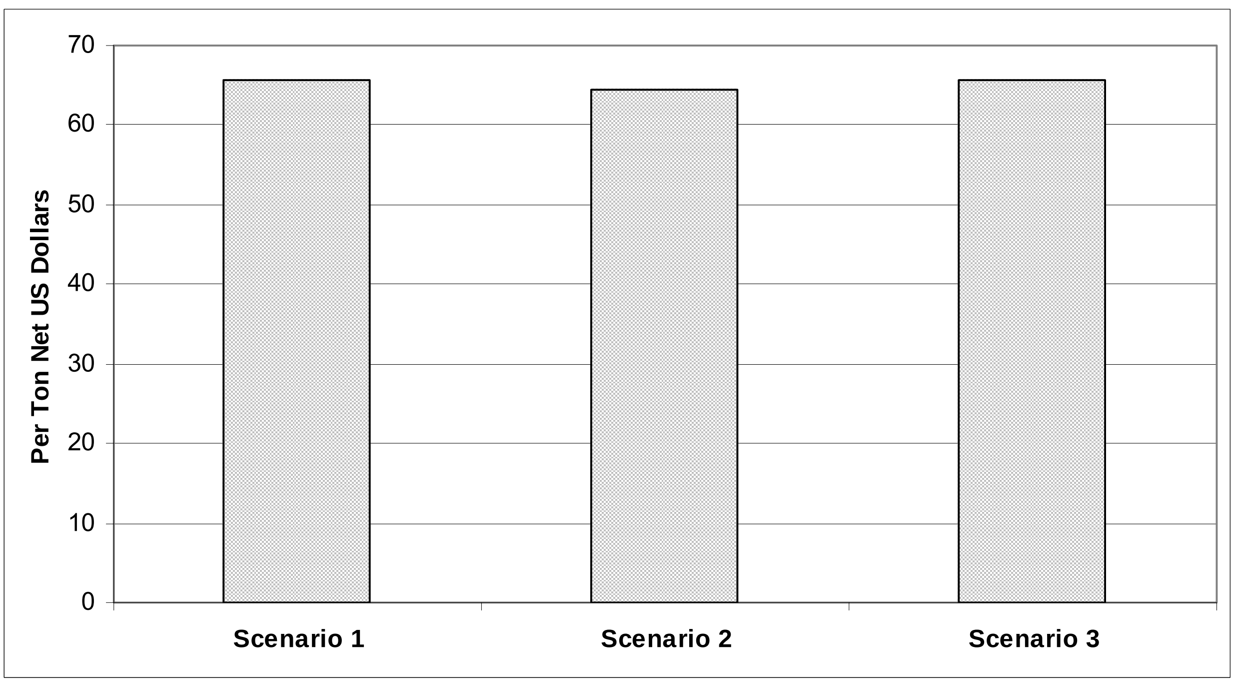



**Figure 2b. Net Per Ton Cost by Scenario.**

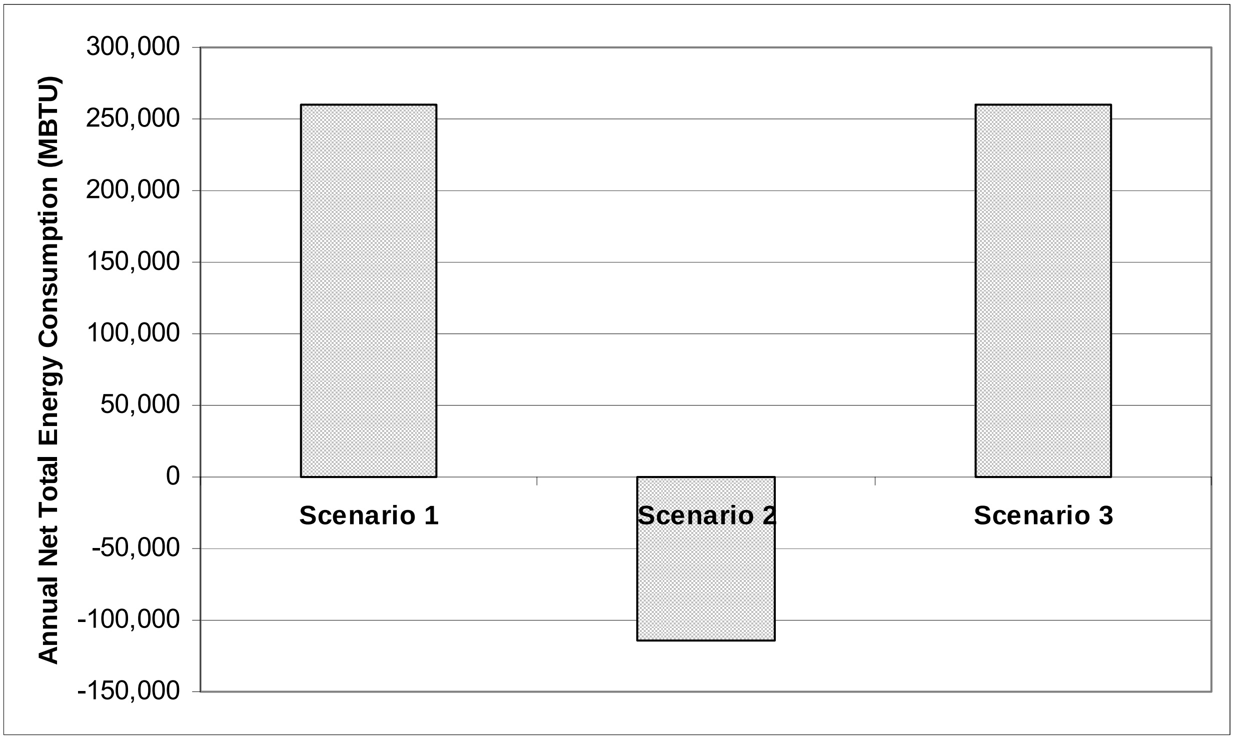



**Figure 3a. Annual Net Total Energy Consumption by Scenario.**

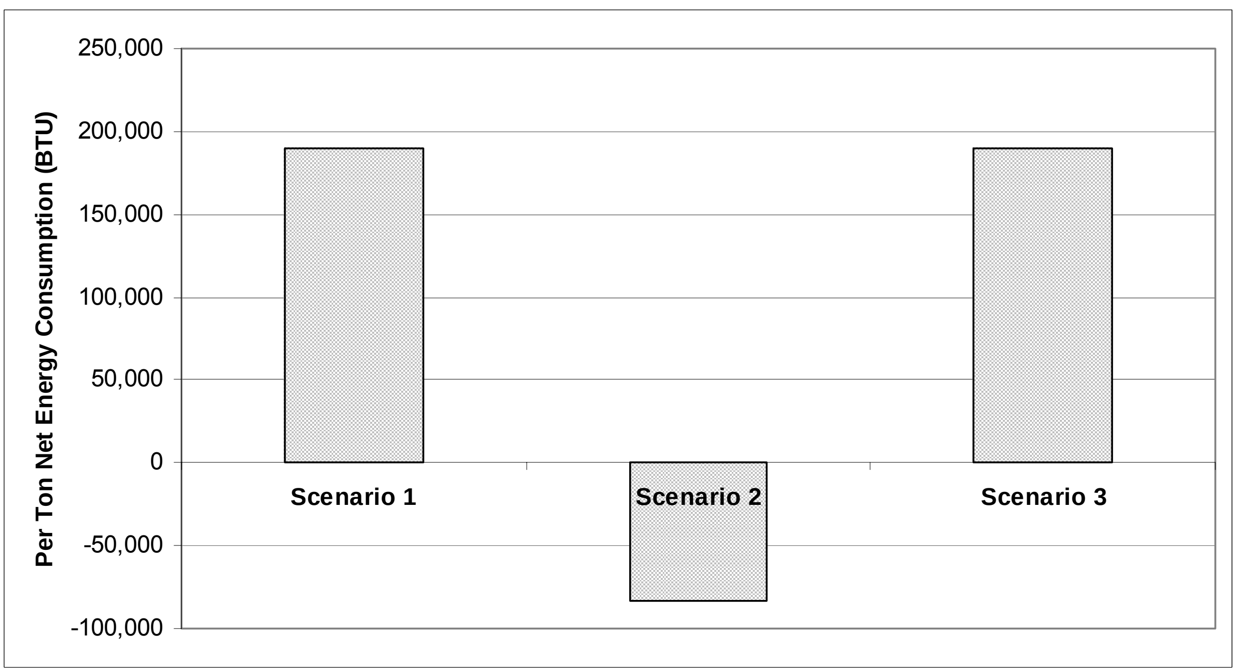



**Figure 3b. Net Per Ton Energy Consumption by Scenario.**

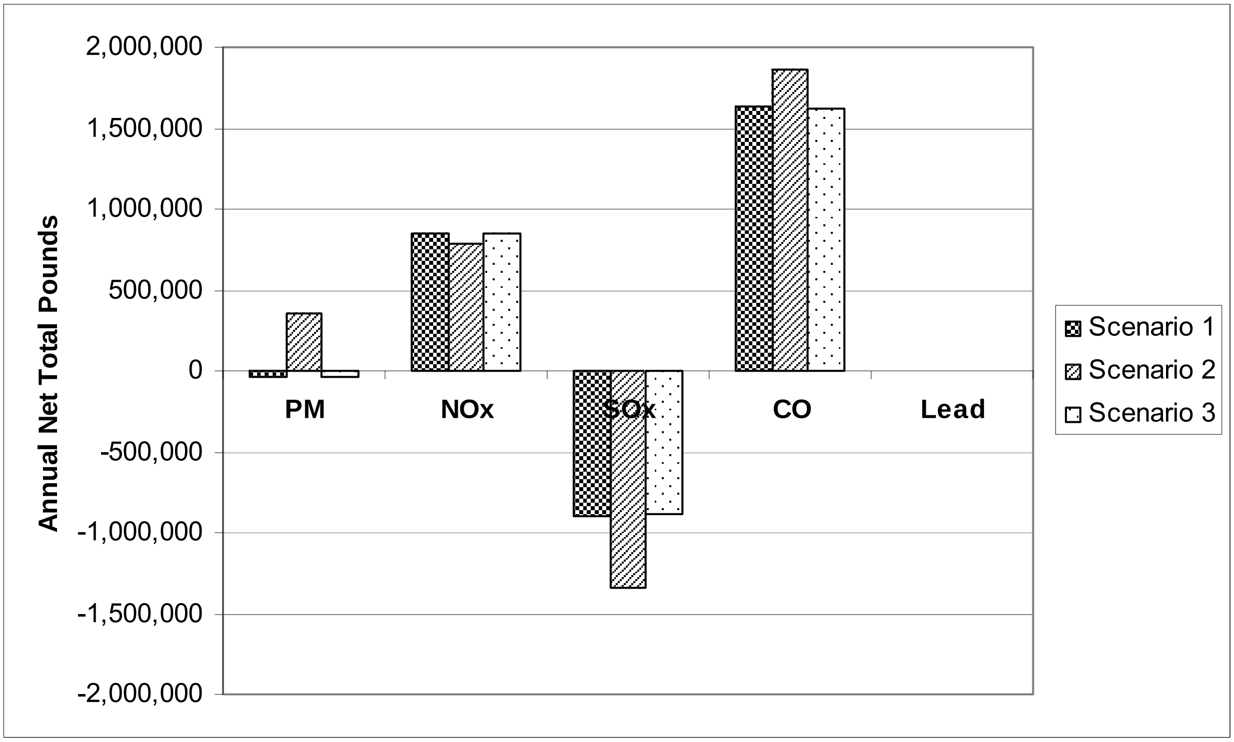



**Figure 4a. Annual Net Total Criteria Air Pollutants by Scenario.**

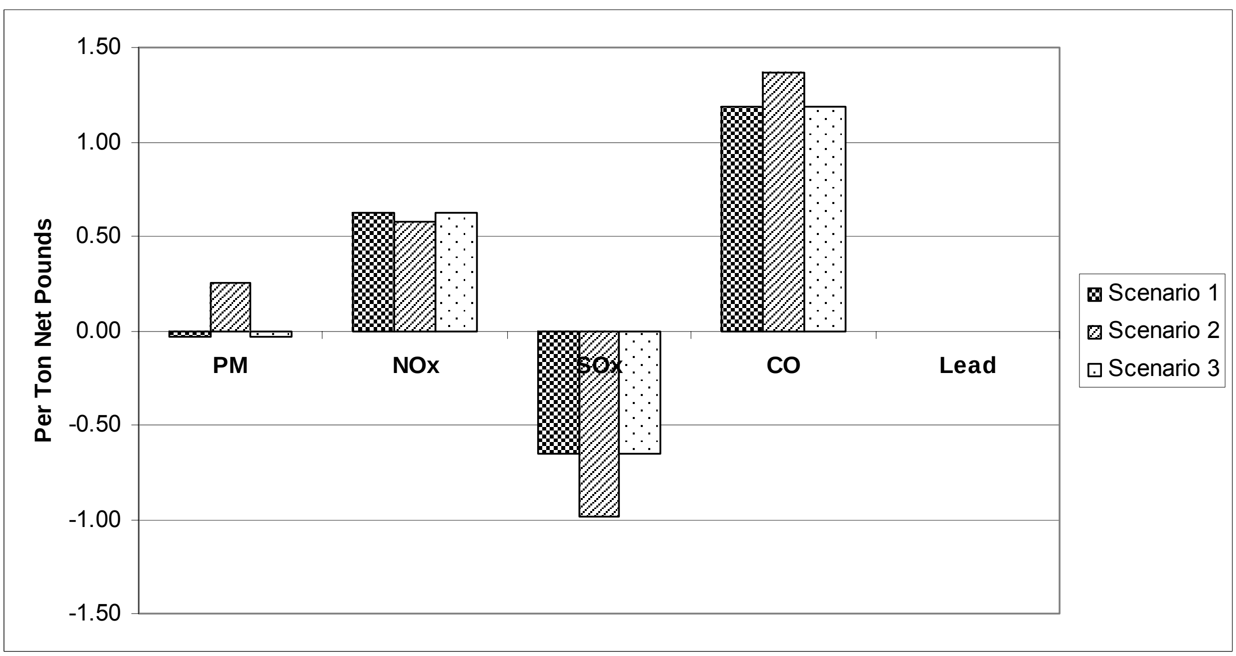



**Figure 4b. Net Per Ton Criteria Air Pollutants by Scenario.**

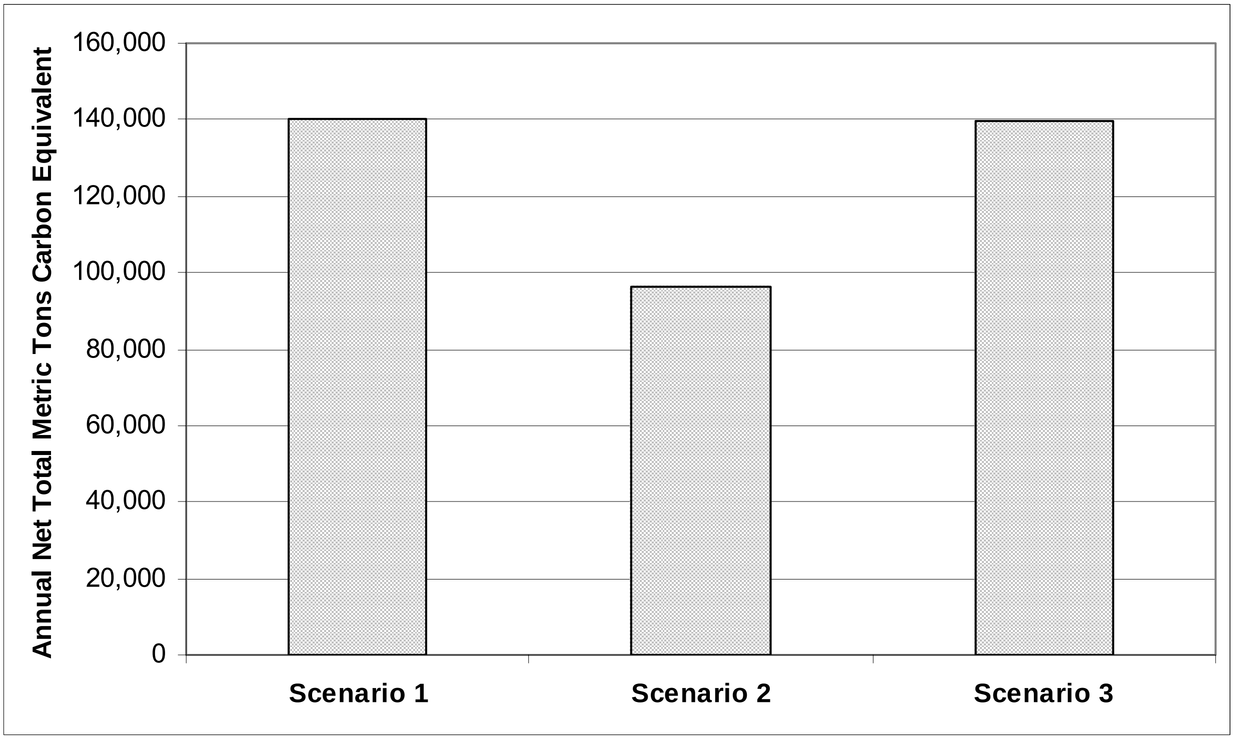



**Figure 5a. Annual Net Total Greenhouse Gas Emissions by Scenario.**

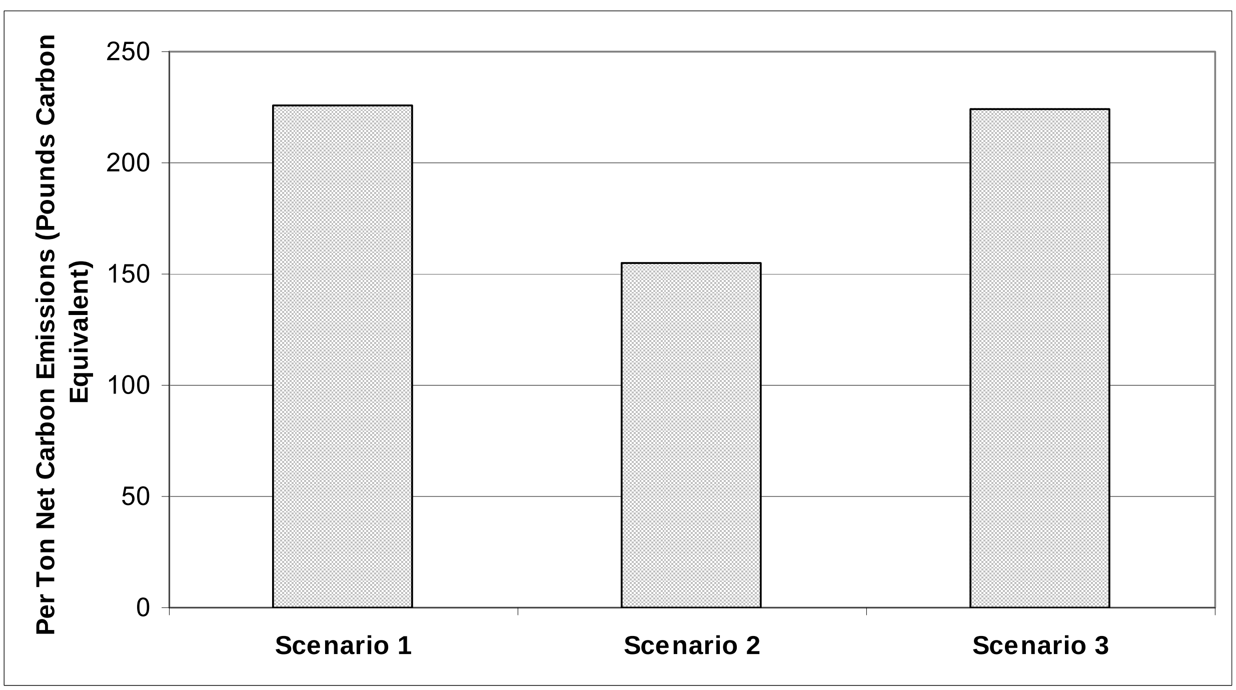



**Figure 5b. Net Per Ton Greenhouse Gas Emissions by Scenario.**

## 5.4 Greenhouse Gas Emission Reductions Associated With The Edmonton Compost Facility

The City of Edmonton sought to obtain accreditation for GHG emission reductions associated with the use of the Edmonton Compost Facility (ECF) as compared to the alternative of landfill disposal. Nodelcorp contracted with RTI to analyze the GHG emissions and emission reductions for the ECF and landfill waste management options on a life cycle basis. The study was performed using RTI's in-house MSW DST that was developed in cooperation with the U.S. EPA, Office of Research and Development and RTI. The MSW DST computer model has been developed with an emphasis on objectivity and scientific credibility and has undergone extensive stakeholder input and peer review, as well as a separate EPA peer review.

The methods used in the MSW DST to calculate the energy and environmental results are built on the principles of Life Cycle Assessment (LCA). LCA is a type of systems analysis that accounts for the complete set of upstream and downstream (cradle-to-grave) energy and environmental aspects associated with industrial systems. The technique examines the inputs and outputs from every stage of the life cycle from the extraction of raw materials, through manufacturing, distribution, use/reuse, and waste management. In the context of integrated waste management systems, an LCA tracks the energy and environmental aspects associated with all stages of waste management from waste collection, transfer, materials recovery, treatment, and final disposal. For each of the waste management operations, energy and material inputs and emissions and energy/material outputs are calculated (see Figure A-1). In addition, the energy and emissions associated with fuels, electrical energy, and material inputs are captured. Likewise, the potential benefits associated with energy and/or materials recovery displacing energy and/or materials production from virgin resources are captured.

Taking a life-cycle perspective encourages waste planners to consider the environmental aspects of the entire system including activities that occur outside of the traditional framework of activities from the point of waste collection to final disposal. For example, when evaluating options for recycling, it is important to consider the net environmental benefits (or additional burdens) including any potential displacement of raw materials or energy. Similarly, when electricity is recovered through the combustion of waste or landfill gas, the production of fuels and generation of electricity from the utility sector is displaced.

In this study, our system is an integrated waste management system is looking only at the portion of the management system that deals with the City of Edmonton's MSW stream. The two main waste management options included in the analysis are the ECF and landfill disposal. The analysis of these options includes waste collection, management, and transportation and management of recovered materials and residuals. The analysis took into account all of the upstream and downstream impacts and benefits associated with the management the following amounts of MSW:

- 2002: 167,202 tonnes
- 2003: 141,884 tonnes
- 2004: 147,341 tonnes

As illustrated in Figure A-1, each waste management activity consumes energy and materials, and creates air and water emissions. Some waste management activities also recover energy and materials. The benefits associated with the recovery of energy and materials are captured in this study. For example, when energy is recovered through landfill gas-to-energy, the generation of electricity from the utility sector is displaced. The benefit associated with the displaced production of that electricity from the utility sector is captured in the landfill results. Similarly, when a material (e.g., metal) is recovered from the ECF, energy and emissions associated with the extraction and processing of virgin materials are avoided. The avoided energy and emissions are accounted for in the life cycle results.

The focus of this study is on quantifying GHG emissions and emissions reductions from waste management activities. GHG emissions contribute to the greenhouse effect; thus, these emissions can lead to climate change and its associated impacts. GHG emissions can result from the combustion of fossil fuels and the biodegradation of organic materials (for example, methane gas from landfills). Offsets of GHG emissions can result from the displacement of fossil fuels, materials recycling, and the diversion of organic wastes from landfills. In this report, we present GHG emissions as carbon emissions in units of tonnes $CO_2$-e, derived as follows:

$$\textbf{Tonnes } \mathbf{CO_2}\textbf{-e = (lb Fossil CO2*1 + lb CH4*21) / 2200}$$

For methane, a CO2-e of 21 was used. The latest version of the IPCC guidance now uses 23 as the CO2-e for methane but Canadian protocols still rely on the 21 weighting value.

**Project Goals**

The overall goal of this study is to quantify and analyze GHG emissions and emission reductions associated with the use of the ECF versus landfill disposal to manage a portion the City of Edmonton’s MSW stream.

The results of this analysis are intended for use in the verification of GHG emission offsets by a third-party verifier. The data and results generated through this project can be used as a generic assessment of the potential tradeoffs in GHG emissions associated with composting and landfill disposal options for MSW. An analysis of other facilities or regions may produce different results than the results obtained for the ECF.

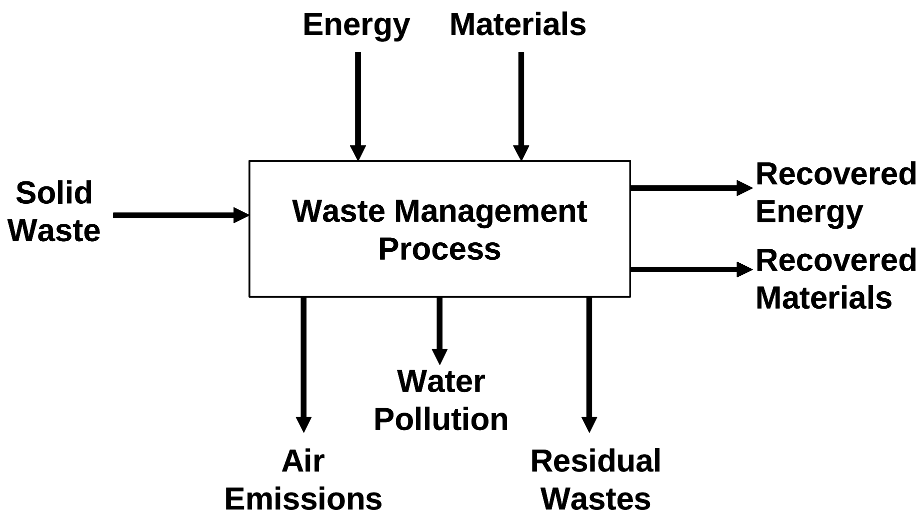



**Figure A-1. Life Cycle Inputs and Outputs of a Waste Management Process.**
All waste management processes that comprise an integrated waste management system consume energy and materials and produce emissions. Some processes, such as WTE, recover energy and materials. The benefits associated with any energy or materials recovered are captured in the life cycle study.

**Waste Management Scenarios Analyzed**

To meet the goals of this project, the following alternative compost and landfill disposal strategies were analyzed and compared:

1) Disposal at CBLF with gas collection and flare.
2) Disposal at WELF with gas venting.
3) 36.5 / 63.5 percent disposal split between CBLF and WELF.
4) ECF with recovery of materials and landfill disposal of residuals at CBLF and WELF.

Landfill gas management specifications were varied in each scenario to better understand the impact of landfill gas management on GHG emissions. Table A-1 lists the mass flow and associated with each of these four scenarios.

**Table A-1. Overall Mass Flow of Scenarios Analyzed.**

| Scenario | Annual Tonnes Managed | | |
|---|---|---|---|
| | **ECF** | **CBLF** | **WELF** |
| | | | |
| ***2002*** | | | |
| **CB** | 0 | 167,202 | 0 |
| **WE** | 0 | 0 | 167,202 |
| **CB/WE** | 0 | 61,029 | 106,173 |
| **ECF** | 167,202 | 50,602* | 24,133* |
| | | | |
| ***2003*** | | | |
| **CB** | 0 | 141,884 | 0 |
| **WE** | 0 | 0 | 141,884 |
| **CB/WE** | 0 | 51,788 | 90,096 |
| **ECF** | 141,884 | 79,094* | 0* |
| | | | |
| ***2004*** | | | |
| **CB** | 0 | 147,341 | 0 |
| **WE** | 0 | 0 | 147,341 |
| **CB/WE** | 0 | 53,779 | 93,562 |
| **ECF** | 147,341 | 68,534* | 14,187* |

*These amounts represent discards and residuals from the ECF.

The following conditions were applied to all four scenarios evaluated:

- Waste composition is based on 2001 sampling data from the City of Edmonton (Table A-3 of the Waste Management Branch Annual Review 2003).
- Waste collection frequency and distances are constant.
- 100-year time frame was used for estimating landfill GHG emissions.
- Landfill gas quality is set at 53 percent methane based on gas sampling and testing at the CBLF.
- Electrical energy produced at the landfill would offset base loaded natural gas-fired electrical energy production for the years 2002-2005 (because the landfill gas was directly used in the EPCOR natural gas-fired power plant during this time period) and would offset base loaded coal-fired electrical energy generation for the remaining future years based on the use of the new ICE gen-set.

The analysis was conducted using RTI's MSW DST. As mentioned above, this tool was developed through a cooperative research agreement between RTI and the U.S. EPA and has undergone stakeholder, peer, and EPA review. Additional information about the MSW DST is supplied in Attachment 1 and can be obtained from RTI.

Additional details and a summary of key assumptions employed in the analysis of the scenarios are included in Table A-2.

### Landfill (Baseline) Scenario Details

In estimating the $CO_2$-e emissions from the landfill scenarios, we analyzed a range of landfill gas collection and management specifications to understand their impact on $CO_2$-e emissions and ECF-related $CO_2$-e emissions reductions. Landfill scenarios analyzed included one case all of the MSW was disposed in the CBLF where gas is collected and assumed to be used to generate electrical power. We believe this to be a best-case scenario for the CBLF and results in a conservative estimate of $CO_2$-e emission reductions in the analysis of the ECF. One highly sensitive parameter in estimating $CO_2$-e emissions from landfills that collect and control gas is the gas collection efficiency. For this analysis, the scenarios with landfill gas collection and management, a landfill gas collection efficiency of 80 percent was assumed. In addition, based on gas sampling and analysis, a landfill gas quality of 53 percent $CH_4$ was used.

The methodology used for quantifying $CO_2$-e emissions from the landfill uses a 100-year time frame. This means that for the annual amount of MSW disposed, $CO_2$-e emissions during a 100-year time period are calculated and attributed to the annual waste disposed.

For the scenarios that include the collection of landfill gas and utilization for electrical energy production, we include the amount of electrical energy produced and delivered to the electricity grid as an offset to electrical energy produced in the utility sector. For this analysis, it was assumed that the electrical energy produced at the landfill would offset base loaded natural gas-fired electrical energy production for the years 2002-2005 (because the landfill gas was directly used in the EPCOR natural gas-fired power plant during this time period) and would offset base loaded coal-fired electrical energy generation for the remaining future years based on the use of the new ICE gen-set.

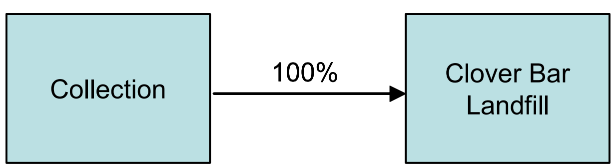



**Figure A-2. Illustration of Scenario 1: Waste Disposal in CBLF.**

**Table A-2. Summary of Key Assumptions Used in This Study.**

| Parameter | Assumption |
|---|---|
| ***General*** | |
| Waste Generation | See Table A-1 |
| Waste Composition | City of Edmonton specific (See Table A-3) |
| Waste Collection Frequency | 1 time per week |
| | |
| ***Transportation Distances*** | |
| Collection to ECF | 10 miles one way |
| Collection to Landfill | 10 miles one way |
| ECF to Landfill | 1 mile one way |
| | |
| ***ECF Facility*** | |
| Basic Design | MSW in-vessel compost |
| Compost Aeration Time | 3 weeks |
| Compost Curing Time | 4-6 months |
| Compost Turning Frequency | 2 times per month |
| | |
| ***Clover Bar Landfill*** | |
| Basic Design | Conventional |
| Time Period for Calculating Emissions | 100 years |
| Landfill Gas Collection Efficiency | 80% |
| Landfill Gas Management | Energy recovery using natural gas turbine from 2002 to 2005 and using ICE Gen-Set for remaining years. |
| Utility Sector Offset | Offset is baseload natural gas (2002-2005) or coal (2006+) power production. |
| | |
| ***West Edmonton Landfill*** | |
| Basic Design | Conventional |
| Time Period for Calculating Emissions | 100 years |
| Landfill Gas Collection Efficiency | 0% (gas is vented) |
| Landfill Gas Management | None (gas is vented) |

**Table A-3. Edmonton Waste Composition.**

| Constituent | Percent by Mass |
|---|---|
| Yard Waste | 29 |
| Food Waste | 23 |
| Paper and Cardboard | 17 |
| Other Organics | 9 |
| Other Wastes | 7 |
| Plastics | 7 |
| Textiles | 3 |
| Metals | 3 |
| Glass | 2 |
| **TOTAL** | **100** |

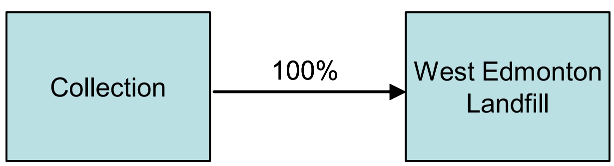



**Figure A-3. Illustration of Scenario 2: Waste Disposal in WELF.**

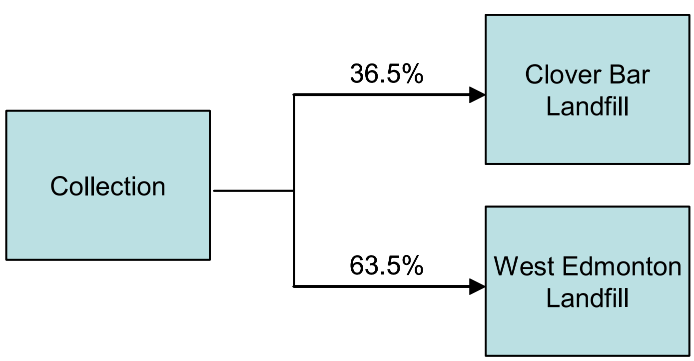



**Figure A-4. Illustration of Scenario 3: 36.5/63.5 Split of Waste Disposal in CBLF and WELF (note: this scenario is used as the baseline landfill scenario in the validation report)**

### ECF Scenario Details

For the ECF scenario, we assumed a mixed MSW compost facility with front-end removal of bulk items and other large non-compostables. The remainder of the MSW is combined with biosolids (primarily to obtain proper moisture content, pH, and carbon/nitrogen ratio) in mixing drums for 1-2 days and then screened and aerated for 3 weeks. In this analysis, only the MSW portion of the compost operation is considered. After aeration, the compost is screened again and placed in windrows for curing for 4-6 months. The final compost product is used primarily as a soil amendment. All discards and residuals from the ECF are assumed to be disposed of in the CBLF.

The detailed ECF mass flow for the years 2002-2004 is shown in Table A-4. As an example, for the year 2004, the ECF received a total of 147,341 tonnes of MSW. Of this amount, 127,307 tonnes was used as input to the composting process to produce 25,871 tonnes of compost product. The remaining materials are discards/residuals/recovered materials.

Because the GHG emissions from the degradation of organic matter are considered carbon-neutral (i.e., part of the short-term carbon cycle and given a $CO_2$-e of zero) the main GHG emissions associated with the ECF come from the consumption of electrical energy and fossil fuels for ECF equipment (e.g., shredders, mixers, aerators, windrow turner).

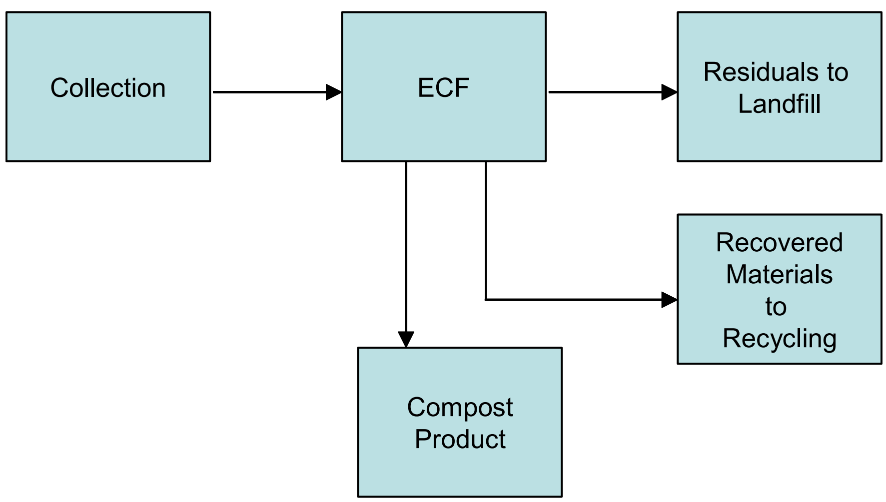



**Figure A-5. Illustration of Scenario 4: Actual ECF Operation (note: this scenario is used as the actual ECF scenario in the validation report).**

**Table A-4. ECF Mass Flow Details (tonnes).**

| Stream | 2002 | 2003 | 2004 |
|---|---|---|---|
| | | | |
| **Total MSW Received at the ECF** | **167,202** | **141,884** | **147,341** |
| | | | |
| Discards | 1,750 | 8,961 | 18,905 |
| Recovered Materials | 1,120 | 1,412 | 1,129 |
| **Total MSW Input into ECF** | **164,332** | **131,511** | **127,307** |
| | | | |
| ECF Primary Residuals to CBLF | 19,790 | 34,368 | 20,311 |
| ECF Primary Residuals to WELF | 15,426 | 0 | 12,458 |
| ECF Secondary Residuals to CBLF | 28,384 | 35,606 | 28,162 |
| ECF Secondary Residuals to WELF | 0 | 0 | 19 |
| ECF Curing Residuals to CBLF | 678 | 159 | 1,156 |
| ECF Curing Residuals to WELF | 8,707 | 0 | 1,710 |
| **Total Discards and Residuals to CBLF** | **50,602** | **79,094** | **68,534** |
| **Total Discards and Residuals to WELF** | **24,133** | **0** | **14,187** |
| | | | |
| **Total Recovered Materials** | **1,120** | **1,412** | **1,129** |
| | | | |
| **Total ECF Compost Product** | **52,313** | **44,045** | **25,871** |

**Results**

The summary level $CO_2$-e emission results for each scenario analyzed are shown in Table A-5. These results are presented as net total tonnes of $CO_2$-e for each scenario and waste management activity. Therefore, a positive value represents a net $CO_2$-e emission whereas a negative value represents a net carbon emission savings or avoidance. For example, the negative value for $CO_2$-e means that the operation or system offsets (or avoids) more $CO_2$-e emissions than it produces by virtue of energy or materials recovery.

The scenario results in Table A-5 are converted into $CO_2$-e reductions in Table A-6 and have been illustrated in Figure A-6. For example, in 2004 the $CO_2$-e reduction of employing the ECF strategy for managing MSW versus disposal strategies using the CBLF, WELF, or mix of CB and WE landfills are 5,984 tonnes $CO_2$-e, 97,918 tonnes $CO_2$-e, and 64,834 tonnes $CO_2$-e respectively.

As the results illustrate, the management of landfill gas significantly affects the amount of $CO_2$-e reduced. In comparing the $CO_2$-e reduction results for the ECF versus CBLF and ECF versus WELF scenarios, the difference of 91,934 $CO_2$-e (97,918 – 5,984) is a direct result of the gas collection and energy recovery system at the CBLF. At the WELF, gas is vented.

### Key Data Sources

The primary sources of data used in this study are from the City of Edmonton and RTI's in-house MSW DST. Data provided by the City of Edmonton staff was used to tailor specific MSW management activities in RTI's MSW DST to simulate site-specific conditions and constraints. A summary of key data sources by MSW management activity is provided in Table A-7.

**Table A-5. Net Total Tonnes of CO2-e Emissions by Scenario and Activity.**

| Scenario | Net Total Tonnes CO2-e | Collection | ECF | Landfill | Transport | *Remfg |
|---|---|---|---|---|---|---|
| ***2002*** | | | | | | |
| **CB** | **17,634** | **1,469** | | **16,165** | | |
| **WE** | **121,961** | **1,469** | | **120,492** | | |
| **CB/WE** | **85,446** | **1,469** | | **83,978** | | |
| **ECF** | **11,933** | **1,469** | **7,588** | **3,557** | **385** | **-1,066** |
| | | | | | | |
| ***2003*** | | | | | | |
| **CB** | **14,964** | **1,246** | | **13,717** | | |
| **WE** | **103,493** | **1,246** | | **102,247** | | |
| **CB/WE** | **72,508** | **1,246** | | **71,262** | | |
| **ECF** | **7,755** | **1,246** | **6,275** | **1,203** | **375** | **-1,344** |
| | | | | | | |
| ***2004*** | | | | | | |
| **CB** | **15,539** | **1,294** | | **14,245** | | |
| **WE** | **107,474** | **1,294** | | **106,179** | | |
| **CB/WE** | **74,389** | **1,294** | | **73,095** | | |
| **ECF** | **9,555** | **1,294** | **6,325** | **2,680** | **330** | **-1,074** |

*Remfg is the remanufacturing benefit of recovering and recycling materials. The negative value signifies that carbon emissions from the manufacture of secondary (recycled) products are less than the carbon emissions for the production of primary (virgin) products and thus carbon emissions are displaced.

**Table A-6. Tonnes of $CO_2$-e Reduced By Employing The ECF Strategy Versus Various Landfill Disposal Strategies.**

| | ECF vs CBLF | ECF vs WELF | ECF vs CB/WE Split |
|---|---|---|---|
| **2002** | 5,701 | 110,028 | 73,513 |
| **2003** | 7,209 | 95,738 | 64,753 |
| **2004** | 5,984 | 97,918 | 64,834 |

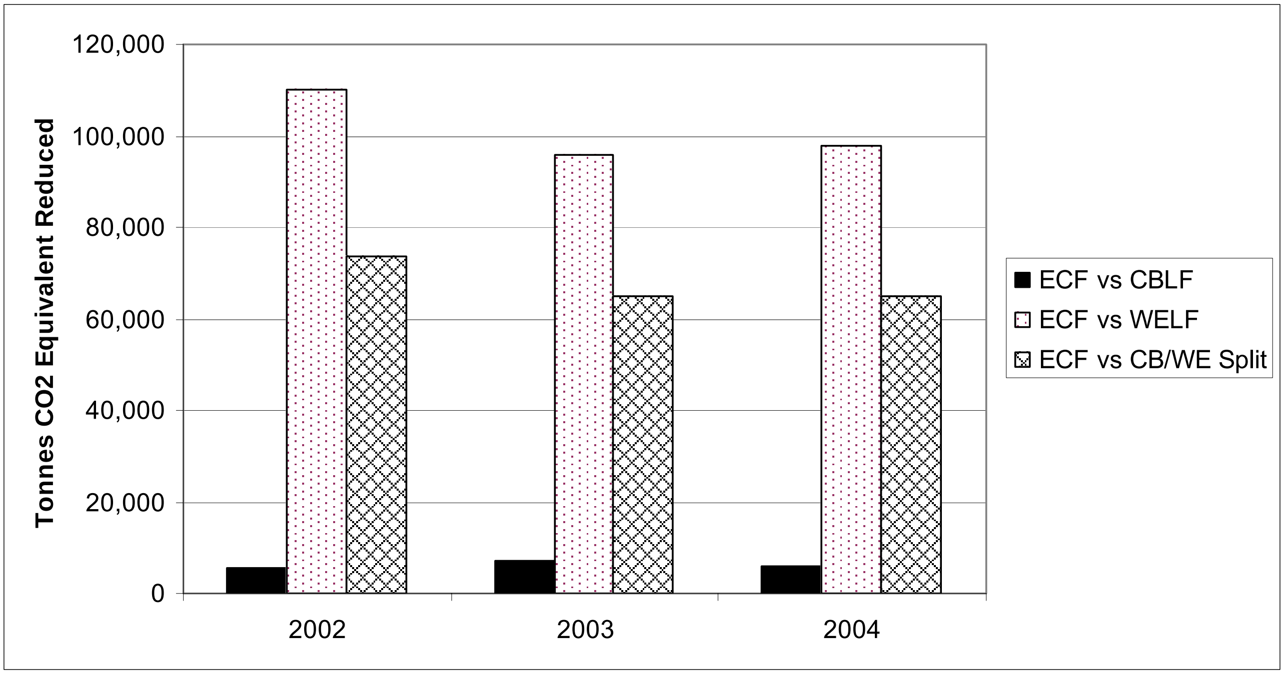



**Figure A-6. Illustration of the Tonnes of CO2-e Reduced By Employing The ECF Strategy Versus Various Landfill Disposal Strategies.**

### Uncertainty and Limitations

The goal of this study was to identify and quantify GHG emission reductions associated with employment of the ECF as compared to baseline landfill disposal. Estimating GHG emissions associated with the ECF was relatively straight-forward since the City of Edmonton was able to provide detailed data about energy consumption for the ECF.

Estimating GHG emissions associated with landfill disposal is more uncertain. Although the quantity and composition of waste disposed is known, and amount of landfill gas collected (where applicable) is measured, determining the exact quantity of landfill gas produced is a relatively uncertain practice. For this study, landfill gas production was calculated using RTI's in-house MSW DST, which relies on the first order decay modeling approach. This model estimates landfill gas production based on the specific quantity and composition of waste materials disposed and their decay properties to ensure that gas production is tied only to the organic fraction.

**Table A-7. Summary of Key Data Sources by Model Activity.**

| Activity | Source | Comments |
|---|---|---|
| Collection | ■ Collect vehicle type and route distance data from City of Edmonton.<br>■ GHG estimates were generated using RTI's MSW DST. | In this analysis, waste collection was identical across all scenarios studied. |
| Compost | ■ Detailed mass flow and operations data from the City of Edmonton<br>■ GHG estimates were generated using RTI's MSW DST. | GHGs from the compost operation are primarily associated with energy consumption. $CO_2$ emissions from the biodegradation of waste were assigned a weighting of zero in the $CO_2$-e calculation. |
| Landfill | ■ Quantity and composition of waste landfilled from the City of Edmonton.<br>■ GHG estimates were generated using RTI's MSW DST. | Landfill gas production and emissions are calculated in the MSW DST using the first-order decay model. |
| Transportation | ■ Haul distance data from City of Edmonton.<br>■ GHG estimates were generated using RTI's MSW DST. | Transportation activity included the haul of ECF residuals and discards to the landfill and haul of recovered materials to manufacturing facilities for recycling. |
| Remanufacturing | ■ Quantity and composition of recovered materials from City of Edmonton.<br>■ GHG savings associated with recycling were generated using RTI's MSW DST. | |
| Energy | ■ ECF energy consumption from Cit of Edmonton. All other energy consumption from RTI's MSW DST.<br>■ GHG emissions associated with the production and consumption of electrical energy and fuels were generated using RTI's MSW DST. | The mix of fuels used to estimate electrical energy related GHG emissions was set at the grid used by Edmonton. Electrical energy offsets (from landfill gas-to-energy) was assumed to include only coal-fired power production. |

## 5.5 Analyzing Waste-to-Energy System Upgrades in Tacoma, WA

The City of Tacoma, Washington was interested in analyzing proposed upgrades to their waste-to-energy system and evaluating the environmental aspects of implementing these upgrades versus disposal of the waste in a landfill. Specifically, Tacoma was interested in comparing the conversion of 75% of their waste stream to refuse-derived fuel (RDF) and then burning the RDF in a waste-to-energy (WTE) facility for energy versus landfill disposal of the waste. The data and results generated through this project can be used to evaluate the cost and life-cycle environmental tradeoffs of the RDF versus disposal options for Tacoma, with the overall goal of identifying waste management strategies that are cost efficient and environmentally protective.

### Objective

The overall goal of this analysis is to identify and characterize the environmental burdens of a proposed RDF/WTE system to the alternative landfill disposal option.

### Method and Results

To develop a baseline model, it is necessary to determine the material flow of MSW throughout the solid waste management system. Tacoma managed a total of 245,186 tons of solid waste in 2003. Of that total, 196,835 were disposed of in a landfill. The remainder was recycled or composted. For this study, we focused on the 196,835 tons of solid waste landfilled and evaluated the alternative of instead using 75% of that amount to produce RDF and generate electricity.

The two scenarios that were analyzed in this study include:

- **Baseline Scenario—**100% of the waste stream disposed in a landfill.
- **Alternative Scenario—**75 % of the waste stream managed by RDF/WTE facilities, with the remaining 25% disposed of in a landfill.

These scenarios are illustrated in Figures 1A and 1B.

For the baseline scenario of landfill disposal, it was assumed that waste is collected and sent to a transfer station where it is compacted and loaded into semi-tractor trailers and long-hauled to a landfill. It was assumed that the landfill collects and flares the landfill gas.

For the alternative scenario of RDF/WTE, it was assumed that 25% of the waste stream (approximately 50,000 tons) is disposed of in a landfill using the same process steps as the baseline scenario. The other 75% of the waste stream (approximately 150,000 tons) was assumed to be collected and sent to an RDF processing plant where it is made into fuel. The fuel (RDF) is then transported to a WTE facility where it is combusted for electricity production. Metals are removed from the RDF processing step and sent for recycling. In regards to the ash produced from the WTE combustion, Tacoma does not landfill most of their ash. Instead, about 90% is typically used as hazardous waste stabilization. For this analysis, we excluded ash disposal. In addition, we excluded any potential benefits created by the use of ash as hazardous waste stabilization. The electrical energy that is produced at the WTE facility is assumed to displace electrical energy that is purchased and/or generated by local/regional utilities. The exact mix of fuels used to product the electrical energy is based on the Western States Coordinating Council grid mix of fuel types. Specific assumptions used in this analysis are listed in Table 1.

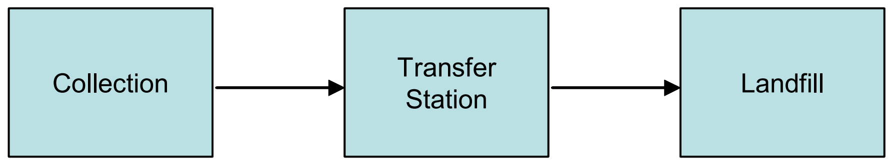



**Figure 1A. Baseline Landfill Disposal Scenario.**

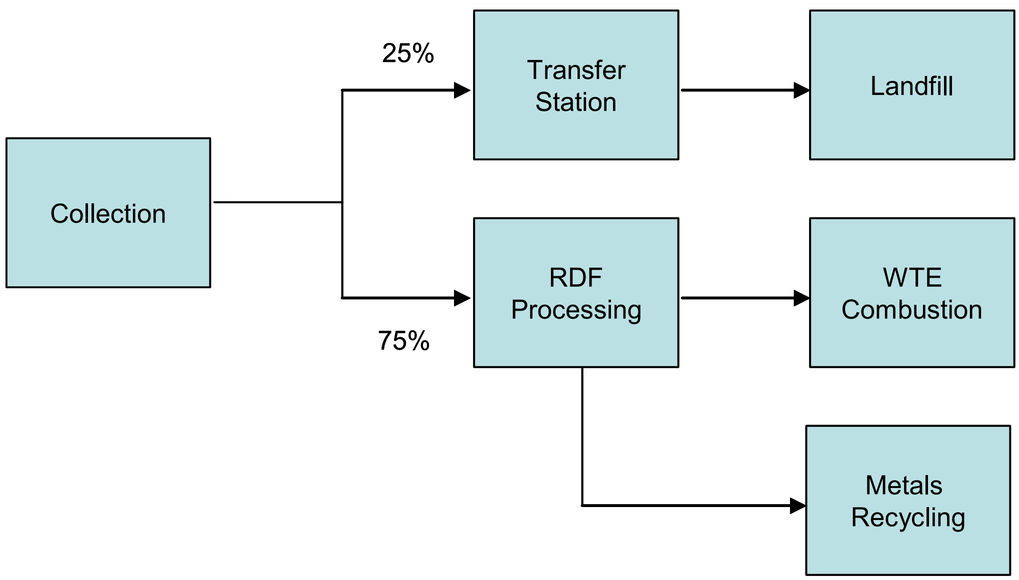



**Figure 1B. Alternative RDF/WTE Scenario.**

**Table 1. Key Assumptions Used in This Analysis.**

| **Parameter** | **Assumption** |
|---|---|
| ***General*** | |
| Waste Generation | 196,835 tons/year |
| Waste Composition | Based on King Country, Washington |
| Waste Collection Frequency | 1 time per week |
| | |
| *Transportation Distances* | |
| Collection to Transfer Station | 5 miles one way |
| Collection to RDF Processing | 5 miles one way |
| Transfer Station to Landfill | 29 miles one way |
| RDF Processing to WTE Combustion | 11 miles one way |
| RDF Processing to Metals Recycling | 500 miles one way |
| | |
| ***RDF/WTE Facility*** | |
| Basic Design | Mass Burn |
| Heat Rate | 18,000 BTU/kWh |
| Waste Input Heating Value | Varies by waste constituent |
| Metals Recovery Rate | 90% |
| Utility Sector Offset | Based on the Western States Coordinating Council grid mix: 41% coal, 30% hydro, 14% gas, 13% nuclear, .5% oil, 1.5% wood. |
| | |
| ***Landfill*** | |
| Basic Design | Subtitle D |
| Time Period for Calculating Emissions | 100 years |
| Landfill Gas Collection Efficiency | 88% |
| Landfill Gas Management | Gas collection and flaring |

## Results

The summary results comparing the baseline and alternative scenarios are shown in Table 2. The detailed results for the baseline and alternative scenarios are shown in Tables 3 and 4, respectively. Negative values in the tables represent a net system avoidance or savings for that particular parameter. For example, the negative value for energy consumption in the alternative scenario means that the scenario generates more energy than it consumes through the combustion of RDF and generation of electrical energy, as well as significant energy offsets created through the recovery and recycling of metals.

**Table 2. Summary Results Comparing the Baseline and Alternative Scenarios.**

| Parameter | Units | Landfill | RDF/WTE |
|---|---|---|---|
| **Energy Consumption** | MBTU | 133,224 | -1,655,531 |
| **Air Emissions** | | | |
| Total Particulate Matter | lb | 23,097 | -144,035 |
| Nitrogen Oxides | lb | 141,999 | -47,788 |
| Sulfur Oxides | lb | 24,815 | -689,762 |
| Carbon Monoxide | lb | 550,762 | 35,749 |
| Carbon Dioxide Biomass | lb | 723,014,521 | 407,473,524 |
| Carbon Dioxide Fossil | lb | 5,052,066 | -61,712,424 |
| Green House Equivalents | MTCE | 107,226 | 16,310 |
| Hydrocarbons (non CH4) | lb | 22,568 | -103,340 |
| Lead | lb | 0 | 7 |
| Ammonia | lb | 5 | -428 |
| Methane | lb | 37,203,573 | 8,634,209 |
| Hydrochloric Acid | lb | 7,003 | 39,439 |
| **Water Emissions** | | | |
| Dissolved Solids | lb | 11,874 | -413,853 |
| Suspended Solids | lb | 824 | -62,791 |
| BOD | lb | 85,331 | 19,893 |
| COD | lb | 237,590 | 50,331 |
| Oil | lb | 32,406 | 475 |
| Sulfuric Acid | lb | 9 | -765 |
| Iron | lb | 43 | -4,537 |
| Ammonia | lb | 2,726 | 56 |
| Copper | lb | 0 | 0 |
| Cadmium | lb | 0 | -18 |
| Arsenic | lb | 0 | 0 |
| Mercury | lb | 0 | 0 |
| Phosphate | lb | 22 | -350 |
| Selenium | lb | 0 | 0 |
| Chromium | lb | 1 | -18 |
| Lead | lb | 0 | 0 |
| Zinc | lb | 0 | -6 |

## Table 3. Detailed Results for the Baseline Landfill Scenario.

| Parameter | Units | Net Total | Collection | Transfer | Disposal | Transport |
|---|---|---|---|---|---|---|
| **Energy Consumption** | MBTU | 133,224 | 36,520 | 2,669 | 88,248 | 5,787 |
| **Air Emissions** | | | | | | |
| Total Particulate Matter | lb | 23,097 | 885 | 1,150 | 19,913 | 1,150 |
| Nitrogen Oxides | lb | 141,999 | 69,136 | 15,110 | 49,767 | 7,986 |
| Sulfur Oxides | lb | 24,815 | 5,987 | 1,788 | 14,773 | 2,266 |
| Carbon Monoxide | lb | 550,762 | 11,397 | 3,790 | 527,702 | 7,873 |
| Carbon Dioxide Biomass | lb | 723,014,521 | 1,407 | 103 | 723,012,788 | 223 |
| Carbon Dioxide Fossil | lb | 5,052,066 | 1,683,786 | 432,960 | 2,004,422 | 930,899 |
| Green House Equivalents | MTCE | 107,226 | 232 | 59 | 106,807 | 127 |
| Hydrocarbons (non CH4) | lb | 22,568 | 12,772 | 1,883 | 4,700 | 3,213 |
| Lead | lb | 0 | 0 | 0 | 0 | 0 |
| Ammonia | lb | 5 | 0 | 1 | 2 | 1 |
| Methane | lb | 37,203,573 | 947 | 82 | 37,202,396 | 148 |
| Hydrochloric Acid | lb | 7,003 | 6 | 1 | 6,995 | 1 |
| **Water Emissions** | | | | | | |
| Dissolved Solids | lb | 11,874 | 8,022 | 580 | 2,001 | 1,272 |
| Suspended Solids | lb | 824 | 187 | 18 | 591 | 29 |
| BOD | lb | 85,331 | 30 | 2 | 85,294 | 5 |
| COD | lb | 237,590 | 201 | 14 | 237,343 | 32 |
| Oil | lb | 32,406 | 187 | 13 | 32,177 | 30 |
| Sulfuric Acid | lb | 9 | 2 | 0 | 7 | 0 |
| Iron | lb | 43 | 5 | 1 | 37 | 1 |
| Ammonia (Water) | lb | 2,726 | 3 | 0 | 2,722 | 1 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 22 | 1 | 0 | 21 | 0 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 |
| Chromium | lb | 1 | 0 | 0 | 0 | 0 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 0 |
| Zinc | lb | 0 | 0 | 0 | 0 | 0 |

## Table 4. Detailed Results for the Alternative RDF/WTE Scenario.

| Parameter | Units | Net Total | Collection | Transfer | RDF | Landfill | Transportation | Remanufacturing |
|---|---|---|---|---|---|---|---|---|
| **Energy Consumption** | MBTU | -1,655,531 | 36,636 | 635 | -663,325 | 21,001 | 4,028 | -1,054,506 |
| **Air Emissions** | | | | | | | | |
| Total Particulate Matter | lb | -144,035 | 887 | 274 | -62,401 | 4,739 | 801 | -88,334 |
| Nitrogen Oxides | lb | -47,788 | 69,306 | 3,596 | -92,121 | 11,844 | 5,559 | -45,971 |
| Sulfur Oxides | lb | -689,762 | 6,006 | 425 | -575,001 | 3,516 | 1,578 | -126,286 |
| Carbon Monoxide | lb | 35,749 | 11,426 | 902 | 88,626 | 125,583 | 5,480 | -196,268 |
| Carbon Dioxide Biomass | lb | 407,473,524 | 1,412 | 24 | 235,409,086 | 172,062,847 | 155 | 0 |
| Carbon Dioxide Fossil | lb | -61,712,424 | 1,688,346 | 103,027 | -40,178,444 | 477,018 | 647,968 | -24,450,338 |
| Green House Equivalents | MTCE | 16,310 | 233 | 14 | -6,024 | 25,418 | 89 | -3,420 |
| Hydrocarbons (non CH4) | lb | -103,340 | 12,780 | 448 | -67,176 | 1,118 | 2,237 | -52,748 |
| Lead | lb | 7 | 0 | 0 | 0 | 0 | 0 | 7 |
| Ammonia | lb | -428 | 0 | 0 | -389 | 1 | 1 | -41 |
| Methane | lb | 8,634,209 | 950 | 20 | -190,423 | 8,853,373 | 103 | -29,814 |
| Hydrochloric Acid | lb | 39,439 | 6 | 0 | 40,139 | 1,665 | 1 | -2,372 |
| **Water Emissions** | | | | | | | | |
| Dissolved Solids | lb | -413,853 | 8,047 | 138 | -358,647 | 476 | 886 | -64,752 |
| Suspended Solids | lb | -62,791 | 187 | 4 | -55,036 | 141 | 20 | -8,108 |
| BOD | lb | 19,893 | 30 | 1 | -350 | 20,299 | 3 | -91 |
| COD | lb | 50,331 | 201 | 3 | -5,010 | 56,485 | 22 | -1,371 |
| Oil | lb | 475 | 187 | 3 | -6,282 | 7,657 | 21 | -1,111 |
| Sulfuric Acid | lb | -765 | 2 | 0 | -698 | 2 | 0 | -70 |
| Iron | lb | -4,537 | 5 | 0 | -4,181 | 9 | 0 | -370 |
| Ammonia | lb | 56 | 3 | 0 | -42 | 648 | 0 | -554 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | -18 | 0 | 0 | -16 | 0 | 0 | -3 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mercury | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | -350 | 1 | 0 | -349 | 5 | 0 | -7 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Chromium | lb | -18 | 0 | 0 | -16 | 0 | 0 | -3 |
| Lead | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Zinc | lb | -6 | 0 | 0 | -6 | 0 | 0 | -1 |

## Interpretation of Results

The results of this analysis indicate that the proposed RDF/WTE strategy outperforms (on a lifecycle environmental basis) the baseline landfill scenario in all categories. This is largely due to two aspects of the RDF/WTE scenario:

- **Energy recovery:** the combustion of RDF and recovery of electrical energy offsets electrical energy produced by local utilities. The calculation for the environmental benefit of the electrical energy offset includes both the environmental burdens that would otherwise be produced at the local utilities plus burdens associated with fossil fuel extraction and processing.
- **Materials recovery:** the additional recovery and recycling of metals from the RDF processing step generates significant environmental benefits by offsetting the extraction and processing of virgin resources.

If the landfill design in the baseline scenario was such that landfill gas was collected and utilized for energy recovery, there would also be an energy recovery benefit for the landfill (baseline) scenario. This would make the landfill scenario look better than the current results with gas flaring. However, it is unlikely that a landfill with energy recovery system will outperform the RDF/WTE scenario because waste-to-energy conversion efficiencies are generally much lower for landfills as compared to combustion type systems.

It is interesting to note that the benefit associated with the additional materials recovery and recycling (see remanufacturing column) is larger than the net benefit associated with the RDF/WTE process. However, the remanufacturing column only represents the difference between metals production using virgin versus recycling resources and does not include the materials separation step. The separation step in this case is actually part of the RDF processing step.

Another key point to consider is that the results represent net total life cycle burdens on a global scale. That is, there is no differentiation between environmental burdens/benefits that occur locally versus globally. This means that the benefits (energy and materials recovery) associated with the alternative RDF/WTE scenario may or may not translate into reductions of environmental burdens for Tacoma, and is dependent on where the utilities and materials production facilities are located.

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# Attachment 1

# November 1997 Peer Review Report

# Attachment 2

# November 1999 Peer Review Report

# Attachment 3

# May 2000 Peer Review Report