EPA
United States
Environmental Protection
Agency

EPA 600/R-15/232 | November 2015 | www.epa.gov/ord

A Comparative Analysis of Life-Cycle Assessment Tools for End-of-Life Materials Management Systems

EPA/600/R-15/232
November 2015

EPA/600/R-15/232
November 2015

A Comparative Analysis of Life-Cycle Assessment Tools for End-of-Life Materials Management Systems

Remediation and Redevelopment Branch
Land Remediation and Pollution Control Division
National Risk Management Research Laboratory
Office of Research and Development
Cincinnati, OH

Foreword

The US Environmental Protection Agency (US EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, US EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by US EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

Executive Summary

The approaches that communities use for providing solid waste collection and management services have a significant impact on their economy, environment, and the health and well-being of their residents. The US EPA recognizes a need for tools that can be used by decision makers to characterize the interaction among social, economic, and environmental impacts associated with the solid wastes typically managed by communities, including municipal solid waste (MSW) and construction and demolition debris (CDD) (US EPA, 2012a). This report evaluates multiple tools that can be used to assess sustainability of the end-of-life (EOL) phase management of these materials.

We identified and evaluated five life-cycle assessment tools that community decision makers can use to assess the environmental and economic impacts of EOL materials management options. The tools evaluated in this report are WARM, MSW-DST, SWOLF, EASETECH, and WRATE. WARM, MSW-DST, and SWOLF were developed for US-specific materials management strategies, while WRATE and EASETECH were developed for European-specific conditions. WARM and MSW-DST are available for free. There is an annual subscription fee for WRATE. EASTECH is offered free to trained users; there is a €5,000 training cost for commercial users. All of the tools (with the exception of WARM) allow specification of a wide variety of parameters (e.g., materials composition and energy mix) to a varying degree, thus allowing users to model specific EOL materials management methods even outside the geographical domain they are originally intended for. The flexibility to accept user-specified input for a large number of parameters increases the level of complexity and the skill set needed for using these tools.

The tools were evaluated and compared based on a series of criteria, including general tool features, the scope of the analysis (e.g., materials and processes included), and the impact categories analyzed (e.g., climate change, acidification). A series of scenarios representing materials management problems currently relevant to communities across the US was simulated to illustrate LCA applications from a decision maker's perspective and to identify issues with tool use. An attempt was made to apply the same parameters across the tools to provide the most meaningful comparison of results; however, input values could not be specified the same across all these tools because of variations such as materials classification and nomenclature, management options included (e.g., single-stream MRF), and user-specifiable parameters (e.g., decay rate constant, residual from MRFs) among tools. For example, plastics in the simulated materials stream were categorized as "hard plastic," "soft plastic," or "drink bottles" in EASETECH while other of the tools allowed simulation of plastics by resin types similar to how EOL plastics are tracked for the MSW stream in the US.

While all of the tools evaluated can assess the environmental impact of common materials management processes such as collection and transport, recovery and recycling, composting (of biodegradable organics), combustion for energy recovery, and disposal in a landfill, only WRATE can be used to assess the impacts of emerging materials management technologies (e.g., pyrolysis). The life-cycle inventories (LCIs) of several of these processes are based on data primarily available at the time of tool development. While all of the tools include MSW materials, most CDD materials are not included (with the exception of WARM). WARM is the only tool among those evaluated in this report that assesses the impact of source reduction. Only MSW-DST and SWOLF are designed to estimate materials management system cost.

The tools differ in the nature of the environmental impacts assessed. For example, WARM only assesses GHG impacts, while other tools include a variety of other impact categories (e.g., acidification, eutrophication). Tools vary in the scope of emissions included in LCA. For example, WARM's and SWOLF's landfill GHG emissions estimates include carbon storage, MSW-DST and EASETECH allow users the flexibility to include or exclude landfill carbon storage, while WRATE excludes carbon storage. Carbon storage, if included, reduces a landfill's net GHG emissions estimate. None of the tools assess social impacts or characterize interactions among environmental, economic, and social impacts.

Significant progress has been made in the last two decades in developing tools to analyze environmental impacts from a life-cycle perspective. Additional research effort is needed to update tool input data (e.g., LCIs) with more recent data than those available at the time the tools were developed and to develop approaches and methods to assess the social and economic impacts and characterize trade-offs among the environmental, economic, and social impacts of EOL materials management on community sustainability for decision making.

Notice

The US Environmental Protection Agency (US EPA) through the Office of Research and Development funded and managed the research described here under contract order number: EP-C-10-060 to Computer Science Corporation, Inc. The research has been subject to the Agency's review and has been approved for publication as a US EPA document. Use of the methods or data presented here does not constitute endorsement or recommendation for use. Mention of trade names or commercial products does not constitute endorsement or recommendation.

The appropriate citation for this report is:

> Jain, P., Dyson, B., Tolaymat, T., Ingwersen, W., 2015. *A Comparative Analysis of Life-Cycle Assessment Tools for End-of-Life Materials Management Systems.* U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH. EPA Report #

Acknowledgements

We acknowledge the help of the following individuals for providing data and information pertaining to tools evaluated in this report:

Dr. Morton Barlaz, North Carolina State University

Dr. James Levis, North Carolina State University

Mr. Keith Weitz, RTI International

Dr. Anders Damgaard, Technical University of Denmark

Dr. Wesley Ingwersen, Sustainable Technology Division, US Environmental Protection Agency

We also appreciate the effort of two peer reviewers who took the time to carefully read and greatly improve the report: Anthony Zimmer (EPA/ORD), and Donnie Vineyard (EPA/ORD).

Table of Contents

List of Tables

List of Figures

List of Abbreviations, Acronyms, and Initials

AD	Anaerobic Digestion
AE	Accumulated Exceedance
APCD	Air Pollution Control Device
BOD	Biological Oxygen Demand
BTU	British Thermal Unit
CDD	Construction and Demolition Debris
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CH_4	Methane
DTU	Technical University of Denmark
EASETECH	Environmental Assessment System for Environmental Technologies
EOL	End of Life
GHG	Greenhouse Gas
HDPE	High Density Polyethylene
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFG	Landfill Gas
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MSW-DST	Municipal Solid Waste-Decision Support Tool
MT	Metric ton
NCSU	North Carolina State University
NH_3	Ammonia
NO_x	Nitric Oxides
PAYT	Pay as You Throw
PET	Polyethylene Terephthalate
pdf	portable document format
PM	Particulate Matter
PO_4	Phosphate
POTW	Publically-Owned Treatment Works
RDF	Refuse-Derived Fuel
SHC	Sustainable and Healthy Communities Research Program
SO_x	Sulfur Oxides
SSO	Source-Separated Organics
SWOLF	Solid Waste Optimization Life-Cycle Framework
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
TSS	Total Suspended Solids
UK	United Kingdom
US	United States
US EPA	United States Environmental Protection Agency
WARM	Waste Reduction Mode
WEEE	Waste Electrical and Electronic Equipment
WRATE	Waste and Resources Assessment for the Environment
WTE	Waste-to-Energy
WWTP	Wastewater Treatment Plant

1 Introduction

1.1 Background

The municipal solid waste (MSW) generation in the US has almost tripled in the last five decades from approximately 80 million metric tons (MT) (at 2.68 pounds per person per day in 1960) to 225 million MT (at 4.38 pounds per person per day in 2010) (US EPA 2014). MSW and construction and demolition debris (CDD) are the primary end of life (EOL) materials that communities (through their local governments) are responsible for managing. Historically, the spectrum of management options and services available to communities has ranged from systems where EOL materials are collected and transported elsewhere for further management to the development and operation of regional EOL materials management facilities which accept and handle MSW from various surrounding communities. MSW management decision-making is primarily driven by the cost of community-preferred options that meet the regulatory standards (local, state, and federal) for protecting human health and the environment. Given the amount of MSW that needs to be managed and its characteristics (e.g., biodegradability, potential for odor release), communities' decisions on the materials and methods used for MSW management also have significant social and environmental impacts that in turn have economic impacts (e.g., the impact on local ecosystem goods and services from a site located adjacent to EOL materials management activities).

The *US EPA Decision Maker's Guide to Solid EOL Materials Management II* (1995) laid the groundwork for decision making for integrated EOL materials management and discusses potential MSW management approaches and the associated constraints. The guide briefly acknowledges life-cycle assessment (LCA) as an approach to comparing several management strategies based on their environmental tradeoffs. The US EPA's Sustainable and Healthy Communities Research Program (SHC) strives to provide tools for community decision makers to more effectively and equitably evaluate and integrate parameters across all three pillars of sustainability (i.e., economic, environmental, social) into their EOL materials-management-related decisions to promote community sustainability (US EPA 2012a). Table 1-1 lists some examples of the key economic, environmental, and social parameters that pertain to MSW management decision making.

Table 1-1. Example Economic, Environmental, and Social Parameters of MSW Management Decision Making

Sustainability Pillar	Example Decision Parameters
Economic	Capital investment, revenue, financial risks, resource requirements, feedstock, end-uses, scaling flexibility, land use, location, job creation, economic impact, impact on the value of surrounding properties
Environmental	Emissions (to water, land/soil, and air), odor, noise
Social	Public safety/risks, transportation congestion, environmental justice, demographic impacts, aesthetics/visual quality

Several available tools can potentially be used for a LCA of materials-management options. Winkler and Bilitewski (2007) and Gentil et al. (2010) evaluated several materials-management LCA tools. Winkler and Bilitewski (2007) reported that large discrepancies among the results of six LCA tools used for the study may lead to contrary conclusions based on the LCA for the integrated EOL materials-management options (landfilling, incineration, or recycling and landfilling) simulated. Gentil et al. (2010) reviewed the methodologies, input parameters, and technical assumptions used for various processes of nine LCA tools including EASEWASTE (EASETECH precursor), WRATE, and MSW-DST, and concluded a need for harmonizing and validating geographically independent assumptions for improving EOL materials LCA modeling capabilities. The evaluations identified issues to be considered in the development of new tools or in improvements to existing tools. In addition, these evaluations focused on the environmental impact aspect of LCA. Decision makers should also consider social and economic impacts in addition to the impact on the environment (USGS 1998, US EPA 2009).

There is a need to identify and evaluate materials management LCA tools from the perspective of the community (decision makers, facility operators, engineers, and regulators) that actively makes or influences the decisions pertaining to EOL materials management systems. The use of LCA tools by this community potentially would have significant impacts on decision making and the ensuing environmental, social, and economic impacts on the community, and on adjacent communities. Considerations such as tool cost, complexity, scope and capabilities, and relevance to the processes of interest are more important to these users, who have limited LCA background, than factors such as tool methodologies, input parameters, and data sources that were the focus of the evaluations conducted by previous studies.

1.2 Report Objectives, Scope, and Approach

The objective of this report is to identify and evaluate the tools that can be used by communities to conduct a LCA of MSW management systems. The project scope included evaluation of up to five LCA tools. Several LCA tools were identified and preliminarily evaluated to select five tools that are specifically developed for the EOL phase management of MSW constituents. Community decision makers control the MSW stream and processes only after the waste is discarded and placed in receptacles for collection. It should be noted that the decision makers may influence consumer choices and subsequently the impacts of upstream processes by implementing programs such as educational outreach to raise awareness among the citizens about the impact of materials and their management alternatives.

The tool selection approach included identifying evaluation criteria, analyzing the tools using these criteria based on a review of each tools' documentation, and then applying the selected tools to a series of scenarios representing currently-relevant EOL materials-management issues. A set of criteria such as processes included, source data (e.g., life-cycle inventory (LCI), characterization factors) used for LCA, impact categories analyzed, user interface, and tool flexibility was identified to evaluate the selected tools primarily from a user's perspective.

The assessment also considers the scope of processes (e.g., whether landfill gas (LFG) generation and emission is included in the landfill process) included in each of the major EOL materials management strategies. A detailed review of the sources and the data included in the life-cycle-inventories (LCIs) of individual processes (e.g., a review of the data and the associated sources used for estimation of LFG generation and emission in each unique tool), and an assessment of the uncertainty associated with the LCA performed by the selected tools is beyond the scope of the evaluation presented in this report, though these factors may have a significant impact on the tool results for a given scenario.

Documentation for each of the final tools selected was reviewed and several EOL management scenarios were simulated to evaluate these tools based on the identified criteria and to illustrate the potential uses and limitations of these tools for community decision making. The scenarios were selected based on the current state of the practice of MSW management and the issues that community decision makers are facing across the US. Data gaps and key research needs are identified.

1.3 Report Organization

The report is organized into six chapters. Chapter 1 presents the background, objectives, and scope of the evaluation presented in this report. Chapter 2 briefly describes the relevance of LCA for EOL materials management, discusses the tools selection process, and briefly describes the five LCA tools that are evaluated. Chapter 3 introduces the tool evaluation criteria and presents a side-by-side evaluation of the five selected tools based on evaluation criteria. Chapter 4 presents a series of EOL materials management scenarios that were analyzed using the tools; the results are compared between the tools. Chapter 5 summarizes the evaluation and presents the identified data gaps and potential areas for future research. References used throughout the report are provided in Chapter 6. The terms “LCA”, “tool,” and “model” are used to describe the appropriate aspect of the comparison, but are not necessarily interchangeable. LCA is the assessment process, while the programs compared in this study are referred to as *tools* that *model* the LCA of the EOL-phase materials-management options.

2 Use of LCA for EOL Materials Management

2.1 Using LCA in the Context of Sustainable Materials Management

Recycling rate is a benchmark commonly used by communities to quantitatively assess the environmental impact of a MSW management system. Recycling rate, which presents the mass fraction of materials recycled out of the total amount generated, does not account for the materials' properties (e.g., LFG generation or leaching potential) that may significantly influence the environmental impact. In addition, the definition of recycling varies from state to state. For example, some communities consider the use of yard waste as landfill daily cover as recycling whereas others do not.

LCA, on the other hand, is a standardized approach for analyzing the impacts across the life cycle or a specific stage of a product or process based on the unique characteristics of individual materials. LCA can be used to analyze the system-wide impact of an integrated EOL materials-management system or that of a specific process (e.g., transporting MSW from curbside to the management facility).

The International Organization of Standardizations (ISO 14040) defines LCA as a "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle." Over its life cycle, a product goes through four distinct stages: raw material acquisition, manufacturing, use/maintenance, and recycling/ disposal. The LCA process generally consists of four distinct steps: goal definition and scoping, inventory analysis, impact assessment, and interpretation (ISO 1997). The goal definition and scoping step primarily entails defining goals (e.g., determine the EOL materials management option with the least impact on the environment) and scope (e.g., should the analysis be conducted for the entire life cycle of the product/system of interest or should it be limited to a particular stage [e.g., manufacturing, use, or end-of-use management]).

The second step in an LCA is inventory analysis. In this step the inputs (e.g., energy, materials) and outputs (e.g., products; byproducts; emissions to air, water, and land) associated with the product(s) or process(es) within the scope of the LCA are quantified. The output of this step is referred to as *life cycle inventories* (LCIs) and consists of a quantitative compilation of all the inputs (natural [e.g., soil mined for use as daily cover for landfill, water] and technosphere resources [e.g., truck transport, electricity]) as well as all the outputs (e.g., emissions to water and air from 1 kg of MSW placed in landfill). One approach to the analysis of manufacturing processes is to consider the region of origin for both virgin and recycled manufacturing given that emissions regulations and the CO_2 intensity of the energy grid vary by country. This level of information is difficult and likely changes with time. An alternative approach is to use global averages for both virgin and recycled manufacturing processes. Similarly, the EOL management practices of the discarded materials destination regions and the associated emissions should be taken into consideration for LCIs if the materials are exported outside the US.

In the third LCA step (referred to as *life-cycle impact assessment* [LCIA]), the LCIs are multiplied with corresponding factors known as *characterization factors* to assess end point (or midpoint) damage categories (e.g., climate change, eutrophication). The final step in LCA is interpretation. The LCA results are interpreted in relation to the goal-definition phase of the LCA study, involving review of the scope of the LCA as well as the nature and quality of the data collected.

Figure 2-1 presents the flow of MSW materials after they are taken out of service. These post-consumer materials may be source segregated and sent directly to a recycled materials vendor or the remanufacturer by large consumers (e.g., regional-scale chain stores) or may be placed in collection containers or recycling bins for collection by community MSW management divisions or their franchised haulers. These materials may be processed further in a material recovery facility, composted, combusted for energy recovery, or landfilled. The materials recovered from material recovery facilities (MRFs) are sent to facilities for remanufacturing, either in the US or abroad.

Several sub-processes (e.g., LFG generation from biodegradation of organics fraction deposited in landfill) and emissions are associated with each of the major processes depicted in Figure 2-1. Each of these sub-processes may have several options with unique environmental, economic, and social impacts that community decision makers would have to evaluate in selecting the most appropriate one. Two examples of decisions that communities may have to make pertaining to these processes are as follows:

1. Should diesel or natural gas trucks fleet be used for waste collection in case a community owns and operates it waste collection fleet?

2. Should we control LFG even if we are not required to by regulations?

The MSW management system for community decision makers generally begins from the point that the EOL materials are discarded and placed on the curbside for collection by the community's MSW management division. Community decision makers usually have no authority over decisions related to upstream processes (e.g., production, packaging, and/or the use of consumer products, backyard composting of food scraps). Therefore, most of the tools evaluated in this study do not include processes outside the direct control of the community decision makers. It should be noted that these decision makers can indirectly impact these upstream processes by influencing consumer products choices with environmental awareness and outreach programs.

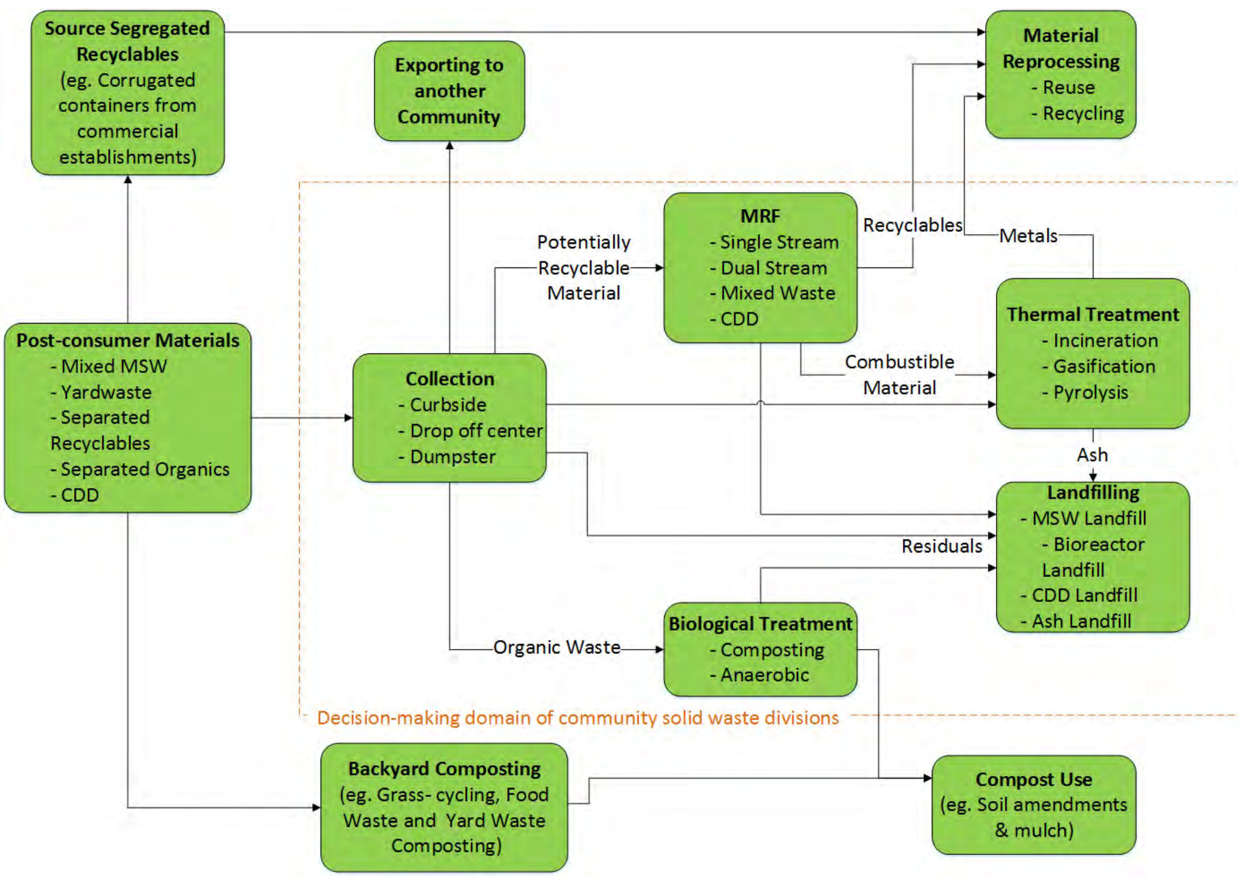


Figure 2-1. Decision-Making Domain of Communities with Respect to EOL Phase Materials Flow

2.2 EOL Materials Management LCA Tools Sieve Analysis

We identified 29 LCA software tools through an extensive literature search. The scope of the EOL materials manager's decision-making domain was used as the primary screening criteria to select tools for subsequent evaluation. As discussed in the previous section, the decision-making domain of the US EOL materials management community, including municipalities and engineers, is limited to the EOL stage of materials. The upstream stages (e.g., raw material acquisition, product manufacturing, and use) are beyond the EOL materials-management community's control; the emissions from upstream stages have already occurred by the time a community EOL materials-management department receives the discarded products. Many of the tools identified for this evaluation (e.g., Simapro, Gabi) can be used to conduct the LCA of the entire life cycle of a material (encompassing all four stages of its life cycle) and are much broader in scope than needed for making EOL management decisions at the community level. Some tools, on the other hand, were specifically developed to conduct an LCA for the EOL phase (e.g., WRATE, MSW-DST). Only the tools that assess impacts of the EOL phase were selected for further evaluation.

Various databases (e.g., Ecoinvent, NREL US LCI database) can be used to assess LCIs for different processes. It should be noted that LCIs are an intermediate and not an end goal of LCA. However, some of the identified tools provided LCIs as the final tool output. These tools (e.g., EPIC-CSR, MIMES, WASTED) were not considered for further evaluation. Some of the tools identified (e.g., Impact 2002+) were determined to be merely the characterization factors databases; these tools can only be used for a life cycle impact assessment (LCIA) for given LCIs and cannot be used for an MSW management system LCA. These tools were excluded from further evaluation. Some tools were also excluded from further analysis due to the scarcity of the information available (e.g., SSWMSS, MSWI), while some (e.g., ORWARE) were excluded based on the developer's recommendation to use other tools due to the specific tool's limitations (e.g., lack of updates since development). The following tools were selected for a second level of evaluation: WRATE, MSW-DST, EASETECH, HOLIWAST, WARM, WAMPS, and SWOLF. The seven tools listed were further evaluated to select up to five tools for the more detailed technical evaluation presented in this report. The tools were evaluated based on release year, documentation/technical support available, and applicability or ability to analyze systems for the geographical region of the interest (i.e. US).

Although many of the location-specific characteristics (e.g., EOL materials composition) can be changed in most of these tools, not all the tools are designed to include the US-specific EOL materials-management processes. Therefore, the tools developed specifically for the US (WARM, MSW-DST, SWOLF) were selected. Of the remaining four tools, EASETECH and WRATE were identified as having the most flexible processes included (e.g., collection, material recovery); therefore, EASETECH and WRATE were also selected for further evaluation. The following subsections provide a brief overview of these five tools; more detailed information on the tool assumptions and emissions factors is provided in Chapter 3, with additional details presented in a series of tables in Appendix A.

2.2.1 WARM

WARM was developed in 1998 and has been updated through thirteen versions. WARM was developed for US EOL materials managers to track the energy use and greenhouse gas (GHG) emissions of alternative EOL materials-management practices. WARM is available in both a spreadsheet and web-based interface that allows the user to compare the net energy use and total GHG emissions of a baseline EOL materials management approach (for example landfilling 1,000 tons of food scraps) with those of an alternative strategy, such as composting 1,000 tons of food scraps. WARM currently recognizes 54 material types (e.g., food scraps, concrete, mixed MSW, yard trimmings, drywall, etc.). The accessibility and ease of use of the tool has allowed for a much wider user base than any other model evaluated in this study.

WARM contains a database of emission factors for the different EOL materials management strategies (i.e., source reduction, recycling, combustion, composting, and landfilling); the tool estimates GHG emissions and energy use based on these emissions factors and the data input by the user. WARM requires at a minimum that the user input the baseline scenario's EOL materials quantities and methods of management, then input the corresponding quantities of the materials that are managed in the comparison scenario (the mass balance between the baseline and alternative scenarios must be consistent or an error message will prevent the tool from generating the output results). The user can adjust default values to describe the management scenarios (e.g., energy grid mix, the type of landfill control system, or transportation distance to management facilities). The results of the assessment provide the user with GHG emissions totals (in CO_2 equivalents and carbon equivalents) and energy use (British Thermal Units (BTUs)) for the baseline and alternative scenario and the difference between the two scenarios.

Three general sets of documentation are available for WARM: management practices (e.g., landfilling, composting), materials (e.g., asphalt concrete, clay bricks), and model background documents (which include links to various additional documents) that are available on the EPA website. The latest version of the tool was updated in June 2014 and is available free of charge through EPA's website.

2.2.2 MSW-DST

MSW-DST development began in 1994 and was designed to help US EOL materials planners evaluate the economic and environmental aspects of integrated MSW management operations, including collection, transfer, materials recovery, composting, waste-to-energy (WTE), and landfill disposal. The tool includes 39 materials (including materials classified as "other"). Most of the key input parameters can be specified by the user. The user begins tool use by entering different EOL materials-management processes to be included in the analysis. Specific values and parameters may be selected within MSW-DST by modifying process inputs.

The tool can estimate the construction and operating costs of EOL materials-management facilities. It also calculates energy consumption, GHG emissions, and other emissions, including criteria air pollutants and releases to water, and assesses the impacts using TRACI (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) characterization factors. The tool can optimize estimates for the single user-specified economic or environmental parameter of choice. The results are generated in excel spreadsheet format. Results for more than one scenario cannot be produced at the same time; therefore, comparing two scenarios requires the user to set up two tool runs and then manually compare the output spreadsheet results.

Both the tool and its documentation are available for download on the RTI website free of charge. A majority of the documentation is dated between 1997 and 2003, with a few materials from 2006 and one document as recent as 2011. The most recent "version number" is version 1.0, which suggest no new "version" has been released; only updates to the original version have been released. Access to the tool requires submitting a login request at RTI's website to obtain permission to use the tool.

2.2.3 SWOLF

This tool is designed for EOL materials planner for LCA of management systems, including transportation, composting, anaerobic digestion, materials recovery, and landfilling, and WTE processes. At the time of this study, the SWOLF tool was under development by researchers in the Department of Civil, Construction and Environmental Engineering at North Carolina State University (NCSU) under grants from the National Science Foundation and the Environmental Research and Education Foundation. Due to SWOLF's current state of development, information on final documentation, license cost, and interface is not final. A developmental version that operates on spreadsheets was evaluated in this study, but the final version is expected to consist of a desktop application.

SWOLF will be made publically available when tool development is complete. There will be no cost to use the full model for non-commercial applications. There may be a royalty-based fee for commercial use, but this has not yet been finalized. Tool documentation has not been published, but the modeling of each process in SWOLF is based on the developer's research, much of which has been published. These separate papers detail the assumptions and data used to construct each process model. Once the tool is published there is expected to be documentation for each process, as well as the overall model. The developers also plan video tutorials and demo guides.

2.2.4 EASETECH

This tool is designed for EOL materials planners for conducting an LCA of integrated EOL materials management operations; these include transportation, composting, resource recovery, WTE and landfilling. EASE-WASTE, the precursor to EASETECH, development began in 2000 at the Technical University of Denmark (DTU). EASETECH development began in 2010 and has been updated through two versions (2.0.0 Internal Institute Version). The latest version of the tool and documentation were released in August 2014 and are available for use only after the user completes training offered by DTU. The approximate cost for training and the software for a commercial license is €5,000 (approximately $5,550 at 2015 exchange rates). Tool technical resources include support from developers, the EASETECH documentation manual, and training exercises.

EASETECH uses an interface that allows the user to create a sequential flow of EOL materials through various processes and to estimate emissions associated with EOL materials management strategies (such as landfilling, recycling, and combusting MSW). It estimates emissions in a format that allows the user to view the net or selected individual process emissions. EASETECH requires the user to enter EOL materials tonnage and then to specify the EOL materials management scenario by directing material flows through the processes of interest. Default values and processes are available for use if, for example, the user does not have site-specific information or more detailed data available (e.g., EOL materials composition data). EASETECH can estimate a variety of environmental impacts; the user has the option of selecting from six impact assessment methods to estimate the impacts of the raw emissions. The default tool inputs such as EOL materials streams compositions and processes are mostly representative of Denmark and Western Europe.

2.2.5 WRATE

WRATE was first released in 2007 and has undergone two major updates, the first in 2010 and the most recent in March of 2014. The tool was originally developed for the Environmental Agency (United Kingdom) but is now owned and supported by Golder Associates (UK) Ltd. A demo version of the tool with limited functionality is available online for free (http://www.wrate.co.uk/Page/Download). Documentation is available for the tool with the software, and process-specific information is provided for each of the processes in the tool. An annual license for the standard version of the software costs £ 1,500 (approximately $2,400 at 2015 exchange rates).

WRATE uses a graphical interface that allows the user to create the EOL materials flow through a desired sequence of processes (such as collection, landfilling, recycling and combusting MSW) for a selected/specified EOL materials stream.

The tool was designed to be primarily representative of UK EOL materials management systems; international data were used if UK data were not available. The tool estimates emissions based on the Ecoinvent database and other sources of emissions factors in a format that allows the user to view the net and individual process emissions. The tool provides outputs in a variety of formats (e.g., tabular, graphical) that can be exported and saved. WRATE requires EOL materials tonnage to be provided by the user. The user must then select the individual EOL materials management processes that the EOL materials mass will be passed through until it reaches its final destination for disposal or reuse. Default values and process are available for use if site-specific information or more detailed data are not available (e.g., EOL materials composition data).

The user has some flexibility in specifying the various management processes, for example, choosing the type of landfill containment design (e.g., type of cap or liner), transportation distances, and treatment technologies. The user can compare multiple EOL materials management scenarios as long as the waste tonnage managed is the same for each scenario. The emissions impacts estimated by WRATE (using CML 2001 method) include global warming potential (GHGs), acidification potential, eutrophication potential, freshwater aquatic ecotoxicity, human toxicity, and resource depletion.

It should be noted that of all the tools, WRATE is the only one with several versions available for use, including a free demo and two versions available for purchase (the Standard and Expert versions). The Expert version has expanded functionally over the Standard version and can create user-defined processes, allowing access to the background Ecoinvent LCI database and providing the ability to change impact assessment methods. The Expert version's annual license costs nearly four times more than the Standard version. Therefore, the Standard version of the tool is evaluated in this report as it was assumed that the Standard version of the tool would be the more frequently used. This report is based on the use of WRATE (Software Version 3.0.1.5) which was issued in 2014, and Database Version 3.0.1.8 which became available in February 2015.

3 Detailed Evaluation of the Selected LCA Tools

3.1 Overview

The tools were evaluated and compared based on general attributes, scope, and analysis and outputs. The results of the tool evaluations are organized in a series of tables for ease of comparison. These tables can also be used as a guide for selecting the most appropriate tool for the LCA of an EOL material's management system. The information presented in this chapter is primarily derived from tool documentation pages. Tables A-1 and A-2 in Appendix A presents basic details such as tool cost, method of availability, developer, prevalence of use/distribution, and available user support. Please note that the tools have been updated since their original release. Table 3-1 presents the versions of the tools that were evaluated in this report. These tools have only become available in the past two decades. WARM was initially developed in 1998 and has undergone 14 revisions since then. SWOLF has not officially been released and is expected to be available for use in the near future.

Table 3-1. Tool Versions Evaluated

Tool	Version Evaluated
WARM	Version 13, prior to March 2015 update
MSW-DST	Version 1.0 published in 2002, last update from June 2014
SWOLF	Pre-release version. Last software update provided 30 March 2015.
EASETECH	Internal Institute Version 2.0.0 (software), August 2014 (database)
WRATE	Version 3.0.1.5 (software) (7 March 2014)

WARM, MSW-DST, and SWOLF have been developed for the EOL materials and management practices specific to the US. With some exceptions, EASETECH is generally representative of conditions in Denmark and Western Europe. WRATE was developed to be representative of the UK EOL material management systems. Based on data provided by the developers, 190 (including 29 copies of trial version) and 161 copies/licenses of MSW-DST and EASETECH, respectively, were distributed as of June 2015. Approximately 230 licenses were sold for WRATE from 2008 through 2013. The US EPA does not track number of WARM downloads. However, there are 300 unique users on WARM's updated mailing list. The preceding usage is only noted as a reference to compare against the overwhelming need; 39,000 local governments (counties, municipalities, and townships) in the US in 2012 (Hogue, 2013) that routinely make decision pertaining to EOL management of materials discarded by the communities.

Table 3-2 compares tool flexibility with respect to key LCA inputs such as the EOL materials stream composition and the energy mixes which the user may specify for modeling purposes. All of the tools provide default values for a range of modeling parameters; however, not all of the tools allow users to replace default values with their own data. Tool flexibility is particularly important for users attempting to adjust input parameters to reflect an alternative geographic area than the one used to develop model default conditions. Although WRATE and EASETECH are designed to represent conditions in Europe, these tools have the flexibility to allow modification of input parameters (e.g. materials composition) to simulate US conditions. Similarly, SWOLF and MSW-DST have flexibility to represent European conditions.

Flexibility can also be evaluated with respect to the individual tool processes (i.e., collection, transportation, specific EOL materials management technologies, etc.). Overall tool processes are evaluated and compared in subsequent sections. While tool adjustability and the user's ability to modify the underlying assumptions and data are desired features, a large number of user-specifiable inputs increases tool complexity. WARM offers the fewest parameters that can be modified by the user among the tools evaluated in this study. EASETECH allows users to create processes not included in the tool. For example, Jain et al. (2014) created a process to simulate landfill mining, which is not included in the tool, to assess the impact of mining of old landfills with and without resource recovery. It should be noted that, as discussed in Chapter 2, the standard version of WRATE was used for this report. The expert version of the tool offers more flexibility than the standard version.

Table 3-2. Comparison of Tool Flexibility for Key LCA Parameters Categories

Flexibility with tool parameters	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Allows user to adjust material composition and generation rate (e.g., 1,000 tons/day)	✓	✓ [a]	✓	✓	✓
Allows modification of material properties	-	✓	✓	✓	-
Allows more than one material stream to be managed at once.	✓	✓[b]	✓[c]	✓	✓
Allows input of additional material types (in addition to those provided by tool)	-	-[d]	-[d]	✓	-
Allows specification of the energy mix of the area of interest	-[e]	✓	✓	✓[f]	✓ [f]
Allows addition/modification of processes (aside from adjusting default values)	-	-	✓	✓	-[g]

a. Population and per capita generation (lb/person-day) are used to calculate overall material generation rate for a year – the user does not directly input the total amount of material managed in a year.
b. However, must include at least one residential material stream.
c. SWOLF requires one initial material composition be defined, but different compositions for different sectors can be added in later processes.
d. The tool includes a limited number of blank materials for which custom properties can be entered.
e. The user can only select a default energy mix for the US national average or for the US state of interest; the user cannot specify a unique energy mix.
f. The tool comes pre-loaded with a variety of different grid mix and specific fuel energy-production processes. The user can create a unique grid mix.
g. Only the Expert version allows the user to create unique processes.

3.2 *Tool Scope*

3.2.1 Overview

The materials, material characteristics, material generation sectors (e.g., residential, multi-family, commercial), energy mix, and the specific management processes (e.g., collection, transportation, and treatment) are some of the key input parameters for an LCA. This section explores and discusses the extent of the adjustability of tool-specific modeling parameters for different materials-management options and includes a comparative discussion of material properties, generation sectors, marginal electricity mix (i.e., the standard grid mix assumed by the model for offsetting purposes) and material handling processes considered by these tools. The information provided in this section was developed from tool documentation and from using these tools for the scenarios modeled (and discussed in Chapter 4).

3.2.2 Material Properties

Each tool allows the evaluation of the EOL management of a variety of materials. The different types of specific materials (organized by general material category [e.g., paper, plastic]) included in each tool are presented in Table A-3 (see Appendix). Of the tools evaluated, EASETECH is the only one that allows the user to input additional custom-defined materials beyond those included by default. While DST has "other" categories for paper, plastic, and aluminum, it does not allow the user to create more categories than those that already exist. The "other" categories in DST are only editable in limited ways. A notable difference between the two European-developed tools (WRATE and EASETECH) and the US-based tools (WARM, MSW-DST, and SWOLF) is that the plastic material categories listed in the US tools specify individual plastic types (i.e., polyethylene terephthalate (PET), high density polyethylene (HDPE)) while the European tools only provide general plastic descriptors (e.g., hard plastic, dense plastic, soft plastic). It should be noted that the US EPA data, which decision makers typically reply upon, tracks plastics discarded in MSW by their resin type. Inconsistencies in material name terminology used by several tools and the names typically used in the US presented a challenge in using these tools, especially WRATE and EASETECH. However, this challenge was addressed by developing a common EOL materials stream composition in all the tools which as closely as possible simulated the same fractionation of materials; this allowed the comparison of tool results for the different material management scenarios evaluated in Chapter 4. More details on how this composition was selected are presented in Chapter 4.

Table A-3 also presents the CDD materials available for modeling in each tool. These materials are classified into the following categories: wood, brick, concrete, wall board, asphalt shingles, asphalt pavement, fines, soil, carpet, and other. As shown in Table A-3, WARM is the only tool which includes a majority of CDD materials generated in the US (e.g., wallboard, wood, carpet, asphalt shingles, or asphalt pavement material). WARM does not, however, assess soil or fines, which is material typically generated from CDD processing activities. Both European tools assess soil and WRATE assesses fines (<10mm and unspecified fines). The tools also evaluate several materials that do not fit under the definition of MSW or CDD materials. These additional materials are compared in Table A-3 and include the following categories: non-hazardous industrial waste/processed materials, biosolids, and other non-MSW materials (e.g., fly ash).

When a potential tool user has material-specific (e.g., moisture content) or material-management-process-specific (e.g., electricity consumption per mass of ferrous metal recovered) data, LCA tools that allow modifying material and process properties and underlying assumptions provide an opportunity for a better simulation of the user's materials stream than a tool that does not offer such capabilities. Table 3-3 compares the tools' abilities to accommodate user-defined physical, biological, and chemical material properties. As shown in the table, it is evident that users have the most flexibility in modifying material properties in SWOLF, EASETECH, and MSW-DST.

Table 3-3. Comparison of Tool Flexibility for Key Material-Specific Properties

Material Properties		WARM	MSW-DST	SWOLF	EASETECH	WRATE
Physical	Moisture content	-	✓[a]	✓	✓	-
	Energy content	-	✓[b]	✓[b]	✓	-
	Ash content	-	✓	✓	✓	-
	Material density	-	✓	✓	-	-
	Combustion efficiency	-	✓	✓	✓[c]	-
Biological	Decay rate constant (k)	✓[d]	✓[e]	✓	✓	-
	Methane generation potential	-	-	✓	-[f]	-
Chemical	Elemental constitution	-	-	✓	✓	-

a. Water content fraction
b. BTU/lb
c. Can be adjusted through modification of a material's volatile solids content
d. Five k rate defaults to select from
e. There is an option to select a "user defined k," but there currently is no place to set this k value.
f. This parameter is not used in the tool per se, however, the fraction of anaerobically degradable carbon can be modified to mimic variation in methane generation potential

3.2.3 Material Generation Sectors

Material generation sectors are the classifications of the sources of materials that require EOL management. These classifications generally include single-family residential (e.g., individual homes with curbside collection), multi-family residential (e.g., apartment buildings), industrial (e.g. factories), and commercial (e.g., retailers, schools, hospitals, prisons). Material generation sectors are an important consideration for performing an LCA of EOL materials management from a decision maker's perspective as local governments have varying control over the flow of materials from these sectors. For example, a local government may have greater control over the collection and management of materials from single-family homes than those from multi-family residences and commercial sectors. In addition, material generation sectors have an important impact on EOL materials composition and on viable options (and corresponding environmental, economic, and social impacts) for material collection and transport. For example, single-family homes typically produce small amounts of EOL materials over a larger area, whereas multi-family homes generate larger amounts within a smaller footprint. Therefore, it is reasonable to conclude that the total fuel consumption and vehicle wear per mass of material collected from these two sectors will likely be different. The different generation sectors that can be selected in each of the tools is presented in Table 3-4.

Table 3-4. Comparison of Materials Generation Sectors Considered by the Tools

Generation Sectors	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Residential (single-family)	-[a]	✓	✓	✓	✓[b]
Multi-family	-	✓	✓	✓	-
Commercial	-[c]	✓	✓	-	✓[d]
Industrial	-	-	-	✓	-[e]

a. Mixed paper is the only material specifically identified as originating from primarily residential sources.
b. Household waste is a defined EOL materials stream.
c. Office paper and mixed paper material categories described as primarily originating from offices.
d. Commercial - office waste is a defined EOL materials stream.
e. Co-collected trade waste is a defined EOL materials stream.

WARM is the only tool that does not allow the selection of sector-specific material streams that include a default EOL materials stream composition. However, WARM does allow the selection of multiple materials and allows user-specified quantities of each material for analysis; so a custom-designed aggregated material stream is possible. Of the other four tools, only WRATE and EASETECH allow the selection of EOL material streams originating from specific generation sectors where sector-specific stream compositions can be readily modified by the user. SWOLF does not currently allow a simultaneous analysis of multiple generation sector materials streams (each with a unique composition); however, the developer indicated that a future version of the tool will have this capability. It should be noted that, unlike the other tools, MSW-DST does not allow the inclusion of additional material categories beyond those included in the default sector-specific material stream composition.

3.2.4 Electricity Energy Mix

The particular fuel feedstock mix used for electricity generation can vary significantly from region to region. LCA tools often use an area's (e.g., national, statewide) typical electricity generation practices as a point of reference for estimating offsets associated with electricity generation from materials-management processes (e.g., anaerobic digestion (AD), materials combustion for electricity generation). Therefore, the ability to select an electricity energy mix used in the user-specific region is important to accurately estimate the environmental burdens avoided as a result of a potential materials-management strategy. This ability is especially critical when considering the use of a non-US tool (e.g., WRATE, EASETECH) to evaluate the environmental impacts resulting from materials management in the US; default European energy mixes may be very different from the energy mix in the US. The baseload fuel mix is the mix of different fuels used to produce the electricity used in the model processes, while the marginal fuel mix includes the fuel use displaced by electricity production in alternative electricity generating processes (e.g., EOL material incineration, LFG-to-electricity). Table 3-5 summarizes the flexibility and some of the background data used to develop the electricity energy mixes for each of the tools.

Table 3-5. Comparison of Tool Flexibility for Baseload and Marginal Energy Mix Data

Energy Mix Data and Parameters	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Geographical source of energy mix data	US-specific, the user has the option of selecting a national energy mix or one specific to each state based on the regional location of the state.	Default values are US specific, and based on US national averages.	Default values are based on US national averages.	Default mixes include Europe (EU-27), Sweden and Denmark. The user may create a custom mix.	Defaults are provided for European countries. A user could enter data specific to another country outside of Europe.
Year of data	2010	Default/User can specify which energy data are used.	2010 (defaults)	2001-2002	Depends on the country selected[a]
Energy sources included in energy mix	Not adjustable	Adjustable; includes coal, natural gas, residual oil, distillate oil, nuclear, hydro, wood, other	Adjustable; has a large variety of options (see note)[b]	Adjustable; default tool energy conversion processes include coal, natural gas, LPG, wind, waste and fuel oil	Adjustable; includes coal, oil, gas CCGT, nuclear, waste, thermal other, renewables thermal, solar PV, wind, tidal, wave, hydro, geothermal, renewable other
Baseload fuel mix parameter	Not adjustable	Adjustable	Adjustable	Adjustable	Adjustable
Energy generating efficiencies	Not adjustable	Adjustable	Adjustable	Adjustable[c]	Adjustable
Marginal fuel mix	Not adjustable	Adjustable [d]	NA	Adjustable	Adjustable
Transmission type	Not adjustable	NA	Adjustable	NA	Adjustable[e]
Transmission losses	Not adjustable	NA	Adjustable	Adjustable[f]	Adjustable[g]

a. Energy mixes have been extrapolated out for some countries. For example, England has default energy mix estimates available from 2002 to 2035.

b. Includes Diesel Oil Combined-Cycle, Diesel Oil Combustion Turbine, Geothermal, Hydroelectric, Conventional, Hydroelectric, Reversible, MSW Steam, Natural Gas Combined-Cycle, Natural Gas Combustion Turbine, Natural Gas Steam, Oil Steam (Resid Fuel Oil LS), Pre-Existing Nuclear LWRs, Residual Coal Steam, Solar Photovoltaic, Solar Thermal, Wind, Wood/Biomass Steam, Biomass Integrated Gasification Combined-Cycle, Geothermal - Binary Cycle and Flashed Steam, Integrated Coal Gasification Combined Cycle, Integrated Coal Gasification Combined Cycle -- CO2 Capt., Natural Gas - Advanced Combined-Cycle (Turbine), Natural Gas - Advanced Combustion Turbine, Natural Gas - Combined-Cycle (Turbine), Natural Gas - Combustion Turbine, Natural Gas Combined Cycle -- CO2 Capture, Nuclear LWRs in 2015, Oxyfuel Coal Steam -- CO2 Capture, Pulverized Coal Steam – 2010, Solar PV Centralized Generation, Solar Thermal Centralized Generation, Wind Generation Class 4, Wind Generation Class 5, Wind Generation Class 6

c. not included as a specific parameter, but can be accounted for in process equations

d. Marginal fuel mix is not available, but fuels can be included or excluded from fuel displacement.

e. high voltage, medium voltage, low voltage

f. not included as a specific parameter, but can be accounted for in process equations
g. corresponds to the transmission type

3.2.5 Materials Collection

There are a variety of ways in which materials may be sorted and stored by the generator for collection. The two broadest classifications of MSW (i.e., mixed waste) material produced in the US include recyclables and non-recyclables. Recyclable materials may be separated from non-recyclable materials as a single category (i.e. single-stream recyclables), which typically includes a combination of containers (e.g., metal, glass, plastic) and fibers (i.e. paper materials); only one recycling bin is placed curbside. However, recyclables may also be further separated into containers and fibers so that there are two recycling bins placed curbside in what is known as a dual-stream recycling program. Some communities have recycling drop-off centers located in more rural areas as a means of minimizing the number of collection points. Other communities sometimes require the segregation of additional EOL materials streams, such as food scraps and yard waste, from other mixed EOL materials.

Several factors, including the collection frequency, dictate the type of collection container selected, which in turn would affect the and the quality of the materials (e.g. rain-soaked recyclable paper from a non-lidded bin, dry paper from an enclosed bin) and the quantity of resources and energy consumed to make the containers. Different EOL materials collection and curbside recycling practices have different impacts on the quality of the recovered recyclable materials (e.g., broken glass mixed with fibers in single-stream collection bins), the overall participation in recycling, the number of trucks which must be sent out to collect the materials, and the type of processing that may be necessary to further segregate and classify the collected materials. All these factors will have an influence on the environmental burdens associated with a specific material collection strategy. Table 3-6 summarizes the types of EOL materials collection configurations available in the tools and the types of LCI data that are incorporated into their analyses.

As shown in Table 3-6, although WARM can evaluate the management of mixed waste, yard waste, and different categories of recyclable materials, WARM appears to only incorporate a general material collection LCI in its analysis; collection strategies specific to single-stream or dual-stream recycling cannot be evaluated. The collection and transport LCIs are linked together in MSW-DST. A user can select from 21 collection scenarios. The collection strategies are organized by material generating sector, whether recyclables are separated and placed curbside or taken to a drop off center, and by the collection vehicle configuration (e.g., multiple single-compartment vehicles, one multi-compartment vehicle provides collection for refuse and recyclables).

Table 3-6. Comparison of Tools for Materials Collection Process Options and LCI Scopes

Collections	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Single-stream recyclables	No	Yes	Yes	Yes[a]	Yes
Dual-stream recyclables	No	No	Yes	No	Yes
Multi-stream	No	Yes	Yes	No	Yes
Mixed waste	No	Yes[a]	Yes	Yes	Yes
Drop-off	No	Yes[b]	Yes	No	Yes
Source separated organics (SSO)	No	No	Yes	No	Yes
Yard waste	No	Yes	Yes	No	Yes
CDD	No	No	No	Yes[c]	Yes
LCI –number of bins adjustable	No	Yes	Yes	No	Yes
LCIs –Collections containers manufacturing and maintenance over its service life	No	No[d]	No[d]	No	Yes
LCI – EOL management of collection container	No	No	No	No	No
Separately accounts for emissions during collection from those resulting from full and empty vehicle transport	No	Yes	Yes	Yes	No

a. components of single stream
b. provided for all sectors
c. includes "bulky waste" which primarily consists of wood, other metal, cardboard, stones/concrete and other non-combustible materials
d. lifespan only considered for cost estimation

WRATE has additional flexibility with respect to the number of collection options from which the user may select, such as a variety of bags, bins, skips (i.e., a larger dumpster-like bin), intermodal containers (i.e., containers that may undergo multiple modes of transport such as rail, ship, and truck), and drop-off options to select from. Within each collection method category there is a drop-down menu of more specific types of collection containers that the user can select from. For example, in the bins category the user can select a bin based on size or based on whether the bin does or does not have wheels. WRATE does not have specific collection processes per se for the pickup of single-stream, dual-stream, or other specifically-named streams, but the tool allows the user to direct the material(s) to the container option(s) of choice and then to select a collection vehicle of choice. Therefore, the collection containers can be adapted to fit the containers that would be needed for types of EOL materials collection methods that are common in the US (i.e., single-, dual-, mixed-EOL materials streams). The user must also specify the total number of containers used to manage the EOL materials. The collection emissions in WRATE vary depending on the type of container (e.g., a bin instead of a bag). Raw material consumption (accounted for with every container type), container maintenance (i.e., washing), and container lifespan are included in the collection emission estimate.

EASETECH has several types of collection processes the user can select from (e.g., residual waste, bulky waste, and paper), and includes the ability to create a custom-defined collection process. The collection scenario is described in each process, with the type of collection (e.g., curbside or drop-off), type of truck, truck load size, where collection occurs (e.g., urban setting), what type of collection container is used, and how often pick up occurs. EASETECH does not have predefined processes for single- and dual-stream recycling collections; the residual waste collection process is for mixed EOL materials streams. However, the user could create processes to simulate dual- or single-stream collection. For the collection process of the tool, fuel consumed between the first and last collection stop is analyzed in the collections aspect of the assessment. Fuel consumed while driving the collection vehicle between the last collection point and the drop-off point and to and from the garage is not included in the collection emission estimate. It is included in the transport process.

3.2.6 Material Transport

MSW-DST and SWOLF include collection vehicle movement prior to and following the completion of collection routes as part of collection transport activities whereas EASETECH and WRATE model this vehicle movement separately from collection. WARM considers only the transport process and also includes emissions associated with collection. The tools generally estimate fuel consumption and the associated emissions resulting from material collection and subsequent transport in one of two ways. WARM, EASETECH, and WRATE estimate the emissions based on the distance over which materials are transported and the total quantity of materials transported. MSW-DST and SWOLF, on the other hand, estimate emissions based on a large number of parameters such as distance of the first collection point from the garage, number of stops, rest breaks, average distance between stops, and distance from the last point of collection to the next management point, and distance to the garage.

LCA tools that can be flexible and incorporate a range of transport vehicle and fuel options can be used to assess the impacts of potential operational changes, such as switching fleet vehicle fuels from diesel to compressed natural gas (CNG). As presented in Table 3-7, WRATE provides a high level of flexibility as it lets the user assess the use of four additional fuels in addition to diesel; however, it should be noted that not all vehicles in WRATE are compatible with all fuel types. For example, electric vehicles can only be specified for collection using a manually-pushed collection cart. Also, the vehicles types included in WRATE are not necessarily the same as those that may be employed in the US for collection, which would make the assessment of a switch to an alternative fuel less relevant for performing a US-based LCA. Transportation fuel types in MSW-DST and WARM cannot be adjusted.

Table 3-7. Comparison of Tool Transportation Fuel Options

Transport Fuel Options	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Diesel	Yes[a]	Yes[a]	Yes	Yes	Yes
CNG	No	No	No[b]	No	Yes
Biodiesel	No	No	No	No	Yes
Gasoline	No	Yes[a]	No	No	Yes
Electric	No	No	No	Yes[c]	Yes[d]

a. but user cannot adjust the fuel that is used
b. developer plans to include this feature in a future version
c. for the freight train option only
d. only available for a pedestrian operated cart

Aspects of transport that impact an LCA in addition to the type of fuel consumed include whether the collection vehicle can be automatically loaded or must be manually loaded by the operator, the size of the collection vehicle (e.g, fewer larger vehicles will be needed for a route), emissions associated with vehicle manufacturing and maintenance, and the road types. The ability to analyze the use of other modes of material transport (e.g., rail, ship) is another tool functionality that can help community leaders select a collection management strategy with a lower environmental impact. Table 3-8 summarizes the general transportation options available, transportation parameters that can be adjusted, and transportation LCIs that are incorporated in each of the tools.

As Table 3-8 shows, the WARM tool cannot be adjusted for different types of transport, whereas MSW-DST and SWOLF have additional flexibility with the option of selecting single- and multiple-compartment vehicles, vehicle material drop-off, and rail transport. Only SWOLF, EASETECH, and WRATE include materials transportation via ship. SWOLF allows the user to specify the size of the collection vehicles while WRATE provides several default vehicles with varying sizes that can be selected from. User can adjust parameters such as number of workers and vehicle time per house in MSW-DST and SWOLF to simulate various collection vehicle types. LCIs incorporating transportation vehicle manufacture and operational lifespan do not appear to be available in the US tools or in EASETECH; however, in addition to operations, WRATE considers environmental impacts associated with vehicle manufacture and maintenance. None of the tools consider how vehicles that reach the end of their useful life are managed (e.g., recycled, landfilled).

Table 3-8. Comparison of Tool Transportation Vehicle Options and LCI Scopes

Transport Mode Options	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Multi-compartment vehicle	No	Yes	No	No	Yes
Automatically-loaded vehicle	No	No	No	No	Yes
Manually-loaded vehicle	No	No	No	No	Yes
Ship	No	No	Yes	Yes	Yes
Rail	No	Yes	Yes	Yes	Yes
Individual drop off	No	Yes	Yes[a]	No	Yes
Ability to specify vehicle capacity	No	Yes	Yes	No	No
Ability to adjust number of transport vehicle	No	No	Yes	No	No
Adjustable transport distance	No	Yes	Yes	Yes	Yes
Ability to specify type of roadway vehicles travel	No	No	Yes	Yes	Yes
LCIs – Vehicle lifespan	No	No[b]	No[b]	No	Yes
LCIs – Vehicle manufacture	No	No[b]	No[b]	No	Yes
LCIs – Vehicle operation and maintenance	No	Yes	Yes	No	Yes
LCIs – Vehicle EOL management	No	No	No	No	No

a. for some streams, not all
b. only considered for cost estimation

Transfer stations, where EOL materials and/or recyclable materials are moved from short- to long-haul vehicles before they are sent for additional processing or treatment, are typically used for materials collection and transport operations in the US. Transfer stations have a covered area for loading, unloading, and storing materials; equipment to move and load materials; loading bays; scale house; and usually include office space. Emissions from transfer stations include those associated with natural resource extraction and manufacturing of materials used for facility construction and maintenance; electricity, fuel and water used for facility operation; and EOL management of materials generated from facility maintenance and decommissioning. Table 3-9 summarizes the options available in each tool with respect to transfer stations and the included LCIs.

WARM does not allow users to include transfer stations in transporting materials. MSW-DST has five types of vehicle transfer stations that are based on the materials processed. The transfer stations vary in whether a tipping floor is used or if materials are directly tipped into a container, the bay loading type (either one or two levels), whether or not compaction occurs, and what type of loading equipment is used. MSW-DST also has three rail transfer station options. Information on the construction and operation and maintenance of the transfer station can be input/selected by the user.

WRATE has four types of transfer stations a user can select based on material transport mode: intermodal containers at seaport, intermodal inland water or rail, rail large/compaction and transfer, and road vehicle transportation. The user has the option to specify the facility's capacity. Emissions estimated from the use of a transfer station in WRATE include the construction, operation, and maintenance of the facility; the user does not have the option to adjust other parameters in the transfer station processes. EASETECH does not have any processes specific to transfer stations; however, the user could adjust the material recovery facility (MRF) process to mimic the emissions of a transfer station.

SWOLF includes four types of transfer stations, each of which receive waste from a different collection process: mixed waste, dual stream, single stream, and separated organics. Each type of transfer station has unique LCIs, and a unique set of operational parameters that can be adjusted. The distance to each transfer station from collection, and the distance from the transfer station to the next process can be defined within the model for each type of transfer station, and each possible destination. Transfer stations also allow collected waste to be transitioned to another transportation method in SWOLF, such as rail or ship transport.

Table 3-9. Comparison of Tool Transfer Station Options and LCI Scopes

Transfer Station[a]	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Type – Road	No	Yes	Yes	No[b]	Yes
Type – Rail	No	Yes	Yes	No	Yes
Type – Port	No	No	No	No	Yes
Type - Inland water	No	No	No	No	Yes
Type – Ship	No	No	Yes	No	Yes
Facility capacity/throughput adjustable?	NA	Yes	Yes	NA	Yes
LCIs – Construction of transfer station	NA	No[c]	No[c,d]	NA	Yes
LCIs – Operation and maintenance of the transfer station	NA	Yes	Yes	NA	Yes
LCIs – Demolition and EOL management of the transfer station	NA	No	No	NA	No

a. based on location and transport mechanism
b. allows the switch between different forms of transport, but no default transfer station process is included in the model
c. considered only for cost estimate
d. developer plans to include this feature in a future version

3.2.7 Materials Recovery

MRFs are used to recover and process recyclable EOL materials or recyclable material streams and generally serve as an intermediate point between material collection and material re-use. MRFs can be designed around a variety of configurations, which in the US are typically based on the type of materials received at the facility (e.g., single-stream recyclables, dual-stream recyclables, mixed EOL materials). MRFs typically include a covered area for tipping and loading materials, sorting equipment, equipment to move and load materials, storage space for material stockpiles, and offices. Emissions attributable to MRFs include those associated with manufacturing (including natural resources extraction) of construction materials and energy used for facility construction; production of energy (electricity and fuels) resources (including water) used for facility operation; emissions (e.g., leachate, dust) from materials processing operations; and EOL management of materials generated from facility maintenance and decommissioning. Factors that impact emissions from a MRF include the facility's level of mechanization (manual sorting would require less fuel than mechanized sorting), process efficiency, the distance from the MRF to a disposal facility (for residuals), the distance from the recovered materials end user(s), and the end-use application of the recovered recyclables (e.g., producing refuse derived fuel (RDF) from recyclables to replace combustion fuel may offset different emissions than using the recyclables as a raw feedstock replacement for virgin materials).

Figure 3-1 presents an example of the material and energy inputs and emissions associated with the recovery of a specific recyclable (e.g., corrugated containers) at an MRF that should be accounted for in an LCA. Table 3-10 presents a side-by-side comparison of the MRF types available, the degree of MRF customization, and the inclusion/exclusion of several types of LCI data specific to MRFs for each of the tools.

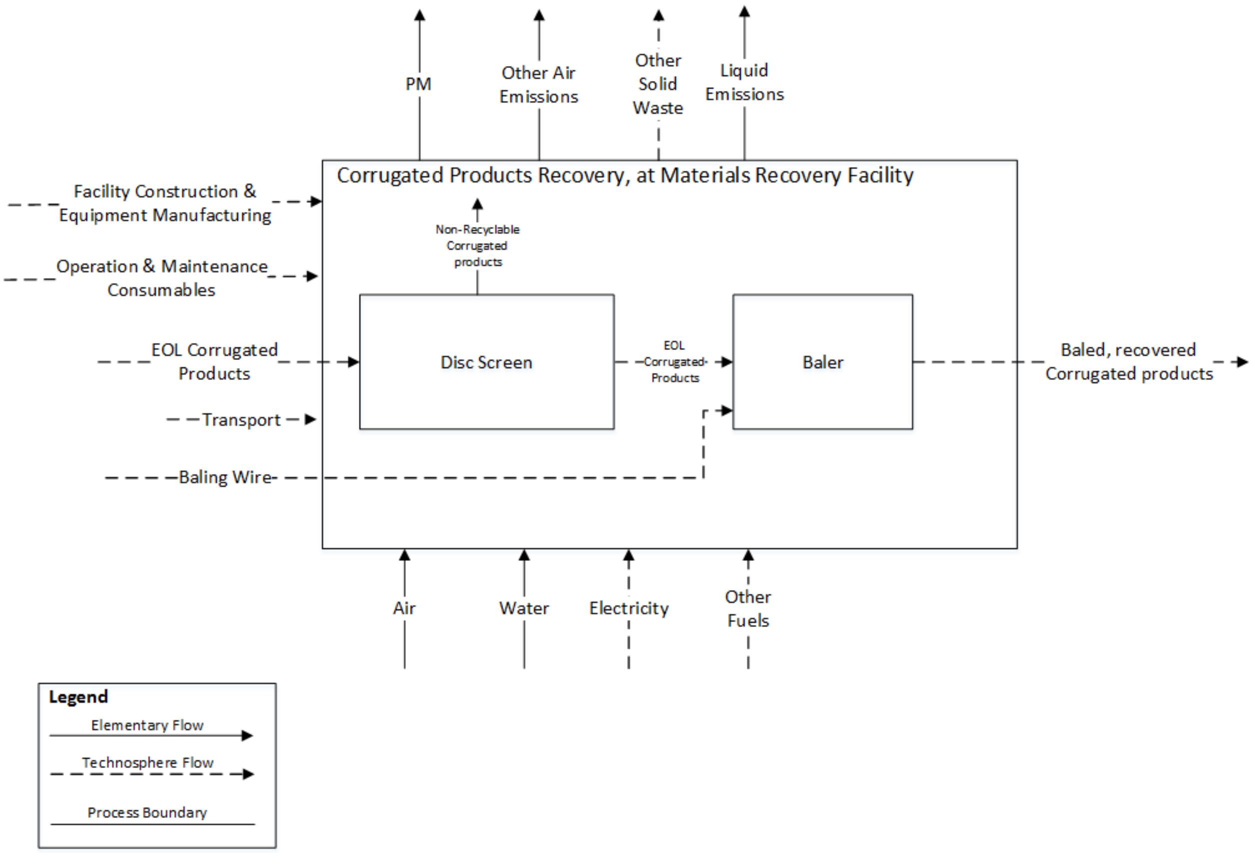


Figure 3-1. Example of Materials and Energy Inputs and Emissions Associated with Recovery of a Specific MSW Constituent

WARM does not account for the environmental impacts associated with MRF construction, operation, or maintenance. WARM uses material-specific recovery rates (i.e. the total amount of a material recycled minus contamination) to estimate the emissions associated with recycling; users cannot adjust these. MSW-DST includes eight MRF designs that can be selected depending on how materials are collected: mixed EOL materials MRF, presorted recyclables MRF, commingled recyclables MRF, co-collection MRF (recyclables and mixed EOL materials collected in a single-compartment truck), co-collection MRF (processes commingled recyclables and mixed EOL materials collected in a three-compartment truck), front-end MRF to a composting facility, front-end MRF to an AD facility, and a front-end MRF to an RDF facility; DST does not include AD process. The degree of mechanical sorting that occurs at MRFs can be selected in MSW-DST. With the mixed EOL materials and commingled recyclable MRFs, users can choose whether there is manual or mechanical opening of bags and aluminum sorting. Also, the user can specify energy consumption for various types of equipment and the recovery rate of each material.

The options for WRATE's MRF facilities include one that processes mixed EOL materials into RDF, one that produces RDF for a cement kiln/gasifier/pyrolysis, an MRF that has a vibrating screen, and an MRF that sorts with an infrared plastics separation. Although WRATE does not have single- and dual-stream material compositions built into the tool, the user can create and route the EOL materials composition that mimics these stream types. The recovery rates for each specific type of MRF in MSW-DST and WRATE are built into the tool and cannot be changed. This could be a problem if a user wanted to compare MRFs with the same equipment configuration but with different recovery percentages. These recovery percentages are specific to UK facilities. WRATE also has a process called *a civic amenity*, which is a facility that accepts and sorts EOL material dropped off by civilians that is typically too large to fit in a garbage container. The process includes LCIs for facility construction, operation, and maintenance.

In EASETECH there is one predefined MRF in the tool, which is a paper-sorting facility. Although this is the only predefined option, it is possible to simulate other types of MRFs that can accept a variety of materials since users can create their own customized processes and can control the mass flows and energy and fuel demands of the facility. However, this type of customized MRF process development will likely be beyond the ability of the average tool user.

SWOLF has unique process models for mixed waste, single stream, and dual stream MRFs each with MRF-specific assumptions on recovery rates and LCIs. Recovery of each individual material in SWOLF can be assigned to sorting streams and/or equipment within the MRF process. This allows allocation the impact associated with each piece of equipment in the MRF to the material fraction it recovers. SWOLF allows simultaneous use of the single-stream and dual-stream recyclables collection and recovery processes for a curbside collection program.

Table 3-10. Comparison of Tool MRF Options and LCI Scopes

MRF	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Single stream	No	Yes[a]	Yes	Yes[b]	Yes
Dual stream	No	No[a]	Yes	No	Yes
Mixed EOL materials stream	No	Yes	Yes	No	Yes
CDD	No	No	No	No	Yes
RDF producing facility	No	Yes	Yes	No	Yes
Materials reuse option available	No	No	No	No	Yes
Facility capacity/throughput adjustable?	No	Yes	Yes	Yes	Yes
Manual sorting option	No	Yes	Yes	No	No
Automated (mechanical) sorting option	No	Yes	Yes	No	No
Semi-mechanical sorting option	No	Yes	Yes	No	Yes[c]
Recovery rate adjustable	No	Yes	Yes	Yes	No
LCIs – Construction of MRF	No	No[d]	No[d,e]	No	Yes
LCIs – Operation and maintenance of MRF	No	Yes[d]	Yes	Yes	Yes
LCIs – Demolition and EOL management of MRF	No	No	No	No	No

a. it is unclear if the comingled recyclables MRF and presorted recyclables MRF represent a single-stream or a dual-steam MRF, respectively.
b. only includes a paper sorting facility
c. all available MRF options are semi-mechanical
d. included only for the cost estimate
e. developer plans to include this feature in a future version

3.2.8 Material Recycling and Source Reduction

EOL materials recovered from MRFs can be recycled either in a closed-loop (i.e., an EOL material is processed and converted back into the original saleable product) or an open-loop process (i.e., the EOL material is converted into an alternate, generally lower-quality product). An example of an MSW constituent recycled in an open-loop process is paper. For example, some of the tools' paper recycling processes take higher-quality paper (e.g., office paper) and convert it to lower-quality paper product. CDD materials, as included in WRATE and WARM, are also typically recycled in open-loop processes. For example, asphalt shingles in WARM are used to offset some of the asphalt necessary for the production of asphalt pavement, and concrete is recycled and modeled as a replacement for aggregate.

The tools may assume a closed-loop or open-loop recycling process or offer the user a choice to select the recycling type depending on material being analyzed. For example, EASETECH provides choices of several paper types (of both the same quality and of lower quality) that can be manufactured from recycled mixed paper. The tools typically model the recycling credit by accounting for the emissions resulting from MRF operation, emissions associated with the avoided virgin material production, and emissions resulting from the additional processing required to convert the recovered material to a virgin-equivalent precursor material at a recycling facility (e.g., converting aluminum cans to aluminum sheets).

A unique feature of WARM is the ability to analyze the GHG impacts associated with the source reduction of an EOL material, where source reduction avoids the emissions associated with product raw material acquisition, manufacturing, transport, and EOL management. Source reduction essentially precludes the existence of a given product or material. For example, a re-usable water bottle can be expected to source reduce a number of PET bottles depending on the re-usable water bottle's expected life span. Except for WARM, it appears that none of the tools allow the exclusive analysis of material source reduction.

3.2.9 Landfilling

Landfilling is the predominant EOL management method of materials in the US, primarily attributed to lower costs compared to other EOL management options in most regions of the country. Different types of landfills (e.g., MSW, ash, CDD) have varying impacts depending on the construction materials used for the facility, the size and operation of the landfill, the types of wastes received, and emissions (e.g., LFG and leachate) as materials in the landfill decompose over time. A material's disposal LCA may include LCIs of material, energy inputs, and emissions associated with landfill construction; EOL materials placement and compaction; biochemical degradation (e.g., emissions associated with LFG and leachate management); and closure and post-closure-care activities. Figure 3-2 presents an LCI flow diagram depicting the energy, materials, and emissions flows that occur over the lifetime of a landfill. Table 3-11 presents the types of landfills a user can select from within each of the tools.

Table 3-11. Comparison of Tool Landfill Type Options

Landfill Options	WARM	MSW-DST	SWOLF	EASETECH	WRATE
MSW	Yes	Yes	Yes	Yes[a]	Yes[b]
CDD	Yes[c]	No	No	No	No
Ash	No	Yes	Yes	Yes[e]	Yes[b]
Inert[d]	No	No	No	No	Yes[b]
Bioreactor	Yes[g]	Yes	Yes[f]	Yes[g]	No

a. household waste
b. landfill process can accept MSW, ash and inert materials – there are no landfill processes specific to these materials
c. CDD material in WARM is assumed to go to a CDD landfill which is modeled as an MSW landfill with no gas collection system
d. inert is not a term typically used in the US, but refers to landfills which contain only material assumed to pose low risk of gas generation or contaminant leaching.
e. bottom ash landfill
f. user can modify the parameters to simulate bioreactor LFG production
g. no discrete option, can set k value to reflect bioreactor operation

A user cannot specify the type of landfill modelled in WARM; however, the user can adjust the landfill's conditions (i.e., moisture level and decay rate) used to simulate different landfill types (e.g., the user can select a decay rate consistent with that of a bioreactor). The domain of landfill disposal-related inputs and outputs considered varies significantly among the different LCA tools. For example, outside of LFG management, WARM only considers GHG emission from materials placement and compaction activities, whereas WRATE includes materials and inputs and emissions associated with landfill construction, operation, and closure. Table 3-12 includes a detailed description of the individual LCIs accounted for in each tool associated with landfill construction, operation, and closure/post-closure care.

Carbon storage represents the carbon fraction that does not biodegrade under the typical anaerobic conditions of a landfill environment (Barlaz 1998). WARM, MSW-DST, SWOLF, and EASETECH include carbon storage for their landfill process whereas WRATE does not. MSW-DST and EASETECH offer flexibility to exclude carbon storage from landfill emissions whereas WARM does not offer such flexibility. Although not included as a default, MSW-DST allows user to estimate carbon storage in an additional calculation step. In SWOLF, carbon storage can be excluded by adjusting the carbon storage factors to zero.

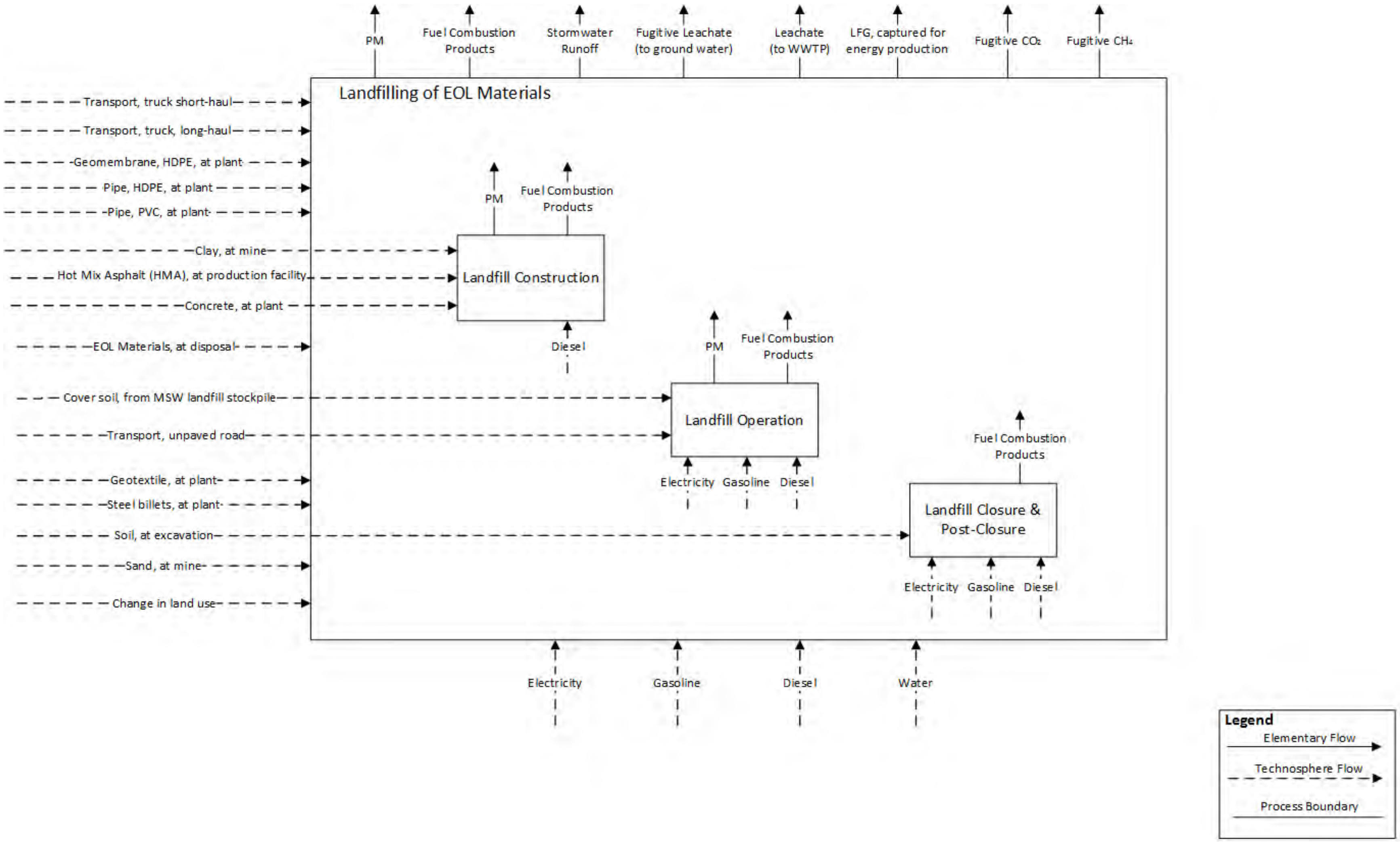


Figure 3-2. Example of Materials and Energy Inputs and Emissions Associated with Materials Disposal in Landfill

Table 3-12. Comparison of Tool LCI Scopes for Landfill Construction, Operation, Closure, and Post-Closure Care Phases

Landfill Parameters		WARM	MSW-DST	SWOLF	EASETECH	WRATE
Construction materials included in analysis	Soil	No	Yes	Yes	No[a]	No[b]
	Geomembrane	No	Yes	Yes	No[c]	Yes
	HDPE pipes	No	Yes	Yes	No[c]	Yes
	Operational equipment manufacturing	No	No	No[i]	No	No
	Operations equipment EOL management	No	No	No	No	No
Construction energy included in analysis	Electricity	No	No	No	Yes	No
	Diesel, gasoline	No	No	No	Yes [d]	Yes
Landfill operations included in analysis	EOL materials placement and compaction (fuel usage and equipment emissions)	Yes	Yes	Yes	Yes[d]	Yes
	Cover material	No	Yes	Yes	Only soil transport	Yes
Liner Type	Geosynthetic clay liner	No	No	No	No	Yes, clay composite
	Clay	No	Yes[e]	Yes[e]	No	Yes
	Other	No	Yes (Single-composite and double composite liner)	Yes (Single-composite and double composite liner)	Geomembrane and clay (1-meter thick) composite liner	Yes (Dense asphaltic concrete (DAC) and HDPE)
Cap Type	Clay	No	No	Yes	No	Yes
	HDPE	No	No	Yes	No	Yes
Landfill carbon storage included in estimate?		Yes	No[f]	Yes	Yes[g]	No
Closure fuel consumption included in estimate?		No	Yes	Yes	No	Yes[h]
Post-closure care included in estimate?		No	Yes	Yes	No	No

a. only transport of soil
b. soil is included in the operation and closure of the landfill but not in construction
c. it is not clear if HDPE granulate consumption is used to estimate emissions from construction of HDPE piping, geomembrane or both
d. unable to differentiate between construction and operation fuel and electricity usage
e. account for clay used in composite liners – a single clay liner cannot be modelled
f. carbon storage not included by default, but tool can calculate
g. can be excluded from estimate
h. includes material resources used to cap the landfill
i. only considered for cost estimation

In WARM, landfilled CDD materials are predetermined to go to a CDD facility that is assumed to have no LFG recovery; all other materials are assumed to be taken to an MSW landfill. While WARM does not allow the user to specify the time-horizon over which EOL materials are placed in an MSW landfill, an average time horizon is accounted for in the tool's calculations. WARM accounts for material-specific LFG collection efficiencies based on user-specified decay rate constants reflecting different landfill moisture conditions. These LFG collection efficiencies are based on user-specified LFG collection operational scenarios (i.e., the schedule of LFG collection system installation and coverage areas), and a 100-year time horizon. WARM does not account for GHG emissions released as a result of leachate generation and management.

MSW-DST estimates LFG emissions and offsets for traditional and bioreactor landfills based on LFG generation rate, collection efficiency, and methane oxidation through landfill cover, electricity generation, and carbon storage. The LFG emission methodology used by the model is very similar to that used by WARM. MSW-DST, however, offers more flexibility for user inputs. For example, unlike WARM, the tool allows users to specify the LFG collection efficiency for each year LFG is collected. The model uses a material-specific methane generation potential to estimate LFG generation for a user-specified MSW composition and a first-order decay model for a 100-year time frame. LFG is assumed to be comprised of 50% methane and 50% carbon dioxide (CO_2) by volume. Potential LFG management methods include venting, flaring, and combustion for energy recovery. The model accounts for a variety of trace LFG constituents that are modeled independently of MSW composition.

MSW-DST's leachate generation rate is estimated based on a time-varying precipitation fraction that enters the landfill. The tool assumes a leachate collection and treatment timeframe of 100 years with 99.8% leachate collection efficiency and assumes insignificant leachate generation in the post-closure period (after 100 years) based on the placement of a low-permeability cap at the end of the operating period. The uncollected leachate is assumed to be released to the environment. The tool specifically accounts for biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia (NH_3), phosphate (PO_4), total suspended solids (TSS), arsenic, cadmium, chromium, lead, mercury, selenium, and silver emissions in leachate. The tool documentation also lists several hydrocarbons, but these do not appear to be included in the model. The generic MSW contaminant yields are allocated to different materials. The BOD, COD, and TSS yields are allocated based on the LFG attributed to the biodegradation of specific material components. NH_3 and PO_4 are allocated to material fractions based on the initial concentration of these contaminants for different materials. The generic MSW metal yields are allocated to individual material components based on the total metal content of specific materials. Emissions from leachate transport to a wastewater treatment plant (WWTP) are based on travel distance, leachate load, and the pre-combustion and combustion emissions of fuel used for transport. The tool also includes emissions associated with electricity use for leachate treatment and biogenic carbon dioxide emissions associated with BOD removal.

SWOLF bases its calculation for LFG generation on a user-specified material-specific methane generation potential and decay rate constant. The tool's default value for the methane content of the LFG is 50%. All trace gases included in the tool are independent of the material composition. Methane and trace gases have individual destruction efficiency values that can be input for each LFG management option (e.g., flare, vent, combustion engine).

Leachate generation and concentration in SWOLF is calculated independent of material composition. Leachate generation is based on annual precipitation, assuming a certain fraction of precipitation becomes leachate. The fraction of precipitation that becomes leachate can be varied every year of landfill operation to account for the effects of covering the working face and capping the cell. The default leachate capture, defined as the fraction of the leachate collected by the collection system, is 99.8%. Leachate not collected by the collection system is released to groundwater untreated. The amount of leachate that is recirculated and the fraction that is sent to a WWTP can be customized. Leachate not recirculated is assumed to be transported by truck to an off-site treatment facility. SWOLF accounts for the electricity used for treating leachate sent to a WWTP and energy used for transportation and disposal of the generated sludge. The BOD removed from the material also creates additional GHG impacts. The WWTP treatment efficiency for BOD, COD, NH_3-N, PO_4, TSS, metals, and trace organics can be user specified. Compounds not removed by the WWTP are assumed to be released to the environment.

For modeling landfill management options in EASETECH, the user has the choice of selecting from pre-constructed landfilling processes (comprised of a number of sub-processes that have already been agglomerated) or selecting individual landfill sub-processes (e.g., LFG generation, oxidation through soil cover, leachate treatment). EASETECH includes a process that can simulate MSW landfills with different LFG recovery options (i.e., flaring, LFG-to-electricity) and another process that simulates ash landfilling. It should be noted that EASETECH models the instantaneous landfill deposition of the entire mass of materials specified by the user – the tool cannot model a progressive increase in LFG generation associated with the annual placement of landfilled material over a user-specified time horizon. This has a significant impact on how the tool estimates LFG production and collection. Because peak LFG production in EASETECH occurs immediately, when compared to other tools such as MSW-DST (which accounts for annual materials placement and an associated annual increase in LFG production over the operation life of the landfill), the EASETECH LFG emission estimate will be greater unless LFG collection is specified to occur at landfill startup. Trace LFG constituents are independent of landfilled material composition, and the conversion and speciation of methane and trace LFG constituents by different LFG destruction devices (and cover soil oxidation) can be specified for individual LFG constituents.

Leachate generation volume in EASETECH is based on an assumed infiltration rate, landfilled material thickness and density, and a leachate collection system efficiency. The model includes leachate management sub-processes, including leachate generation, simulation of a leachate collection system, storage of carbon in leachate and soil, leachate treatment, and treated effluent emissions to surface water and the ocean. Concentrations of specific contaminants in leachate are not related to landfilled material composition. However, different concentrations for individual contaminants can be modified over different user-selected time horizons. The user also can add or delete from the list of contaminants included in the model. The default leachate collection efficiency of the landfill liner is assumed to decrease over time, where lower collection efficiencies are assumed after 80 years. The user also has the option of including storage of carbon in the leachate and soil. Energy use for the treatment of leachate is included in the WWTP process available in the tool. The WWTP also accounts for some electricity produced onsite as a result of the use of biogas from the AD of the sewage sludge. The WWTP process includes air emissions from the AD of treatment sludge. Management of the remaining sludge includes dewatering, drying, burning, and assuming that the burned sludge is applied to industrial soil. The emissions to water from treatment effluent are also included in the estimate.

WRATE's documentation states that the leachate-simulating tool LandSim (Version 2.5), developed by the UK Environmental Agency, was used to assess leachate impacts. The tool assumes a 20,000-year period, by which time it was assumed that the liner and cap of the landfill would have degraded. WRATE is the only tool that assumes such a long time horizon; the other tools assume a 100-year time period. WRATE leachate emissions are estimated using a linear regression incorporating the three landfill size options available in the tool (i.e., 2.5, 5, and 10 million MT total capacity) and material types that contribute to each contaminant. The leachate emissions for each contaminate are therefore related to the capacity of the site in which it is produced. The total amount of leachate emissions is the sum of leakage plus discharge to sewer, including the removal factors after treatment at a WWTP.

WRATE LFG emissions were estimated using GasSim (v1.5). The tool estimates LFG generation and partitions the LFG between collection, LFG migration, surface emissions, and biological methane oxidation. It can analyze the impact of having a combustion plant for collected LFG destruction and also accounts for LFG energy recovery, including an assessment of gas atmospheric dispersion. The landfill fill rates in GasSim were assumed such that each landfill size would be filled after 20 years and assuming that progressive capping would occur over time to maximize LFG capture. Methane oxidation in the cap was assumed to be 10%. GasSim modeling was run to simulate a 150-year period since LFG production was assumed to be negligible following this extended time horizon.

Two landfill process options are available in WRATE. One allows the user to select a LFG collection efficiency and choose whether collected LFG is simply vented, used for energy recovery, or combusted in a flare. The other process does not allow the user to specify collection efficiency and estimates emissions by assuming maximum energy recovery. Table 3-13 summarizes landfill leachate and gas-related parameters considered by tools. WARM does not consider leachate generation and the associated emissions. It includes the emissions associated with LFG.

Table 3-13. Comparison of Tool Flexibility and LCI Scope for Leachate and LFG

Consideration	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Leachate					
Leachate collection included in emissions estimate	No	Yes	Yes	Yes	Yes
Are emissions based on material composition?	NA	Yes	Yes	No	Yes
Leakage from liner included in emissions estimate	NA	Yes	Yes	Yes	Yes
Leachate transport to treatment plant included in emissions estimate	NA	No	Yes	No[a]	No
Leachate treatment plant -construction and maintenance LCIs included in emissions estimate	NA	No	No	No	No
Leachate treatment-energy use included in emissions estimate	NA	No	Yes	Yes	No
Management of leachate treatment residuals included in emissions estimate	NA	Yes	Yes	No (POTW) Yes (WWTP)	Unknown
Leachate treatment plant removal factors included in emissions estimate	NA	Yes	Yes	Yes	Yes
Assumed leachate generation time horizon	NA	100 years	100 years	100 years	20,000 years
Landfill Gas					
Gas collection system construction	No	Yes	Yes	Yes[b]	Yes
Are emissions based on material composition?	Yes	Yes	Yes	Yes	Yes
Is generation rate adjustable?	Yes[c]	No	Yes	Yes[d]	No[c]
Gas collection efficiency adjustable?	Yes[e]	Yes	Yes	Yes	Yes
Methane oxidation adjustable?	No[f]	Yes	Yes	Yes	No[g]
LFG destruction option (flare)?	Yes	Yes	Yes	Yes	Yes
Assumed LFG generation time horizon	100 years[h]	100 years[i]	100 years	100 years	150years[h]
Beneficial use of collected gas: Direct use (e.g., use in a boiler)	No	No	Yes	Yes	No
Electricity generation	Yes	Yes	Yes	Yes	Yes
District heating	No	No	No	Yes	No
Equipment manufacturing	No	Yes	No	No	No
Equipment EOL management	No	No	No	No	No

a. but the user can add a transport process leading to the treatment process
b. through flare treatment only
c. by decay rate from available defaults
d. by manually adjusting decay rate LFG generation can be adjusted
e. can select from four default options, each material has its own collection efficiency based on the moisture and recovery scenario
f. fixed at 20% for landfills with LFG collection before final cover.
g. fixed at 10% as modeled in GasSim
h. user cannot adjust

i. tool documentation states that user can select from 20 years, 100 years, or 500 years; however, this was not seen in the tool

3.2.10 Incineration

In addition to those emissions directly resulting from material combustion (also referred to as *incineration* or *waste-to-energy* [*WTE*]), the environmental burdens associated with material incineration include preprocessing that may occur prior to the combustion of the EOL materials (depending on the incineration technology used); and the construction, operation and decommissioning of the incineration facility including air pollution control devices; and solid (e.g., ash), liquids (e.g., leachate from ash disposal in landfill), and gaseous emissions (e.g., CO_2, SO_x). A general life cycle flow diagram that identifies material, energy and emissions flows through a general WTE process is depicted in Figure 3-3. Incineration facility types, energy recovery options, and some of the key LCI data necessary for an LCA associated with the management of materials by incineration are included in Table 3-14.

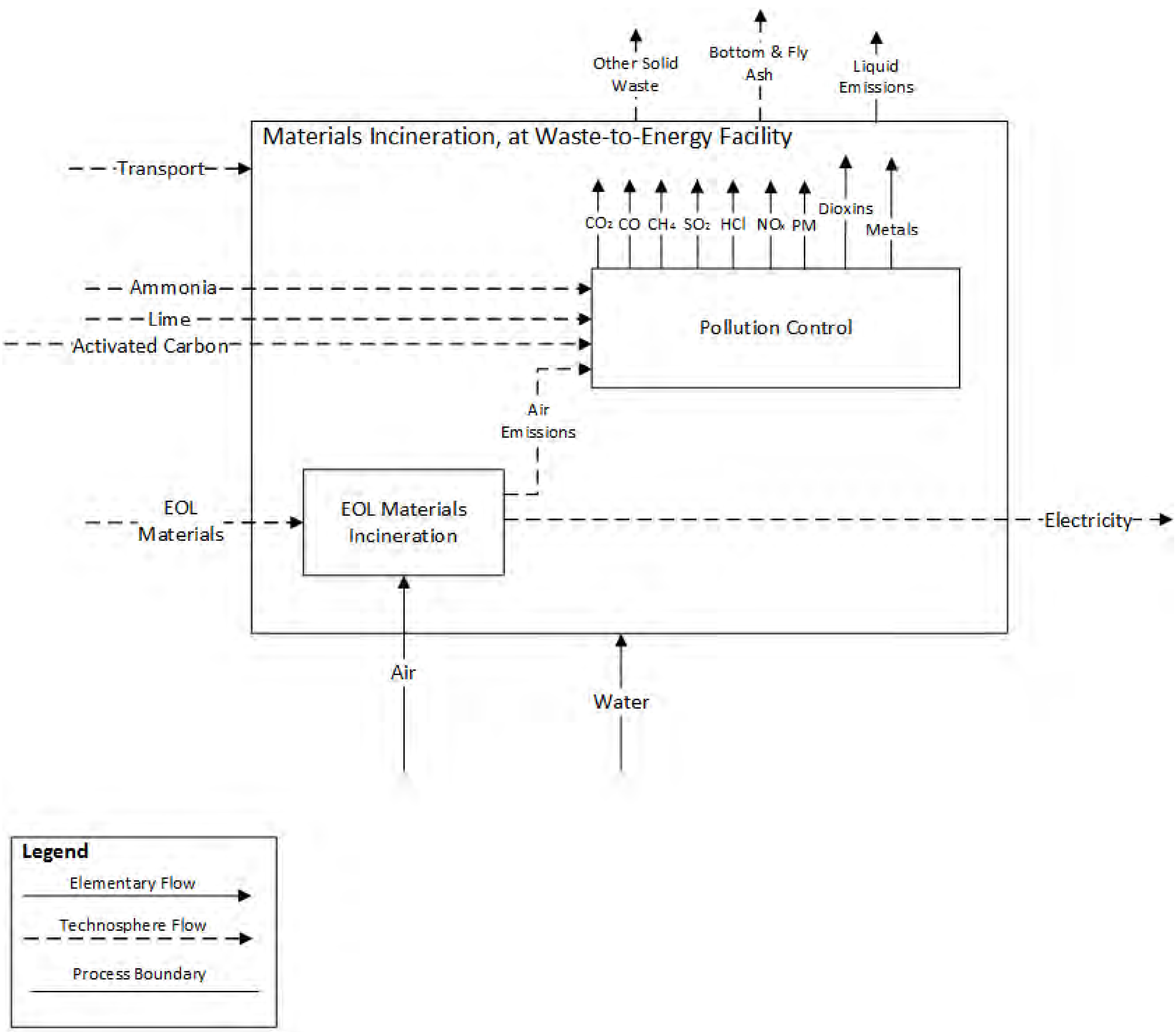


Figure 3-3. Example of Materials and Energy Inputs and Emissions Associated with Materials Incineration for Energy Recovery

Table 3-14. Comparison of Tool Flexibility and LCI Scope for Materials Incineration Processes

Combustion facilities		WARM	MSW-DST	SWOLF	EASETECH	WRATE
WTE facility, mass burn		Yes	Yes	Yes	Yes	Yes
WTE facility, RDF		No	Yes	Yes	No[a]	Yes
Incinerator (without energy recovery)		No	No	Yes[b]	Yes[b]	No
Autoclave		No	No	No	No	Yes
Energy recovery options that can be selected	Electricity generation?	Yes	Yes	Yes	Yes	Yes
	District heating?	No	Yes	Yes	Yes	Yes
	Cogeneration of electricity and steam?	No	Yes	Yes	Yes	Yes
Distance to combustion facility adjustable?		Yes	Yes	Yes	Yes	Yes
Transport of ash residual to ash landfill adjustable?		No	Yes	Yes	Yes	Yes
Steel recycling offsets included in analysis?		Yes	Yes	Yes	Yes	Yes
Air emissions?		Yes	Yes	Yes	Yes	Yes
Combustion products disposal and leachate emissions from landfill?		No	Yes	Yes	Yes	Yes[c]
Gross electrical efficiency adjustable?		No	Yes	Yes	Yes	Yes
Heat efficiency adjustable?		No	No[d]	Yes	Yes	Yes
Adjustable mix of electricity and district heating available?		No	No	Yes	Yes	Yes
Metals recovery rate fixed?		Yes	No	No[e]	No	No
LCIs – Construction of combustion facility		No	Yes	No[e,f]	No	Yes
LCIs – Operation of combustion facility		No	Yes	Yes	Yes	Yes
LCIs – Demolition and EOL management of combustion facility		No	No	No	No	No
LCIs – Ash landfill construction and operations		No	Yes	Yes	Yes	Yes[c]

a. there is not a designated RDF WTE process to select; however, this type of facility can be simulated by using generic processes
b. energy recovery can be disabled
c. does not specifically have an ash landfill process, however the tool user could specify any of the landfill processes to accept only ash and therefore the emissions associated with that process would be included in the assessment
d. cannot model heat recovery
e. developer plans to include this feature in a future version
f. only considered for cost estimation

None of the models account for the environmental burdens resulting from the decommissioning of the incineration facility once it has reached its EOL. All of the tools provide the ability to account for the benefit associated with ferrous metal recovery from incinerator ash. It is also interesting to note that while all tools can account for incineration energy recovery for electricity production (commonly practiced), the tools (with the exception of WARM) also allow for specifying energy recovery for district heating (a less common practice in the US).

3.2.11 Composting

Composting is becoming an increasingly popular method of managing organic materials. The overall environmental impact resulting from a specific composting operation would depend on its size (e.g., small-scale home composting versus industrial-sized yard waste composting), the type of materials being composted, the methods of managing the compost at the facility, and emissions released (e.g., biogas and leachate) as the compost is processed and matures over time. An LCA for a composting process should include materials and energy inputs and emissions associated with constructing, operating, maintaining, and decommissioning the infrastructure and mobile equipment used at composting facility. Figure 3-4 presents, as an example, materials and energy inputs and emissions that could be considered for an LCI of composting yard waste which represents a commonly composted MSW material. Table 3-15 lists the types of default composting options a user can select from for each LCA tool.

Table 3-15. Comparison of Tool Flexibility and LCI Scope for Composting Processes

Composting facilities		WARM	MSW-DST	SWOLF	EASETECH	WRATE
Facility type options that can be selected for	Backyard composting	No	No	No	No	Yes
	In-vessel composting	No	Yes	Yes	Yes	Yes
	Windrow composting	Yes	Yes	Yes	Yes	Yes
Moisture control adjustable?		No	No	Yes	Yes	No
Aeration energy adjustable?		NA	No	Yes	No[a]	No
Distance to composting facility adjustable?		Yes	Yes	Yes	Yes	Yes
LCIs – Construction of composting facility		No	No	No[c,d]	No	Yes
LCI – Operation of composting facility		Yes	Yes	Yes	Yes	Yes[b]
LCI – Decommissioning of composting facility		No	No	No	No	No

a. can adjust amount of overall processing energy
b. maintenance also included
c. developer plans to include this feature in a future version
d. only considered for cost estimation

WARM assumes windrow composting for all compostable materials. Also, except for WARM, all the tools can simulate composting using in-vessel technology. WRATE is the only tool that can simulate backyard, in-vessel, and windrow composting. Finally, similar to the other management processes discussed previously (e.g., MRF, incinerators), none of the tools accounts for the emissions resulting from the EOL management of the composting facility and its associated equipment.

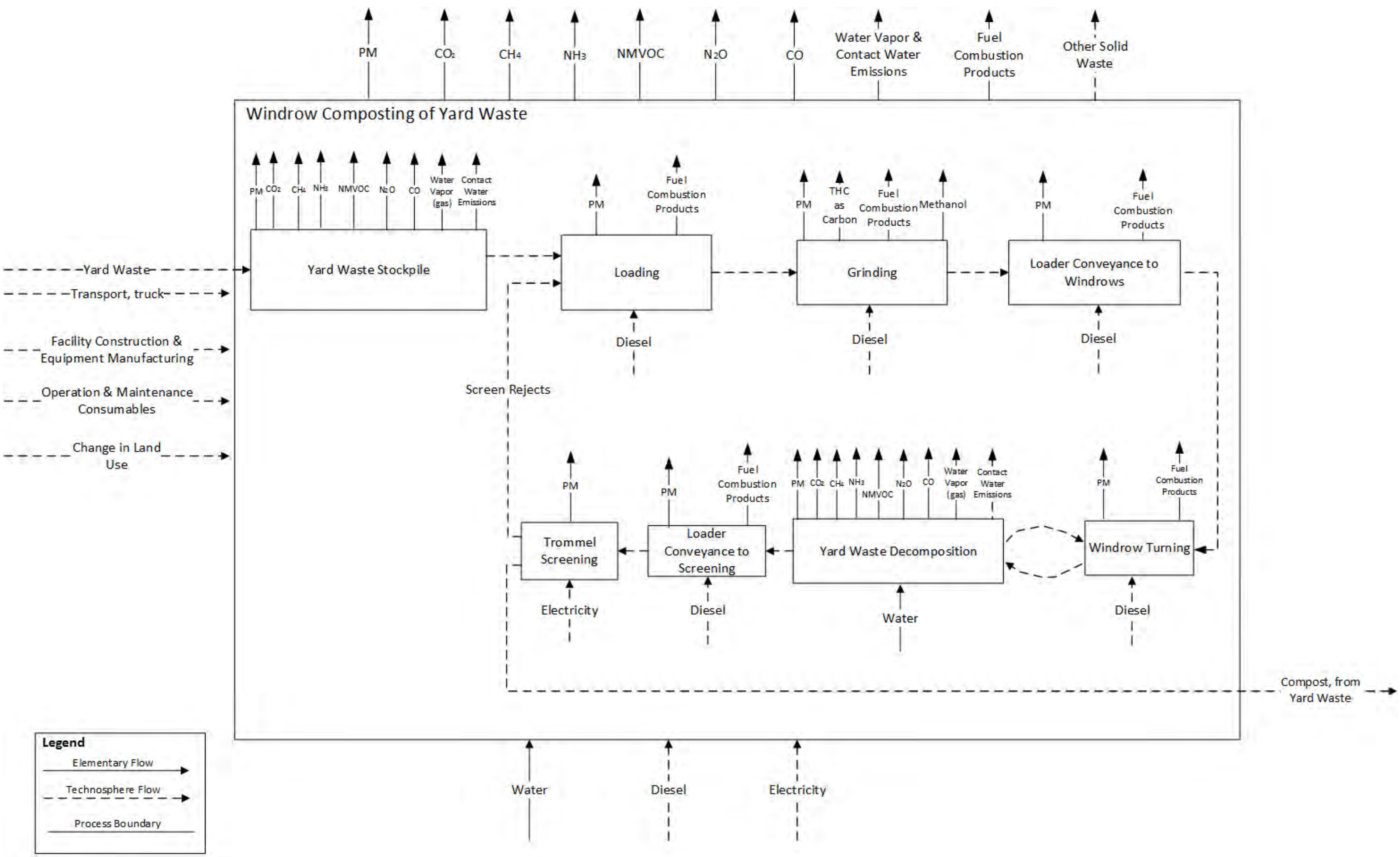


Figure 3-4. Example of Materials and Energy Inputs and Emissions Associated with Composting of Yard Waste

3.2.12 Change in Land Use

Prior to the construction of facilities and infrastructure necessary for material processing and management, it is usually necessary to develop greenfield areas for anticipated use. Undeveloped land may provide environmental services that could be accounted for in an LCA. For example, wetland areas may serve as points of groundwater infiltration and aquifer recharge, woodland areas serve as sinks for carbon dioxide, and vegetated strips of land between residences and highways may provide sound buffers to mitigate traffic noise pollution. None of the tools consider the removal of the existing environmental services of undeveloped land.

3.2.13 Alternative Materials Management Methods

Community decision makers are exploring alternative materials management technologies to reduce economic and environmental impacts associated with materials management. This section discusses the inclusion of several these treatment alternatives in the five tools evaluated. Specifically, these technologies include AD, pyrolysis, and gasification. The following paragraphs present a brief description of each of the technologies and some of the environmental considerations associated with each.

AD involves the biodegradation of organic matter by microbes in the absence of oxygen to produce biogas with high concentrations of methane as well as a semi-stabilized solid residual. While AD is commonly used for treating sludge and manure, the method can also be used to treat the organic fraction of MSW (e.g., food scraps and yard waste). The captured methane from organic degradation can be used directly in a thermal application (e.g., space heating, boiler fuel) or it can serve as an energy source for electricity generation. Digester solid residues may be beneficially applied as a soil amendment following additional stabilization.

Pyrolysis is thermal decomposition of materials in the absence of oxygen to a combustible gaseous stream (commonly referred to as *syngas*), a liquid fuel, and a solid residue (i.e. slag or char) (Tchobanoglous et al., 1993). Size reduction, removal of inorganics, and material drying are the primary pre-processes that are used for MSW pyrolysis and are commonly recommended or required by current technology providers (Tchobanoglous and Kreith, 2002). Pre-processed MSW is placed in a pyrolysis reactor and maintained at elevated temperatures ranging from approximately 400 to 800 °C utilizing an external heat source for its thermal decomposition.

Gasification involves the thermochemical conversion of carbon-based materials at high temperatures (usually in excess of 600 °C) into a synthetic fuel gas (i.e., syngas) mainly comprised of carbon monoxide (CO) and hydrogen. While gasification reactions differ from strict pyrolysis by the addition of a limited amount of an oxidant, gasification requires a pyrolysis step where carbonaceous material is volatilized and reduced to lower weight compounds (char). Syngas from gasification (and pyrolysis) may be directly combusted for steam-cycle power generation or, after varying degrees of cleaning and refining, may be fired in internal combustion engines and gas turbines. It can also potentially be converted into other chemicals, liquid fuels, or fertilizer products. The char is then subsequently gasified through partial oxidation.

As shown in Table 3-16 below, SWOLF is the only US tool to include any of these technologies in its software and although both AD and gasification are listed as processes the tool has available, the gasification process is currently not available for use. WRATE offers a variety of options for alternative material treatment technology processes simulations. However, as described in tool documentation, some of the data for the alternative treatment processes come from limited experience and were developed from a single operating or hypothetical facility. EASETECH includes AD processes reflective of hypothetical facilities and a single Swedish facility, where the hypothetical facility uses recovered biogas for a combined heat and power production process, while the Swedish facility uses the biogas for heat recovery and vehicle fuel production.

Table 3-16. Comparison of Tools for Alternative Materials Treatment Options and LCI Scopes

Alternative treatment facilities and parameters	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Anaerobic digester-food	No	No	Yes	Yes	Yes
Anaerobic digester-MSW	No	No	Yes	Yes	Yes[a]
Anaerobic digester-yard waste	No	No	Yes	Yes	Yes
Pyrolysis	No	No	No	No	Yes
Gasification	No	No	No[b]	No	Yes
Mechanical biological treatment[c]	No	No	No[b]	No	Yes
Distance to treatment facility adjustable?	NA	NA	Yes	Yes	Yes
LCI – Construction of alternative treatment facility	NA	NA	No[b,e]	No	Yes
LCI – Operation of alternative treatment facility	NA	NA	Yes	Yes	Yes[d]
LCI – Demolition and EOL management of alternative treatment facility	NA	NA	No	No	No

a. with restrictions
b. developer plans to include this feature in a future version
c. mechanical biological treatment combines mixed material stream sorting and material recovery with a form of biological treatment (composting or AD)
d. maintenance also included
e. only considered for cost estimation

3.3 Economic Impacts

The economic impacts resulting from the selection of a particular EOL materials management strategy are often some of the most critical factors considered by community decision makers when evaluating different materials management options. Among all the tools evaluated in this report, only MSW-DST and SWOLF provide process-specific annualized cost estimates as an output. Table 3-18 presents a listing of the user-adjustable parameters used for process-cost estimation. Cost estimates provided by these tools include labor and equipment capital costs for varying degrees of process complexity, and quantify costs associated with energy and process-related material consumption. Many of the default cost values (e.g., market price of recyclables) are representative of the market conditions at the time of tool development and may need to be adjusted for a reliable cost estimate.

Some of the cost models included in the tools account for economies of scale where a larger facility is more cost-effective. The cost models, in general, are linear and do not account for economies of scale. SWOLF offers flexibility to define and specific cost inputs for several facility sizes to account for economies of scale. Although annualized process-specific cost estimates such as those presented by MSW-DST and SWOLF are some of the key considerations used in decision making, EOL management options have other economic impacts such as affecting area property values and through job creation. None of the tools evaluated can assess these broader economic impacts.

Table 3-17. Comparison of Tool Flexibility for Process-Specific Cost Data

Consideration	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Energy Price					
Diesel Fuel Price	-	Yes	Yes	-	-
Purchased Electricity Price	-	Yes	Yes	-	-
Waste as Fuel	-	Yes	No	-	-
Electricity Buy-Back Rate	-	Yes	Yes	-	-
Collection					
Fringe Benefit Rate	-	Yes	Yes	-	-
Other Expense Rate	-	Yes	Yes	-	-
Administrative Rate	-	Yes	Yes	-	-
Hourly Wage of a Collector	-	Yes	Yes	-	-
Hourly Wage of Driver	-	Yes	Yes	-	-
Workers per Vehicle	-	Yes	Yes	-	-
Unit Price of a Bin	-	Yes	Yes	-	-
Capital and Maintenance Cost for Vehicles		Yes	Yes		
Number of Containers at each Commercial Location	-	Yes	Yes	-	-
Transfer Station					
Life of structure	-	Yes	Yes	-	-
Building Construction, Energy Use, Maintenance Rate	-	Yes	Yes	-	-
Engineering, Permitting Contingency Rate	-	Yes	Yes	-	-
Land Acquisition Rate	-	Yes	Yes	-	-
Paving and Site Work	-	Yes	Yes	-	-
Equipment Installation, Operating & Maintenance	-	Yes	Yes	-	-
Labor Rate and Productivity Data	-	Yes	Yes	-	-
Vehicle Throughput	-	Yes	Yes	-	-
Fuel Requirement	-	Yes	Yes	-	-
MRF					
Equipment Cost	-	Yes	Yes	-	-
Equipment Fuel/Electricity Consumption	-	Yes	Yes	-	-
Equipment Maintenance Cost	-	Yes	Yes	-	-
Market Prices of Recyclable Materials	-	Yes	Yes	-	-
Building Costs	-	No	Yes	-	-
Baling Wire	-	No	Yes	-	-
Labor Cost and Productivity Data	-	Yes	Yes	-	-

Table 3-17 (cont). Comparison of Tool Flexibility for Process-Specific Cost Data

Consideration	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Composting					
Site Preparation	-	Yes	Yes	-	-
Paving	-	Yes	Yes	-	-
Fencing	-	Yes	Yes	-	-
Building Construction (Office, Compost Pad and Equipment)	-	Yes	Yes	-	-
Land Acquisition	-	Yes	Yes	-	-
Engineering	-	Yes	Yes	-	-
Operating and Maintenance	-	Yes	Yes	-	-
Compost Amendment Costs	-	No	Yes	-	-
Equipment Repair	-	No	Yes	-	-
Revenue from Sold Compost	-	No	Yes	-	-
Waste-to-Energy/Refuse-Derived Fuel/Process Refuse Fuel Production Facility					
Lifespan	-	Yes	Yes	-	-
Capacity Factor	-	Yes	Yes	-	-
Heat Rate	-	Yes	Yes	-	-
Construction Cost	-	Yes	Yes	-	-
Operating and Maintenance	-	Yes	Yes	-	-
Landfill					
Landfill Characteristics (e.g., dimensions, slope, height, depth below grade)	-	Yes	Yes	-	-
Number of Cells/Facility Life	-	Yes	Yes	-	-
Landfill Engineering and Construction	-	Yes[a]	Yes[b]	-	-
Operation and Maintenance Cost (including labor, leachate treatment and disposal, groundwater monitoring, Overhead)	-	Yes	Yes	-	-
Beneficial Use of Collected Gas					
Capital Cost of Turbine	-	Yes	Yes	-	-
Capital Cost of Internal Combustion Engine	-	Yes	Yes	-	-
Electric Buy-Back Revenue	-	Yes	Yes	-	-
Revenue from Thermal Energy	-	No	Yes	-	-
Equipment EOL management	-	Yes	No	-	-

a. Over 40 user-specifiable parameters
b. Over 180 user-specifiable parameters

3.4 Tool Analysis/Output

Only MSW-DST and SWOLF analyzes and provide cost data as an output. The output of an LCA can generally be separated into three levels: raw emissions, emissions characterized into impact categories, and normalized characterized impacts. With the exception of WARM, all tools provide a breakdown of the emissions by each major process used in the management system studied. This gives the user an indication of the major emission contributors and therefore an idea of some of the more environmentally critical components of the system. Although WARM documentation can be used to assess the contributions of individual processes, the tool outputs only aggregated emissions.

Raw emissions (e.g., amount of methane released to air, amount of mercury released to air) can be characterized into environmental impact categories (e.g., global warming, human toxicity) through the use of a life cycle impact assessment method (LCIA). LCIAs include emission- and impact-category specific conversion factors which allow the quantification and aggregation of individual raw emissions in terms of a common reference emission (e.g., methane and dinitrogen monoxide are converted to units of carbon dioxide equivalents). All the tools incorporate at least one LCIA, while EASETECH and SWOLF allow the user to select from among several LCIAs.

The outputs format can impact the ease with which the user can manipulate and use the analysis to crosscheck and compare results between the management scenarios modeled. All of the tools allow the user to export data in a tabular spreadsheet format, which facilitates analysis and comparison of the results. A summary of the results and data analysis generated from each of the tools is shown in Table 3-18. MSW-DST was the only tool that could do optimization and perform a cost analysis; SWOLF developer plans to implement optimization feature in a future version. Some tools such as EASETECH and WRATE can analyze multiple scenarios simultaneously to facilitate result comparison.

Using the models' default/recommended LCIA methods, EASETECH (i.e. "EDIP97 wo LT") has the most impact categories of all the tools, with fourteen, followed by MSW-DST with twelve, SWOLF (default) and WRATE each with six, and WARM with one (as listed in Table 3-18). SWOLF allows user to add additional impact categories and the associated impact factors from several databases (e.g. CML, ReCiPe) included in the tool. Not all of the tools try to measure the same impact categories, and when they do they do not always use the same set of impact methods. This results in different impact categories and multiple impact category units, making comparison across tools difficult. This is evident in Table 3-19, which compares the units of the LCIA results for four of the tools. This table does not include WARM, which only calculates GHG impacts (CO_2-Eq) and total energy usage (Million BTU). Other than global warming, the only impact category analyzed across all tools is acidification, which is reported with different units in every tool. While all tools measure toxicity, each tool distributes the impacts of toxicity differently. For example, EASETECH and MSW-DST account for carcinogenic and non-carcinogenic human toxicity separately while WRATE lumps them into a single category. Converting impacts into the same unit and category for the sake of tool result comparison requires understanding the underlying impact method calculations and is beyond the effort that most tool users are likely to invest.

Table 3-18. Comparison of Tool Analyses and Output Data Options

Tool Analysis/Output	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Inventory emission results provided in/exportable to spreadsheet-based format	Yes	Yes	Yes	Yes	Yes
Allows selection of different LCIA methods	No	No	Yes	Yes	No[a]
Shows emission contributions from each process	No	Yes	Yes	Yes	Yes
Presents the contribution of each process to each impact category	No	No	Yes	Yes	Yes
Allows selection/ adjustment of normalization factor (i.e., person equivalents)	No	No	No	Yes	Yes
Out of range error feedback	Yes	Yes	No	No	Yes
Output data format	Can view in tabular formats only;	Prints four reports in xls format: mass flow, recycling, cost and inventory analysis report, and impact assessment report.	Can view in tabular format;	Can view in tabular format or export to CSV. Can group impacts by process or list raw emissions.	Can view in tabular and graphical formats (bar charts and spider chart), also view LCIs or LCIAs, can also chose to normalize data,
Does tool allow the LCIA factor modification?	No	No	Yes	Yes	No
Impact assessment methods used in analysis	NA	TRACI	Several LCIA methods (e.g., TRACI, CML, EDIP, ReCiPe) included	7 Available including versions of IPCC, ILCD and EDIP	CML 2001
Allows scenario optimization or selects the “best case” scenario	No	Yes	No[b]	No	No
Provides side-by-side comparison of different scenarios	Yes	No	No[b]	No	Yes
Allows execution of a Monte Carlo simulation (sensitivity analysis)	No	No	No	Yes	No

a. while the user can select from a default or CML 2001 options, the results appear the same
b. developer plans to include this feature in a future version

One potential use for materials-management tools beyond environmental evaluation is economic evaluations. MSW-DST and SWOLF can estimate the economic impact of materials management, along with the environmental impacts. These economic evaluations use many of the same mass and energy flows as the environmental emissions estimates. The equations and methodology used in developing the earlier MSW-DST tool form the framework being used to develop the SWOLF cost-estimate methodology, so the resulting cost estimates are similar. Both tools report cost as an annualized cost, which is the annual operation cost plus the capital cost divided by the expected lifetime.

Table 3-19. Comparison of Analyzed Tool Impact Categories and Associated Units

Impact	MSW-DST	SWOLF	EASETECH	WRATE
Global Warming	kg CO_2-Eq	kg CO_2-Eq	kg CO2-Eq	kg CO2-Eq
Ozone Depletion	-	-	kg CFC-11-Eq	-
Human toxicity, general	-	-	-	kg 1,4-DCB-Eq
Human toxicity carcinogenic	CTU[a]	-	CTU[a]	-
Human toxicity non-carcinogenic	CTU[a]	-	CTU[a]	-
Ionizing radiation	-	-	kg U235-Eq	-
Smog formation	kg O_3-Eq	kg NO_x-Eq	kg NMVOC	-
Eutrophication	kg N-Eq	kg N		kg PO_4-Eq
Freshwater Eutrophication	-	-	kg P-Eq	-
Marine Eutrophication	-	-	kg N-Eq	-
Ecotoxicity	CTU[a]	-	CTU[a]	-
Freshwater aquatic ecotoxicity	-	-	-	kg 1,4-DCB-Eq
Depletion of abiotic fossil fuel resources	-	MJ – Eq	MJ	-
Depletion of abiotic non-fossil fuel resources	-	-	kg antimony-Eq	kg antimony-Eq
Acidification	kg H+ moles-Eq	moles H+ Eq	AE[b]	kg SO_2-Eq
Terrestrial eutrophication	kg N-equivalent	-	AE[b]	-
PM	kg PM10-Eq	-	kg PM2.5-Eq	-

a. Comparative Toxic Units
b. Accumulated Exceedance (AE)

4 Applications of the Tools from a Decision-Maker's Perspective

4.1 Relevant EOL Material Management Scenarios

A series of scenarios representing some of the most pressing EOL materials management questions decision makers are currently encountering were modeled using these tools to assess their applicability and practicality for US communities. The scenarios are selected based on observed industry trends and the experiences of the authors. Table 4-1 lists the scenarios, associated major material handling processes, and the question we attempted to answer with each of the simulations.

A hypothetical US community was developed (based on field experience and conditions relevant to the US communities) to simulate specific material management challenges. The existing MSW management system of the community is identified as the "baseline scenario" throughout the discussions presented in this chapter. Unless otherwise specified, the baseline scenario is the starting point from which all of the scenarios are derived. The baseline scenario that follows is provided to give the reader a point of reference from which to compare the subsequent scenarios that have key assumption permutations (discussed in the following subchapter).

Baseline scenario: *A City consists of 40,000 single-family and 10,000 multi-family residences and 6,000 commercial entities. The EOL materials generation rate for a single-family residence (2.5 people per home) and multi-family residence (2.07 people per home) is 2.04 kg per capita per day. The average EOL materials generation for commercial establishments is 10 kg per entity per day. This results in an annual EOL materials generation of approximately 122,000 MTs of EOL materials. The City collects EOL materials from all three sectors and transports the EOL materials to a City-owned landfill 70 km from the City center. All the cells at the landfill are lined (single-composite liner) based on Subtitle D landfill specifications. None of the cells is closed yet. Due to its size, the City is not required to install a LFG collection system and LFG is emitted to the atmosphere. The City does not have any provision in place for curbside recycling. The City separately collects yard waste from the other EOL materials; 50% of the total amount of yard waste is captured and sent to a composting facility 70 km from the center of the city and 30 km from the landfill.*

Table 4-1. EOL Materials Management Scenarios Evaluated Using the LCA Tools

Process	Question	Scenario Title and Section Number
Baseline	What are the environmental and economic impacts of the current EOL materials management system?	Baseline Scenario (4.4)
Landfill	What are the environmental and economic impacts of different LFG management schemes (i.e., venting, flaring, LFG to electricity, and LFG to electricity from a landfill operated as a bioreactor)?	LFG Treatment Options (4.5)
Organics Collection and Processing	What are the environmental and economic impacts of instituting a biological organics management process for a source-separated organics stream (e.g., composting, AD)?	Source-Separate Organics Processing (4.6)
	What are the environmental and economic impacts of increasing backyard composting to reduce organics collection?	Backyard Composting (4.7)
Material Recovery	What are the environmental and economic impacts of different types of MRFs (i.e., single stream, dual stream, mixed waste)?	Materials Recovery (4.8)
	What are the environmental and economic impacts of manual versus automatic processes at MRFs?	MRF Automation (4.9)
	What are the environmental and economic impacts of recycling plastic compared to recycling glass?	Recycling Plastics vs Recycling Glass (4.10)
	What are the environmental and economic impacts of instituting a Pay-as-you-throw (PAYT) collection scheme to encourage recycling and source reduction?	Pay-as-You-Throw (4.11)
	What are the environmental and economic impacts of recycling versus landfilling CDD?	CDD Recycling (4.12)
	What are the environmental and economic impacts of instituting an e-waste collection system to capture and recycle e-waste currently being landfilled?	E-waste Collection and Recycling (4.13)
Collection and Transport	What are the environmental and economic impacts of using different fuels in a collection vehicle fleet (i.e., diesel, CNG, biogas)?	Collection Vehicle Fuels (4.14)
	What are the environmental and economic impacts of different levels of recyclables collection vehicle automation (i.e., manual for dual-stream versus automated for single-stream recycling)?	Collection Vehicle Types (4.15)
	What are the environmental and economic impacts of having a centrally located transfer station?	Transfer Station (4.16)
Thermal Treatment	What are the environmental and economic impacts of instituting different thermal treatment processes for EOL materials (i.e., incineration at a WTE facility, gasification, and pyrolysis)?	Thermal Treatment Options (4.17)
	What are the environmental and economic impacts of incinerating plastic for energy recovery compared to recycling plastic?	Plastic Incineration vs Recycling (4.18)
Landfill Mining	What are the environmental and economic impacts of RDF production and thermal treatment of as-discarded EOL materials versus RDF production and thermal treatment of reclaimed materials from landfill mining?	RDF Recovery Before and After Landfilling (4.19)

4.2 Basis for Material Composition Assumptions

The composition of the materials stream used for LCA has significant impact on the modeling results. Therefore, it is important when comparing different tool results, such as this report does, that all of the tools are using the same initial composition of materials. It should be noted that all the tools allow the user to specify the percent composition or the amount of different material categories. The default EOL material compositions of each of the tools were assessed to determine if they needed to be adjusted to reflect a common composition. To assess the default tool material composition variation, materials were combined into more general categories, consistent with the general categories used in the US EPA Facts and Figures report (US EPA 2014). For example, plastic types (e.g., HDPE, PET, hard plastic, soft plastic) were pooled into a single "Plastics" category.

Figure 4-1 presents the default materials composition of the tools as well as the composition of EOL materials generated in the US in 2012 based on the US EPAUS EPA (2014). Figure 4-1 does not include the composition for WARM as a default "mixed MSW" composition could not be found in the tool documentation.

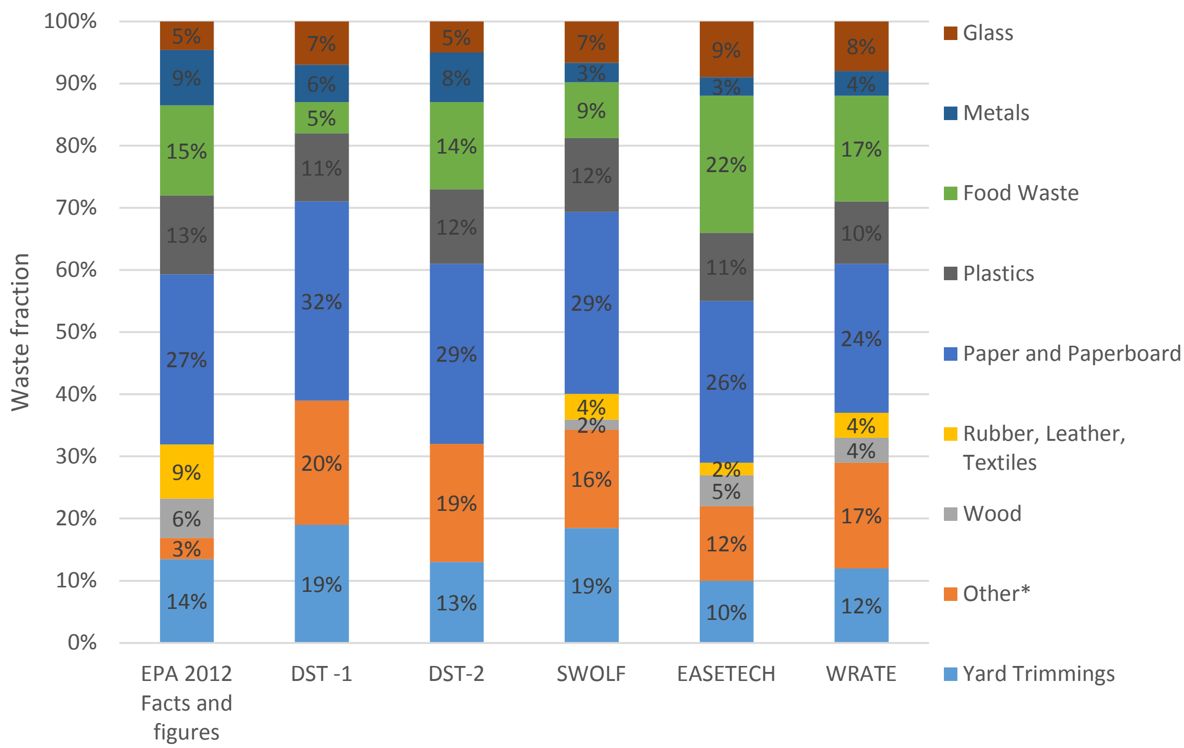


Figure 4-1. Comparison of 2012 US EPA Fact and Figures and Tools' Default MSW Composition

Although many material categories are common among the tools, some of these categories have appreciable proportional differences, (e.g., MSW-DST assumes 10% and EASETECH assumes 22% food scraps) and some material categories typically present in the US EOL materials stream were not included (e.g., rubber, leather, textiles, and wood are not included in MSW-DST). Additionally, although the material compositions among the tools were relatively similar to US EPA (2014), an EOL materials composition representative of US material generation was desired for a meaningful comparison of tool results for the intended audience (decision makers of the communities in the US). Therefore, the material composition of all the tools was adjusted to reflect the US EPA (2014) data.

Many of the material categories in the US EPA (2014) report are not consistent with the material categories presented in the tools. Assumptions were made to fit the US EPA composition categories into the most similar categories in each tool. Table A-4 in (see Appendix A) provides the detailed EOL materials composition from the US EPA (2014) from which the uniform EOL materials composition is derived. For each material category in the US EPA (2014), the corresponding best-match EOL materials category for the tool is also presented. The final column of the table defines whether the material is considered "recyclable" for the scenarios which evaluate the impacts of recycling. The use of the US EPA (2014) material composition presented the following challenges:

1. Because the US EPA report has more categories than the tools provide, many categories had to be pooled together into the nearest appropriate category. This means that some material categories that may have both recyclable and non-recyclable components had to be combined. For example, multiple paper types included in the US EPA report were assigned to the "mixed paper, primarily residential" category in WARM. Additional material category assignments are identified in Table A-4.
2. When determining a best fit for a material not available in a tool, several characteristics and material properties had be considered, for example, whether the material is likely to be clean or dirty, recyclable or non-recyclable, combustible or non-combustible, or alone or mixed with other similar materials in a mixed stream. Paper and plastic materials have the greatest number of unique specific materials in the US-based EOL materials composition and consequently have the highest number materials that do not match up with materials available for selection in each of the tools. For example, the non-durable paper material category in the US EPA report composition had a subcategory for paper plates and cups. None of the tools have comparable materials described so specifically; therefore, more general materials had to be selected which were assumed to include paper plates and cups. In EASETECH, "dirty paper" is the surrogate material for paper plates and cups; in MSW-DST it is "paper non-recyclable"; in SWOLF it is "Paper-Non-Recyclable"; in WARM it is "mixed paper (primarily residential)"; and in WRATE it is "unspecified paper."
3. The US EPA (2014) composition identifies plastics based on resin type (i.e., PET, HDPE, LDPE, etc.) while EASETECH and WRATE classify plastics based on their use or characteristics (i.e., plastic film, soft plastic, hard plastic, packaging, etc.). Additionally, although MSW-DST and SWOLF do classify plastics based on PET and HDPE resin types, the US composition is more specific and includes plastics not included in MSW-DST. Therefore, the material category "plastic non-recyclable" is used for all the other resin types in MSW-DST and SWOLF, as it is assumed that these plastics most closely fit the non-recyclable category. With EASETECH and WRATE a best effort is made to match up each plastic category with available materials which most closely matched the description of the material used and the resin type provided in the US composition. For example, the US EPA (2014) has a material category "durable goods" made of PET; therefore, the material category "hard plastic" and "other dense plastic" were selected in EASETECH and WRATE, respectively, to represent "durable goods." Some plastics seemed to match well between the US composition and EASTECH and WRATE. For example, bottles and jars made of PET is a material in the US EPA (2014). EASETECH and WRATE have plastic materials for, respectively, "bottles" and "drink bottles" and these types of bottles are typically made of PET.
4. The rubber and leather composition category in the US EPA report was also not available in some of the tools. If there were no comparable materials in the tools, a combustible materials category was used as a surrogate for rubber and leather.
5. WRATE and EASETECH both have general categories for wood waste, whereas WARM has categories for MDF and dimensional lumber and MSW-DST has no category for wood but does have an undefined category called "CCCR" (which it appears to model similarly to wood since it has a methane generation potential and heating value comparable to wood). All wood waste in the US EOL materials composition was, therefore, assigned to the dimensional lumber category for WARM and the CCCR category for MSW-DST.

6. Carpet appeared to be the best fit material for textiles in WARM. WARM assumes residential carpet to be composed of face fiber, woven backing, carpet backing adhesive, and a latex adhesive. The face fiber comprises 45% of the total carpet weight, which makes up the largest single component in carpet. The face fiber is comprised mostly of nylon (65%) and then PP and PET (US EPA 2014). Nylon is a synthetic fiber that is used in making textiles; therefore, since the WARM tool does not have a textile category, the carpet category was used as a surrogate for textiles.
7. The "other" and the "other wastes-miscellaneous inorganics" materials in US EPA (2014) do not match well with the materials available in the tools. Since the "other" material is comprised primarily of combustible types of materials and the "other wastes-miscellaneous inorganics" is comprised of non-combustible (inorganic) materials, it is assumed that the materials these most closely resembled are combustible and non-combustible materials. In WARM, a non-combustible material is not available; therefore, clay bricks are used as a surrogate for "other" since this is an inert, non-combustible material.
8. Some tools also have multiple materials that could be acceptable for matching a material in the US composition. For example, in MSW-DST there are two material categories for HDPE plastic, translucent and pigmented. Since the US composition data do not divide the category into more specific categories, it is assumed that 50% of the material quantity in MSW-DST is translucent HDPE and 50% is pigmented HDPE.
9. EASETECH and MSW-DST have multiple materials (grass, leaves, and branches) that could fall under yard trimmings, so a representative composition of yard trimmings (50/30/20, which is the default value for these materials in MSW-DST) is used to determine what percentage of each of the materials is in the yard trimmings. EASETECH also breaks food scraps down into vegetable waste and animal food scraps; therefore, a representative composition of vegetable and animal food scraps (90/10) has been selected for EASETECH (Jones, 2002).

It should be noted that none of the tools can completely match the EOL materials composition as described in the US EPA (2014). Depending on the objectives of the tool user, certain tools may be more amenable to modeling certain materials. For example, as was described earlier, modeling plastics accurately using WRATE and EASETECH is challenging if the user's EOL materials characterization data are provided in terms of plastic resins (e.g., PET, HDPE). A surrogate materials assignment (i.e., the next closest material) would, in general, be necessary to model a US-specific EOL materials stream due to the variability and inconsistencies in the naming conventions of specific EOL materials.

As described earlier, EOL materials are generated from three sectors of the community (single-family, multi-family, and commercial). The composition of materials from all three sectors was assumed to be the same as the US EPA (2014) for the purpose of the simulations conducted in this study; in reality, the materials compositions are dependent on the sector of origin. All three materials streams were simulated individually for WRATE. The total materials mass calculated based on the annual materials generation rates were used for WARM simulations. For MSW-DST, not all material fractions were available for commercial, single-family and multi-family. This made it difficult to model a uniform composition across all the sectors. To ensure a uniform composition, the categories in US (2014) which were only included in the commercial or single-family categories were weighted more heavily in those fractions to make the overall composition match. Because of the difficulty in matching compositions among the three streams, multi-family streams were not modeled. Instead, single family population densities were increased to match the average between single-family and multi-family at 2.83 people per residence. The population was increased to 134,000 residents in single-family housing to account for the loss of the multi-family stream. For EASETECH, population is not considered, but only the total mass of materials generated, set at 121,000 MTs per year, consistent with other models. The parameters used to model the community across all the tools are summarized in Table 4-2. It should be noted that not every parameter is relevant to every tool.

Table 4-2. Global Assumptions for Baseline Scenario

Global Assumption – Description	Parameter Units
EOL materials composition	Section 4.2
Population Single family Multi family Commercial	 113,000 people 21,000 people 6,000 entities
Material generation rate	4.5 lbs (2.04 kg) per person per d
MSW recycling rate	0%, no existing recycling program
Yard waste collection rate	50% of the generated mass
Collection bins, single-family	2 bins, 360 liters each
Collection bins, multi-family	2 bins, 1.1 m^3 each, for every 5 residences
Collection bins, commercial	2 bins, 1.1 m^3 each
Transport distance from end of material collection to disposal in landfill	70 km
Transport distance from end of material collection to yard waste composting facility	70 km
Transport distance from composting facility to landfill	30 km
Short-haul vehicle (diesel truck, 7.5 – 12 MT capacity)	≤50 km
Long-haul vehicle (diesel truck, 14 – 20 MT capacity)	>50 km
Yard waste composting method	Windrows
Landfill capacity	2 million MTs
Landfill annual capacity	65,000 MTs/year
Landfill liner type	Composite
Landfill cover type	Clay
EOL materials decay rate (k)	0.05 yr^{-1} for EASETECH and SWOLF 0.052 yr^{-1} for WARM 0.057 yr^{-1} for MSW-DST Tool default for WRATE
Methane oxidation	10%
LFG recovery	No recovery

4.3 Additional Global Modeling Assumptions

To avoid repetition of common assumptions made throughout the scenarios evaluated, this section discusses global assumptions that are assumed for all tools and modeling scenarios (unless otherwise noted). Global assumptions are discussed from two perspectives; those that are assumed in the baseline scenario (as is described in Section 4.4) and those that are generally assumed and could be applicable for any of the scenarios (referred to here as *global modeling assumptions*). In some scenarios there will be instances when there will be differences between the global assumptions and the assumptions specific to the scenario; those assumptions are identified in the beginning of each scenario description.

Baseline assumptions are used to simulate the material management circumstances of a representative community in the US and are based on industry standards, available information on US demographics, reasonable estimates based on the experiences of the authors, and on the baseline scenario previously described. Some of the assumptions are based on flexibility limitations of one or more tools. For example, energy mix assumptions are based on the limitations of WARM, which cannot be adjusted to accommodate a specific energy mix. WARM's 2010 energy mix assumptions were adopted for all of the tools for consistency, where possible. WARM uses a baseload fuel mix to calculate emissions resulting from electricity consumption, as presented in Figure 4-2. This baseload energy mix was used to simulate the emissions resulting from electricity consumption in all the tools.

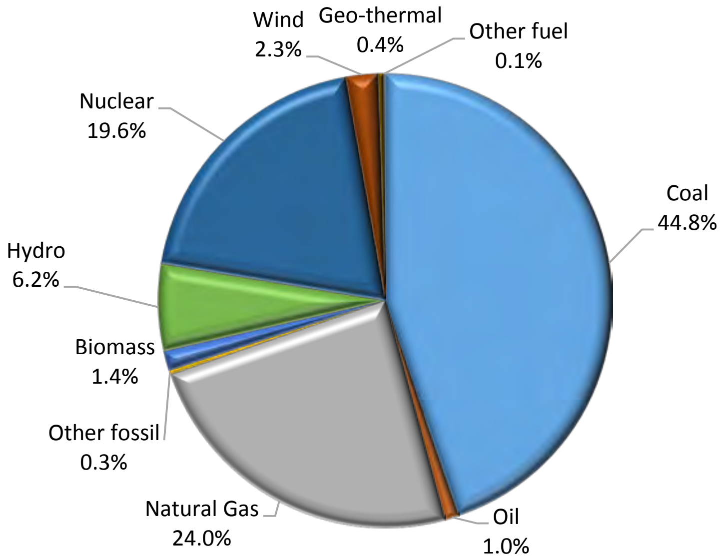


Figure 4-2. Baseload Energy Mix Used for Simulations

Figure 4-3 presents the marginal (non-baseload) energy mix estimated from WARM; because WARM documentation does not provide the energy mix for marginal (or non-baseload) sources, the mix was assumed to be derived from fossil fuels in the same proportions as those used in the WARM baseload energy mix.

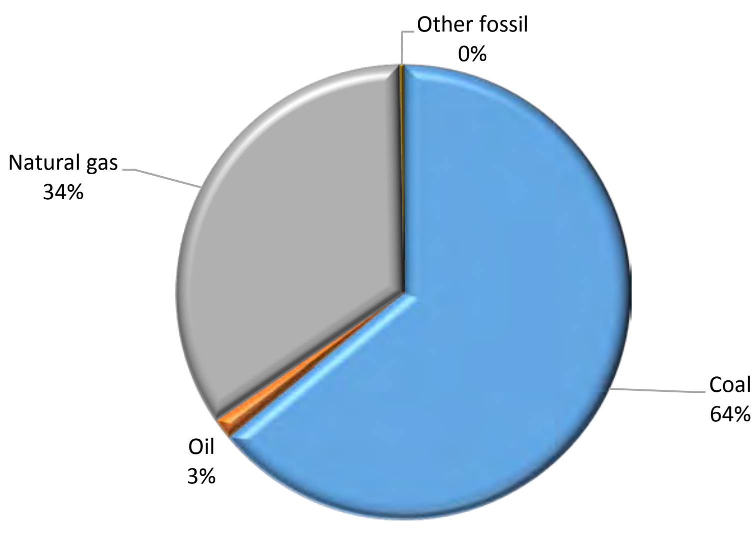


Figure 4-3. Marginal Fuel Mix Used for Simulations

The marginal energy mix presented in Figure 4-3 was used in MSW-DST and WRATE. However, the marginal energy mix used for EASETECH was 100% coal; adjusting the marginal mix in EASETECH to reflect the WARM non-baseload energy mix could not readily be accomplished because processes which directly simulate electricity generation from natural gas and oil-fired utilities are not currently available in the tool. A 100% coal-derived marginal energy mix represented the mix closest to the marginal mix presented in Figure 4-3. For SWOLF, all electricity produced was assumed to displace electricity based on the tool's baseload mix, as the tool does not appear to allow the assignment of a unique displaced electricity mix.

Collection container assumptions for specific bin types are based on the container types available in WRATE (which are similar to those commonly used in the US). As discussed in Chapter 3, the collections portion of WRATE is the most specific of all the tools, whereas the collection process in WARM is the most general (e.g., is not specific to any bin type or collection vehicle type). Transportation distances are assumed based on reasonable estimates and the truck types are based on what types are available in the tools. In WARM, specific collection vehicles cannot be assigned; however, vehicles can be selected based on a variety of parameter in the other tools. Vehicles most common to all tools (with the exception of WARM) are used in the baseline assumptions. Since diesel fuel is most commonly used in US road transportation, it is assumed these vehicles are diesel fueled. A set collections route is not established for the tools since some tools cannot account for this; MSW-DST, SWOLF and EASETECH are the only tools that can accommodate a collection route distance. Assumptions for short-haul distances (≤50km) assume a smaller vehicle than that used for longer-haul distances (>50 km).

The average size of the US landfill was based on the sizes included in WRATE, since many of WRATE's underlying assumptions are based on landfill size. Only three landfill sizes can be selected in the tool, so the US landfill size that is exempt from LFG collection (i.e., 2.5 million MT) is used to select the closest landfill size in WRATE. The material decay-rate constant (k) cannot be adjusted in WRATE and the underlying metadata are not reviewable through the tool. WARM has limited adjustability; k values are limited to five predefined values. Although MSW-DST gives the option for a user-specified k value, discussions with the developer revealed that this field is no longer used in the tool's calculations. The tool default option of 0.052 yr^{-1} and 0.057 yr^{-1} was used for WARM and MSW-DST, respectively. A decay rate of 0.05 yr^{-1} was used for EASETECH and SWOLF, similar to WARM's value of $k = 0.052\ yr^{-1}$. Methane oxidation through the landfill's cover soil is assumed to be 10%. LFG is not collected in the baseline scenario. EASETECH, MSW-DST and WARM are the only tools that allow the user to model the absence of a LFG collection system; 0% LFG collection was selected for the other tools to simulate the absence of LFG collection. The tool default landfill operational life (i.e. the timeframe over which EOL materials are deposited in the landfill) was used for MSW-DST and SWOLF (i.e., 10 years) and for WRATE (i.e., 20 years). Landfill operational life assumptions are not used in EASETECH or WARM since all post-consumer materials are modeled as being instantaneously placed in the landfill at year zero.

As specified in Subtitle D landfill rules, a composite liner (or equivalent) is required for MSW landfills in the US; therefore, it is assumed that the landfill has a composite liner. A clay cap final cover was selected for WRATE and SWOLF, while the model default cap was used for MSW-DST. Emissions associated with constructing a final cover in EASETECH and WARM are not considered. Where possible, a windrow facility was specified in the tools for composting yard waste, since windrowing is the management method assumed in WARM.

Assumptions related to processes such as transportation distances, material recovery, and recycling that are common for multiple scenarios are included in Table 4-3. The materials composition, population, material generation rate, yard waste collection rate, energy mixes, collection bins, transport distances to the composting facility and the landfill, and general long- and short-haul transportation vehicles are the same as the baseline scenario and are therefore not repeated in this table.

Information on the average residual rates for MRFs is approximated based on the data reported by Berenyi (2007), which presents a range of residual rates for single- and dual-stream MRFs. For a mixed-waste MRF, 20% of the incoming EOL materials are assumed to be recovered, which is comparable to the value observed for other communities. Some of the tools allow the user to assign a material-specific substitution ratio defined as the amount of recycled materials needed to replace a unit of virgin materials. The tools' default substitution ratios were used for all the simulations as this parameter cannot be changed for many of the tools.

Table 4-3. General Global Assumptions

Global Assumption – Description	Parameter Units
Transport distance from the last collection point to treatment facility [including MRF, SSO composting, thermal treatment (i.e., combustion/incineration, gasification, pyrolysis)]	70 km
Transport distance from thermal treatment to ash landfill	1 km
Transport distance of MRF residuals management (to landfill disposal)	30 km
Transport distance of MRF recovered materials to remanufacturer plant	100 km
MRF residual rates: Single stream Dual stream Mixed EOL materials stream	 12% 6% 80%
Substitution ratio	Tool default

4.4 Baseline Scenario

4.4.1 Scenario Description and Assumptions

To provide a common point of comparison across scenarios, the baseline scenario described in detail above was simulated in each of the tools. Unless otherwise noted, all assumptions listed in this scenario are also assumed in the other scenarios. When the scenario descriptions refer to a community, the community it is referring to is the one described in Section 4.1. Figure 4-4 below provides a visual representation of the materials flow for the baseline scenario showing the routes by which the EOL materials are generated, transported, and managed.

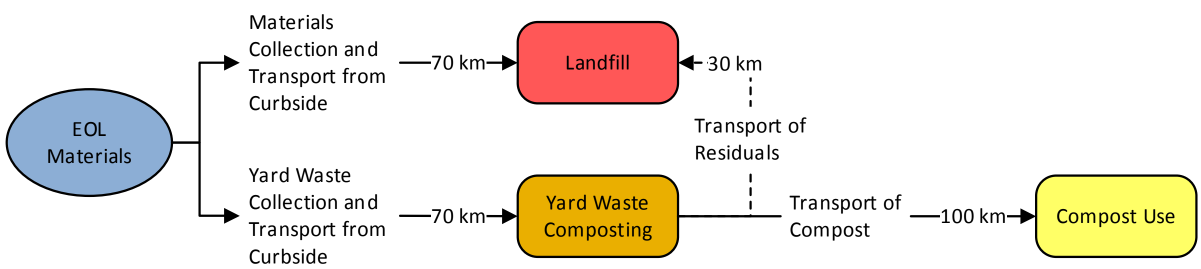


Figure 4-4. EOL Materials Flow with Composting of Yard Waste and Disposal of Remaining Materials (Baseline Scenario)

4.4.2 Results and Discussion

As discussed in Chapter 3, each tool includes a different set of impact categories, often with different units and different calculation methodologies (as discussed in Chapter 3). Therefore, it is difficult to compare results from the different tools for most impact categories. In addition, WARM only provides GHG emissions. GHG emissions are common to all tools and calculated using similar methodologies, so GHG emissions were used as the primary point of comparison among the tools.

Figure 4-5 presents process-specific (and net) GHG emissions for the baseline scenario for each tool. All tools suggest that landfilling is the largest GHG-emitting process among all of the processes. The landfill GHG emission estimate ranges from 8,000 MT CO_2 eq (for EASETECH) to 179,000 MT CO_2 eq (for MSW-DST) neglecting carbon storage. Considering carbon storage, the landfill GHG emission estimate ranges from 28,000 MT CO_2 eq (for EASETECH) to 144,000 MT CO_2 eq (for MSW-DST). All the tools suggest that the GHG emissions contributed by the EOL materials collection, transport and composting processes are negligible compared to that of the landfill. Composting emissions represent 1% or less of the GHG emissions of landfilling. At most, collection and transportation together represent 10% of the GHG emissions of landfilling for SWOLF and less than 5% for all other tools. MSW-DST and SWOLF provide aggregated emissions for collection and transportation processes whereas EASETECH and WRATE provide individual emissions for collection and transport processes. For consistency, collection and transport emissions from WRATE and EASETECH were aggregated into one category for all the data presented in the rest of the chapter.

It should be noted that the way data presented in Figure 4-5 is formatted is not necessarily the same formatting that is output by each of the tools. For example, MSW-DST reports emissions values (LCIs) of individual contaminants for each contributing process (e.g., CH_4 values from landfill and transportation are individually provided by the tool), but only one global warming impact value (MT CO_2 eq) aggregating all the processes (e.g., transportation, landfill, composting) is reported. The LCIA impact values were distributed in the same proportions as the emissions from the LCIs to estimate the process-specific emissions. Similarly, transportation and landfill disposal emissions factors from WARM (as reported in documentation) were used to distribute the overall landfill emissions into LFG and transportation-specific categories (including material placement into landfill). The GHG emissions were distributed among processes to compare process-specific emissions across the tools.

Two categories of GHG emissions that occur from landfilling are biogenic and fossil. Biogenic emissions are those associated with biodegradation of organic materials (e.g., LFG) whereas fossil emissions corresponding to those released as a result of the combustion of petroleum-based materials or fuels (e.g. from combustion of fuel used for EOL materials placement, raw materials extraction and manufacturing of various materials used for landfill construction if considered by the tool). All the tools except WARM provide fossil and biogenic GHG emissions. The fossil GHG emission constituted 3.7%, 1.5%, <1%, and <1% of the overall GHG emissions for SWOLF, EASETECH, MSW-DST, and WRATE, respectively. WARM GHG emissions corresponding to the combustion of fuel used for EOL materials transport to the landfill and placement at the landfill are reported to be 0.04 MT carbon dioxide equivalent (MT CO_2 eq) per short ton (US EPA 2014). The fossil GHG emission for the community's entire EOL materials stream is, therefore, estimated to be approximately 5,400 MT CO_2 eq, which represents approximately 4% of the overall landfill GHG emission estimate for WARM. As WRATE includes emissions associated with energy and materials used for liner construction, fossil GHG emission amounting to less than 1% of the overall GHG emissions suggests that the GHG emissions corresponding to liner construction are insignificant in comparison to those associated with LFG emissions.

An additional consideration that should be taken into account for comparing GHG emissions from the selected tools is carbon storage. As discussed in Chapter 3, carbon storage is equivalent to the biogenic carbon dioxide emissions that would have been released if the materials were placed in an aerobic environment; carbon storage lowers the net GHG emission estimate from landfilling. The results for WARM and SWOLF incorporate the offsets of carbon storage, whereas EASETECH presents carbon storage offsets separately. WRATE and MSW-DST (default) results do not include carbon storage. WRATE assumes all carbon will eventually be released from the landfill. MSW-DST does not include carbon storage in the model results, but carbon storage can be estimated using the tool post-processor. For a meaningful comparison between tools, with the exception of WRATE, the global warming impact of carbon storage is separately presented for each tool in the results of each applicable scenario as the green bar located beneath the x-axis. Carbon storage estimates for WARM and SWOLF were added to the net landfill GHG output to estimate the GHG emission if carbon storage is not accounted for solely to compare results from these tools to MSW-DST, WRATE, and EASETECH.

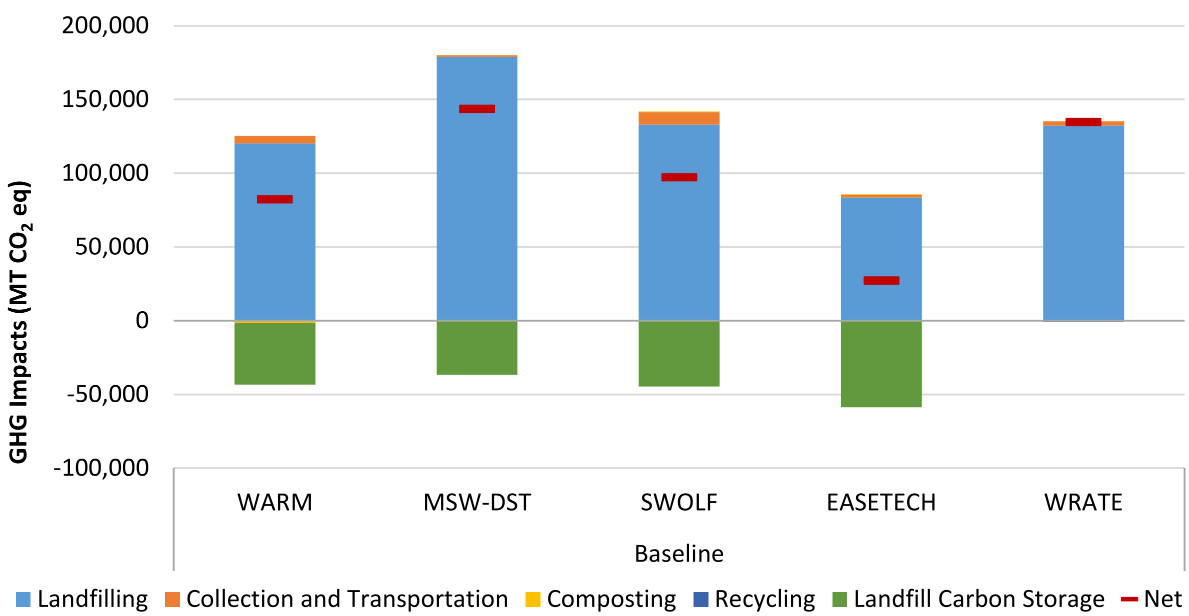


Figure 4-5. Comparison of the LCA Tools' GHG Emissions Estimates for Baseline Scenario

Although WARM, MSW-DST, and SWOLF use the same first-order decay model to estimate LFG generation, the variation in the results for GHG impacts for these three tools are primarily attributed to variations in constituent-specific methane generation potentials used for these tools. The aggregated methane generation potential used for MSW-DST and SWOLF are55% and 27% higher than the values used for WARM; as mentioned earlier, the tool-default methane generation potentials were used for modeling as a majority of the tools do not allow flexibility to modify these values. The carbon storage estimate ranged from 36,500 MT CO_2 eq (for MSW-DST) to 56,500 MT CO_2 eq (for EASETECH). The carbon storage for MSW-DST presented in Figure 4-5 assumes that the tool provides the carbon storage in CO_2 eq units and not in C eq as displayed in tool output; the conversion of C eq. to CO_2 eq would have resulted in an unreasonably greater carbon storage estimate when compared to those from the other tools. Carbon storage has significant impact on the net landfill GHG emission estimate.

Acidification potential is the only impact category apart from global warming (i.e., GHG emission) common to all tools except for WARM, which has only GHG emissions and energy as outputs. Unlike GHG emissions, the units presented and methodology used differ across all tools. Because of differences in units and methodology with acidification potential, the results across tools are not comparable with one another. Figure 4-6 shows the relative fraction of acidification potential emissions by process all the tools except WARM. All tools except SWOLF suggest that collection and transportation is the process with the greatest acidification potential. SWOLF and EASETECH suggest that landfilling and composting have significant acidification impacts. A wide variation in contributions by different sectors among different tools potentially results from the lack of uniformity in assumptions and calculations among LCA tools.

Figure 4-6. Comparison of the LCA Tools' Acidification Impact Estimates for Baseline Scenario

Two (MSW-DST and SWOLF) of the five tools provide total cost as an output. Figure 4-7 compares cost estimates from MSW-DST and SWOLF for the baseline scenario. Both tools use the same sets of cost equations, leading to similar cost results. Interestingly, collection and transport, while contributing insignificantly to GHG emission, has the greatest cost when compared to landfilling and yard waste composting processes of the baseline scenario.

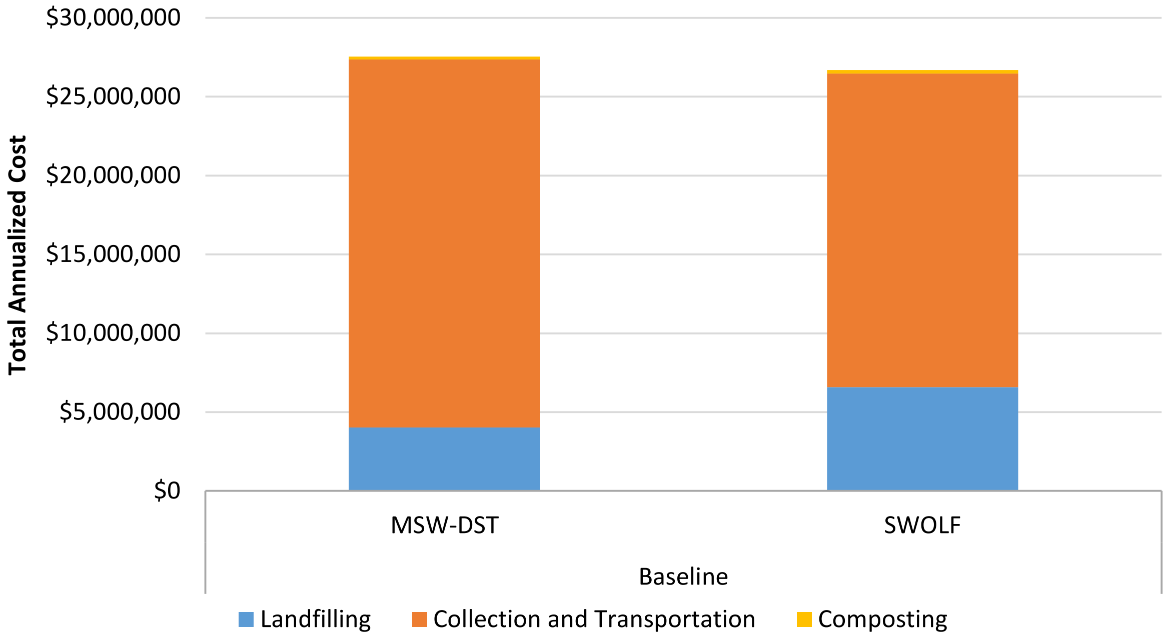


Figure 4-7. Comparison of the LCA Tools' Total Annual Cost Estimates for Baseline Scenario

4.5 LFG Treatment Options

4.5.1 Scenario Description and Assumptions

As discussed in the previous section, uncontrolled LFG emission is the major contributor to the overall GHG emission from the community's MSW management system; LFG is currently emitted to the atmosphere. This scenario simulates the economic and environmental impacts of alternative LFG management strategies such as active LFG collection and destruction via flaring, active LFG collection coupled with electricity generation. The environmental and economic impact of operating the landfill as a "bioreactor" to enhance the LFG production rate and the associated electricity generation were also simulated. This section compares the environmental and economic impacts of the following three alternative LFG management options. Figure 4-8 presents the flow of material for these options. The LFG collection efficiency for all options is assumed to be 85%.

1. "LFG flare" option. The LFG is actively collected and combusted in a flare in the option. The methane destruction efficiency of the flare is assumed to be 99.96%.
2. "LFG-to-electricity" option. LFG is actively collected and combusted in an internal combustion engine to generate electricity. The generated electricity replaces the marginal electricity mix. The methane destruction efficiency of the internal combustion engine is assumed to be 98.3%. The energy conversion efficiency of the internal combustion system is assumed to be 34%.
3. "LFG-to-electricity with bioreactor" option. The landfill is operated as a bioreactor landfill to enhance LFG generation. The LFG is actively collected and combusted in an internal combustion engine for electricity generation. A decay rate "k" of 0.12 yr^{-1} (i.e., the WARM default value for bioreactor operation) was used for simulating the enhanced LFG generation from bioreactor operation. All the assumptions of the LFG-to-electricity option including collection efficiency were used for this option as well.

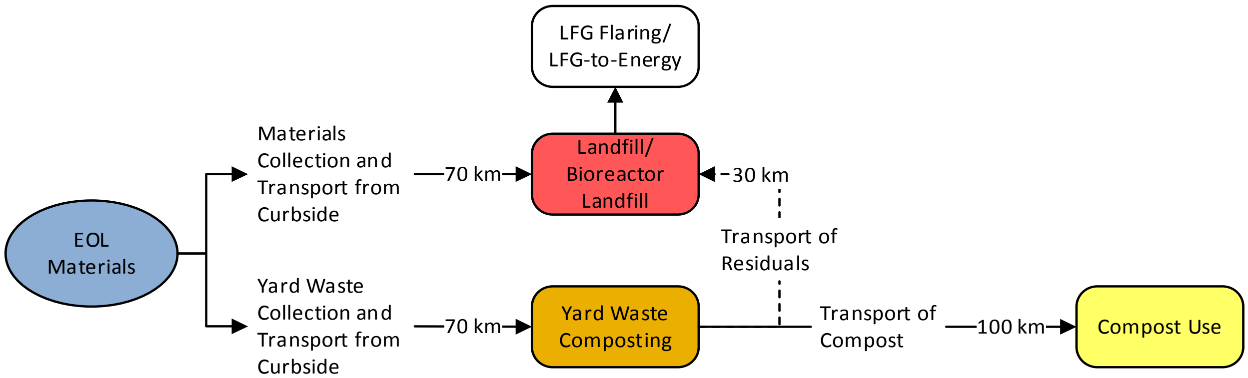


Figure 4-8. EOL Materials Flow with Materials Disposal in Landfill or Bioreactor Landfill with LFG Collection and Treatment with or without Electricity Generation

All of the tools have options to select different LFG management strategies. All tools have the option of sending the LFG to a flare or to a gas-to-electricity system with user-specified values for methane destruction and energy conversion efficiency. All of the tools except for WRATE also have the option of selecting bioreactor landfill operation. The tool default k value of 0.12 yr^{-1} was selected for WARM and MSW-DST. SWOLF's decay rate was manually adjusted to 0.12 yr^{-1}. The bioreactor option in SWOLF appears to be under development and is expected to be included in a future version. This option would allow the user to specify time-varying LFG collection efficiency to model methane emission from landfill. WRATE does not have a bioreactor option or the ability to set an equivalent k value, so bioreactor operation could not be modeled with WRATE. The results of these options were compared with the baseline scenario (the scenario discussed in Section 4.4 where LFG is not collected).

4.5.2 Results and Discussion

Figure 4-9 shows that all tools predict a decrease in GHG emissions impacts when methane destruction is employed through a flare or through a gas-to-electricity system. Electricity generation further reduced the impact or increases the benefit by offsetting the emissions associated with avoided electricity production. The most dramatic effect is seen in the transition from not collecting LFG to flaring LFG due to avoidance of the high global warming impact associated with methane emissions. As discussed previously, WRATE estimate a greater reduction in GHG impacts than WARM, MSW-DST, and SWOLF due to methane destruction through flaring or implementing a gas-to-electricity system.

Implementation of a bioreactor landfill (with LFG-to-electricity) does not significantly reduce overall GHG emission over the LFG-to-electricity case because bioreactor landfills are generally assumed to release the same amount of methane but over a shorter time horizon. For the bioreactor landfill case, EASETECH and WARM predicts greater GHG emission than the LFG-to-electricity case, which is contrary to the estimations from MSW-DST and SWOLF. This, probably, is a result of the differences in LFG generation rate estimation algorithm used by these tools.

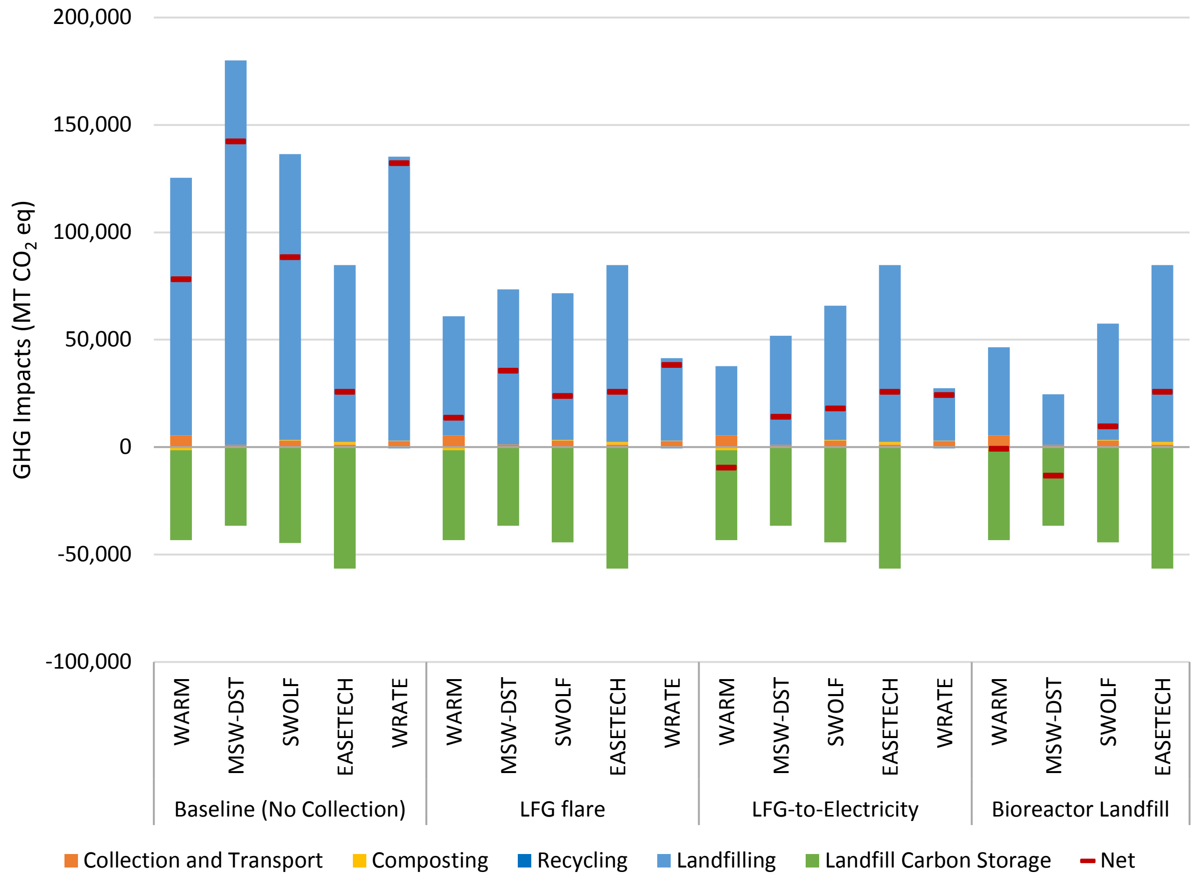


Figure 4-9. Comparison of the LCA Tools' GHG Emissions Estimates for Different LFG Treatment Options

All tools include a credit for GHG impacts for gas-to-energy production in the net output, since it displaces the combustion of other fossil fuels. EASETECH and WRATE are the only tools that provide the emission offsets from implementing a LFG-to-electricity system as an output. The GHG impacts of electricity generation based on EASETECH can be seen in Figure 4-10.

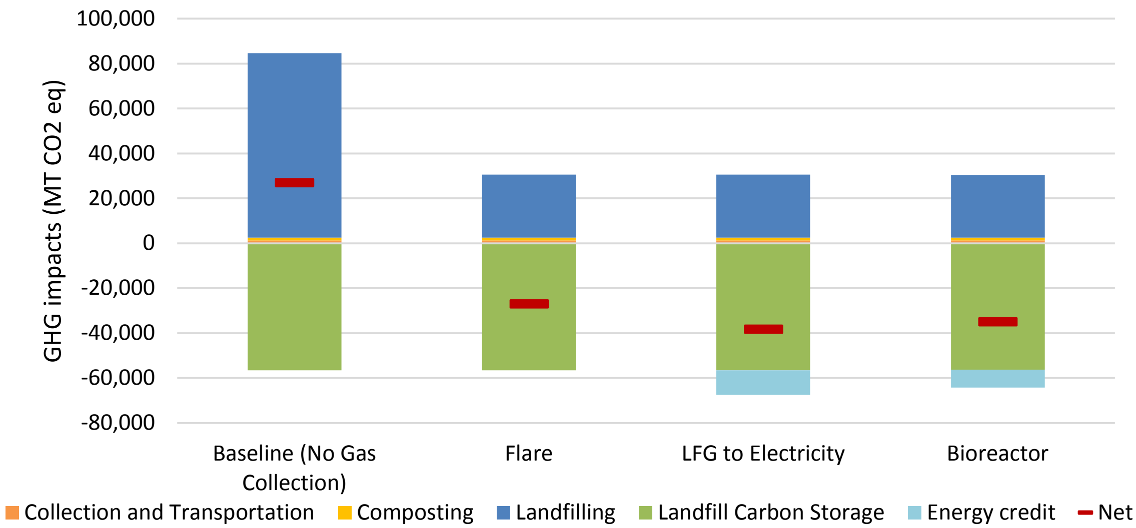


Figure 4-10. EASETECH GHG Emissions Estimates with Offsets for LFG-to-Electricity Option.

All tools estimate a 45% to 75% reduction in GHG impacts through implementing a flare. Implementing a gas-to-electricity system provides an additional 5% to 20% decrease in emissions due to electricity production offset. Depending on the assumptions for LFG collection early in the system, operating the landfill as a bioreactor either has a positive (MSW-DST, SWOLF) or negative (WARM, EASETECH) effect on GHG impacts, as previously discussed.

Figure 4-11 presents the acidification impacts on different LFG treatment options. In general, the tools suggest LFG flaring increases the acidification impacts over the baseline scenario with no LFG collection. Increases in the acidification impact from LFG flaring are the result of an increase in sulfur dioxide emissions (i.e., oxidation of numerous reduced sulfur compounds, some of which are not accounted for in the acidification impact category), an increase in thermal nitrogen oxide emissions (resulting from oxidation of nitrogen in ambient air), or both. All tools suggest reduced acidification impacts with LFG-to-electricity option over LFG flaring option. This reduction is associated with offset associated with displacement of marginal fuel mix with electricity generation from LFG. The magnitude of the impact and variations among different LFG treatment options vary significantly among tools. For example, MSW-DST suggests that LFG-to-electricity has a net negative impact (i.e., benefit) whereas all the other tools suggest a net positive acidification impact. The large range in impact magnitude among tools is probably a results of variations in the LFG composition and impact assessment methodologies used by these tools.

Figure 4-12 shows the estimated annual cost of operating a landfill based on MSW-DST and SWOLF results. Surprisingly, both tools suggest no change in overall landfilling cost with LFG collection and flaring option compared to the baseline scenario. The venting option was used for simulating the baseline case (with no LFG collection). There are a few components such as gas wells that are common to venting and active LFG collection system. These tools appear to assume mandatory installation of LFG collection for cost estimation irrespective of whether the user specifies LFG collection. The overall landfill cost would not change if these tools automatically include LFG collection system cost in the landfill cost. Both the tools estimate reduction in landfill cost with LFG-to-electricity option, which is attributed to revenue from the sale of the generated electricity. MSW-DST and SWOLF estimated 23% and 8%, respectively, lower cost for LFG-to-electricity case over LFG flare case. The difference in the tools' default electricity sale prices and internal combustion engine installation cost account for the difference in the cost estimated by these two tools for options with electricity generation; tool defaults for these parameters were used for LFG-to-electricity simulations. MSW-DST assumes a 7.1-cent per kWh revenue for the sale of generated electricity, whereas SWOLF assumes a 5-cent revenue. The cost of implementing a bioreactor landfill (with LFG-to-electricity) is greater than that of a traditional landfill with LFG-to-electricity due to increased costs associated with installing and operating a leachate recirculation system.

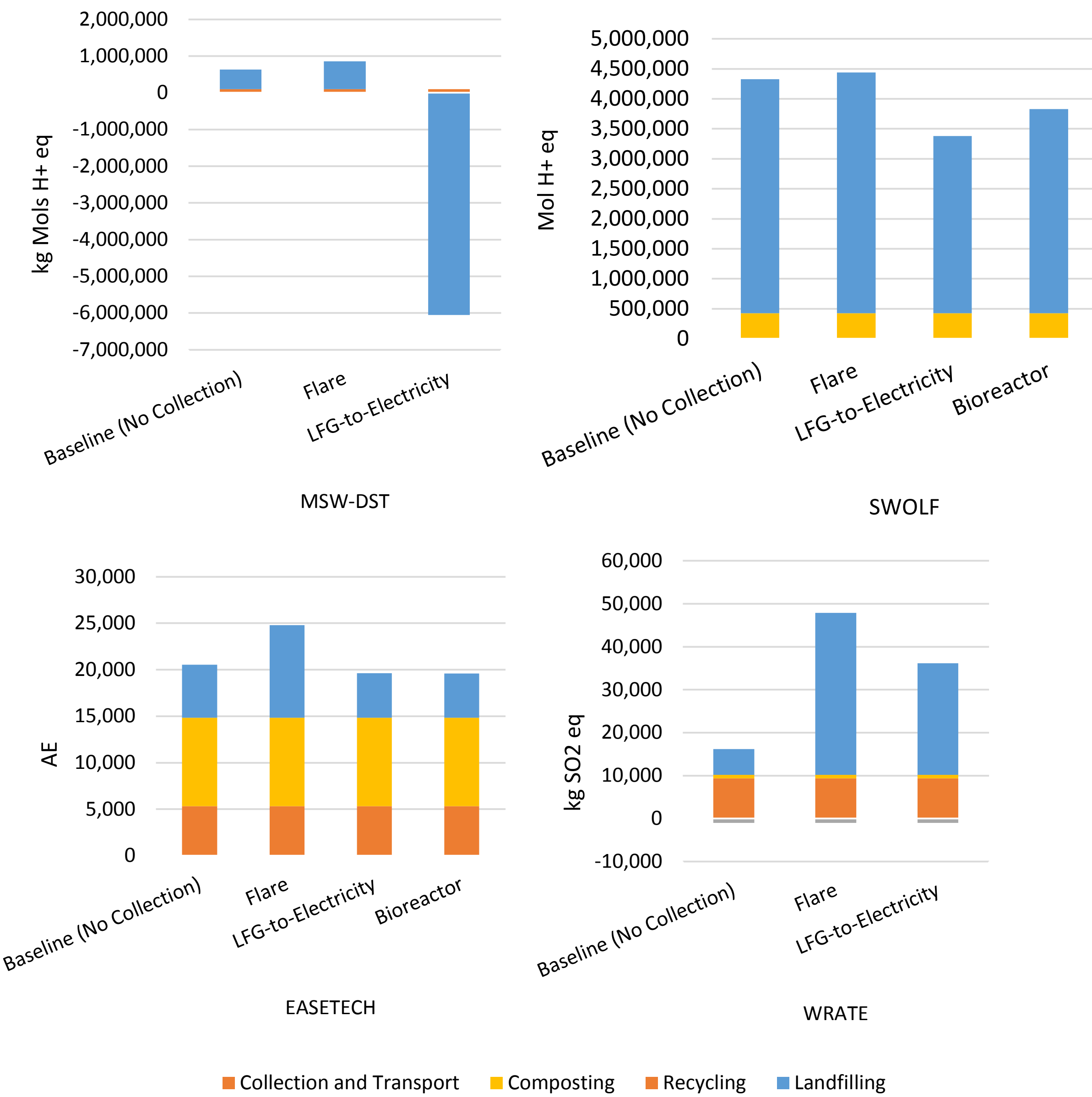


Figure 4-11. Comparison of the LCA Tools' Acidification Impact Estimates for Different LFG Treatment Options

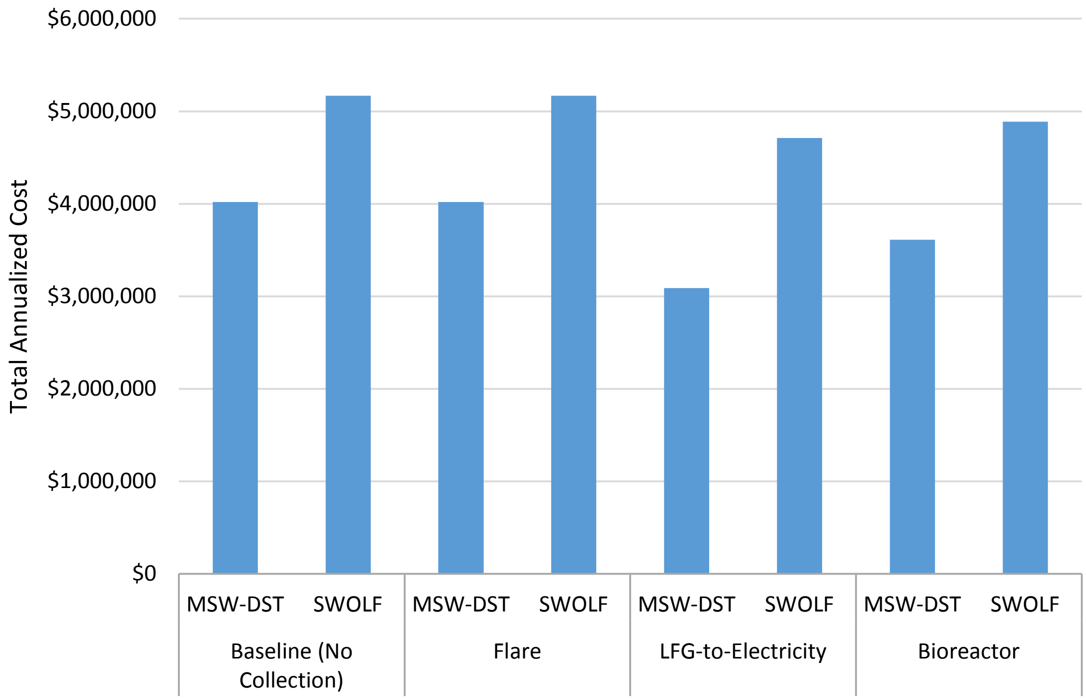


Figure 4-12. Comparison of the LCA Tools' Annual Landfill Cost Estimates for Different LFG Treatment Options

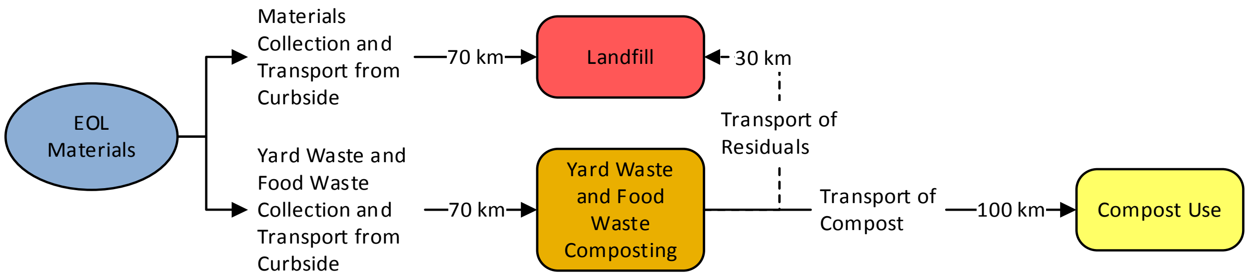
4.6 *Impacts of Source-Separated Organics Processing*

4.6.1 Scenario Description and Assumptions

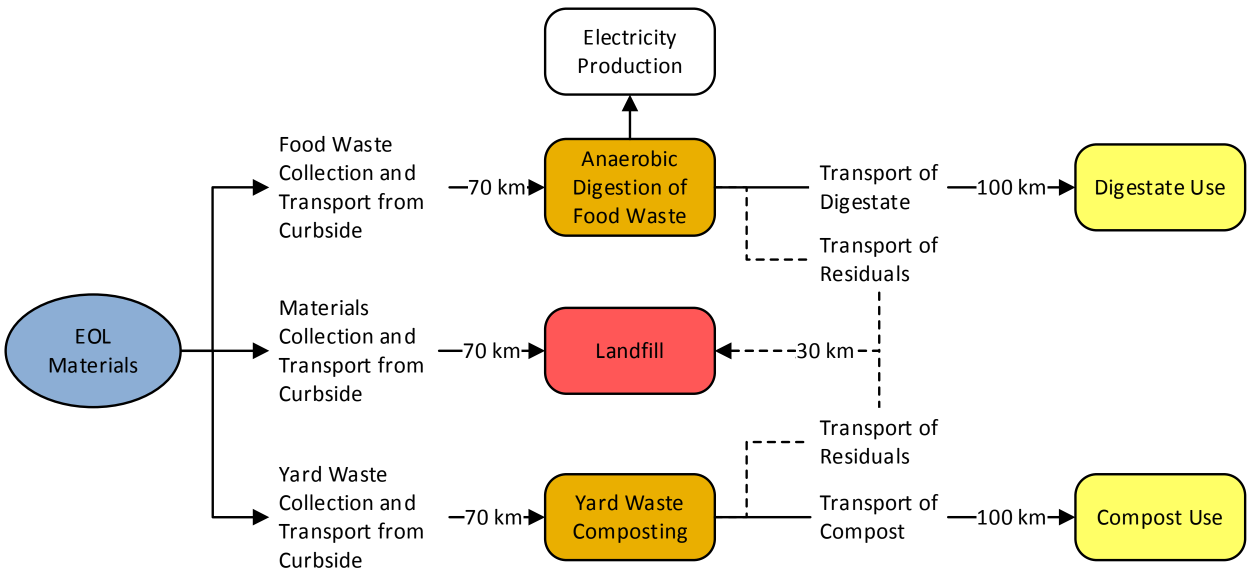
As can be seen in the previous section, the LFG contributed the most to the GHG emission among all EOL materials management processes. Source-separation and diversion of organics from the landfill may potentially reduce LFG GHG emissions. The community would like to understand the environmental and economic impacts of source-separated organics (food and other organics) (SSO) collection and management via composting or AD. Organics constitute a significant fraction of the EOL materials stream with a high methane yield and a tendency to contaminate recyclable materials. Separating this EOL materials stream can reduce the methane production in the landfill, make the recyclable streams more recoverable, and produce useful byproducts in a composting facility or anaerobic digester where biogas may be managed more efficiently than LFG produced in a landfill.

To analyze this scenario, three cases are considered. The first case is the baseline scenario (Section 4.4) where organics are deposited in the landfill with other EOL materials; LFG from landfill is vented to the atmosphere. A fraction of the organic (food scraps and soiled paper) in EOL materials stream is source-separated and composted with yard waste (Figure 4-13a) in the second case. The third case includes the same organic collection system as the second case, but rather than composting, the organics are processed in an anaerobic digester to produce biogas, which is used to generate electricity (Figure 4-13b). Other than these specific changes, all assumptions of the baseline scenario as applicable were used. All composting is assumed to occur in windrow systems. Tools default decay rate (k) and methane generation potential for AD were used. It was assumed that 50% of the food scrap and non-recyclable paper of the total present in EOL materials will be collected and processed as SSOs. The SSOs for the composting option are assumed to be collected with the yard waste stream. The SSOs for the AD option are collected and transported separately.

MSW-DST is excluded from this analysis as a SSO stream collection could not be modeled with MSW-DST. It should be noted that an additional SSO material stream had to be created and modeled separately from the rest of the EOL materials in EASETECH. WARM can model organic composting but not AD, so it is excluded from the anaerobic digester analysis.



(a)



(b)

Figure 4-13. EOL Materials Flow with Collection and (a) Composting, and (b) AD of Source-Separated Organics

4.6.2 Results and Discussion

Figure 4-14 compares GHG emissions estimates from four relevant LCA tools for a system with and without an SSO collection and processing program. Because the scenario modeled the entire EOL materials stream, the effects on composting of food scraps are reported as one number in WARM, SWOLF, and WRATE (as with AD) and cannot be separated from the effects of composting yard waste, which is included in the default scenario. For this reason and due to the relatively minor impact of composting and digestion compared to the impact of landfilling and carbon storage, these impacts of composting and AD are combined into as a single "Composting and Digestion" category.

As expected, all the tools suggest a decrease in GHG impacts with the progression from the baseline case to composting to the implementation of an anaerobic digester, which stabilizes SSO and beneficially uses the resulting biogas. Both EASETECH and WRATE GHG emissions estimates from the AD option are only slightly smaller than that for the composting option. The offsets associated with electricity generation from biogas recovery appear to have a negligible impact on GHG emissions.

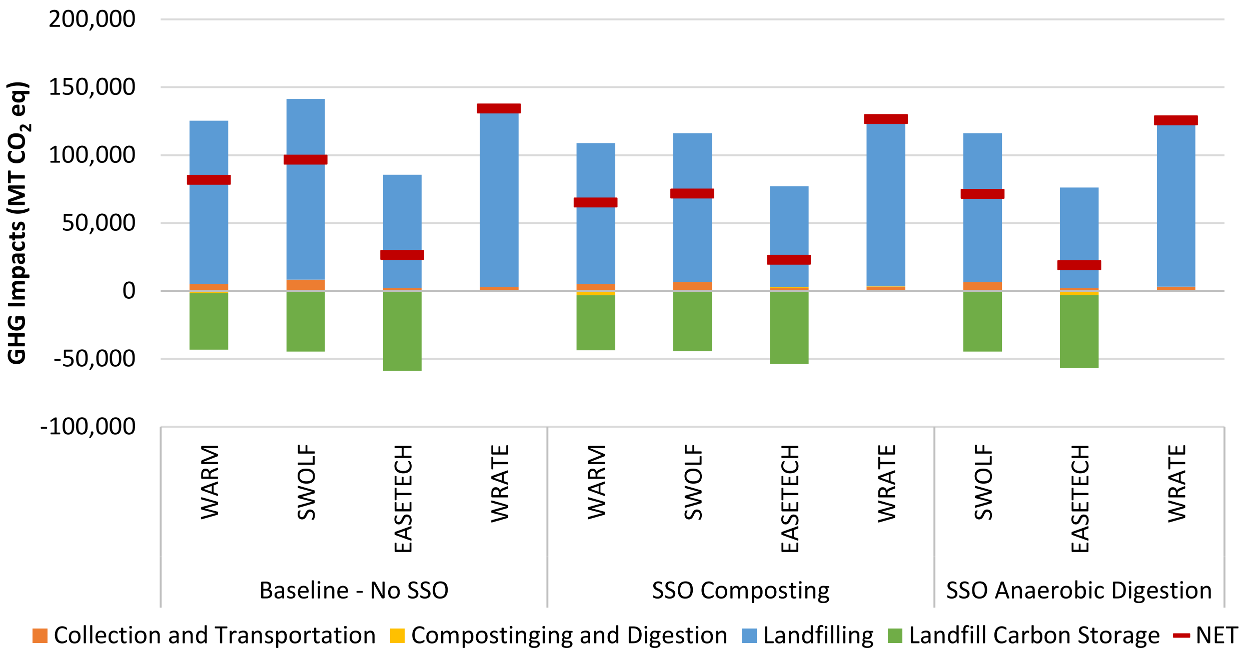


Figure 4-14. Comparison of LCA Tools' GHG Emission Estimates for Source-Separated Organics Processing

Figure 4-15 presents system costs with and without an SSO collection and processing program. MSW-DST could not model the separate organics stream. As expected, instituting an SSO collection and composting or AD program is estimated to reduce the cost of landfilling due to materials diversion from landfill. The cost for collection is also estimated to increase slightly potentially due to collection of SSOs with the yard waste stream (in the SSO composting scenario), which the tool assumes to have a lower density in the collection vehicle than that of MSW. The cost of landfilling is expected to decrease with diversion of more organic wastes from the landfill. As expected, composting costs increase, but are negligible compared to decrease in landfilling costs. Overall, the decrease in landfilling costs is greater than the increase in composting and collection, making SSO AD and composting a net benefit. The cost of other composting options such as in-vessel composting are expected to be greater than the windrow composting option simulated in this scenario and may result in overall cost that are greater than the baseline scenario. These alterative composting options offer advantages such as better odor control over the windrow composting. The process cost for AD is estimated to be lower than for composting due to the revenue generated from the sale of electricity generated from the resulting biogas.

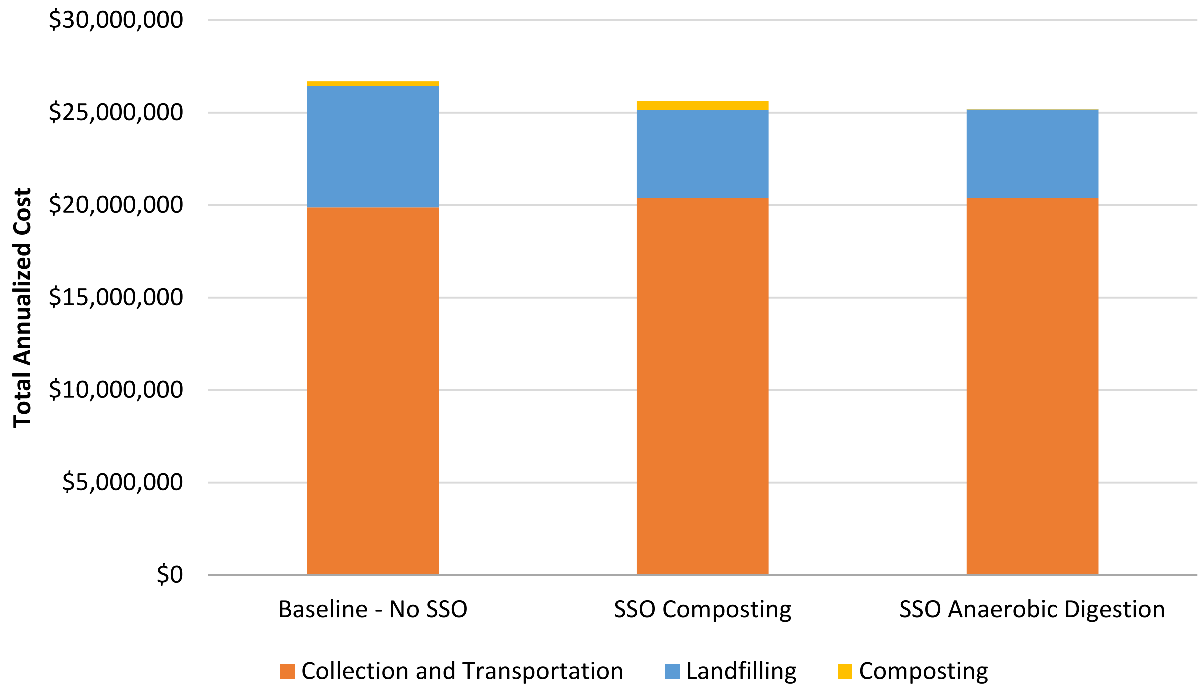


Figure 4-15. Comparison of Total Annual Cost Estimates from SWOLF for the System with and without Source-Separated Organics Processing

4.7 *Impacts of Backyard Composting*

4.7.1 Scenario Description and Assumptions

As discussed in the previous section, an SSO collection and composting program reduced the GHG emission by 4% to 26% due to diversion of readily biodegradable organics from the landfill. Although the program was estimated to reduce the landfill cost, it is estimated to increase the collection and transport cost. One approach to realizing the benefit of reduced GHG emissions from SSO diversion from the landfill while reducing the transport cost is instituting a backyard composting program. This section assesses the environmental and economic impacts of implementing a community-wide backyard composting program. Backyard composting programs typically involve community outreach such as advertisements, hosted events, and subsidized home composting units (Composting Council, 1996). These programs reduce the total EOL materials amount entering the MSW and yard waste collection streams by allowing residents to manage organics such as yard waste and food scraps in their backyards. This option reduces collection and transportation costs and emissions as the targeted EOL materials constituents are managed at the source location.

The estimated average yard waste diversion from landfills by backyard composting is 14% of the total amount of yard waste produced in the US (Sherman, 1996, Composting Council, 1996). This estimate is corroborated by Oregon DEQ (2014), which observes comparable diversion (from landfill) of the state's yard waste via backyard composting. Backyard composting in the simplest form, involves the combination of brown material with green material; brown material being organic material high in carbon (e.g., leaves, twigs, hay) and green material being high in nitrogen (e.g., grass clippings, vegetable and fruit peels, and other food scraps). It is assumed that yard waste (comprises the bulk of the "brown" material) constitutes 50% (by wet weight) and food scraps (provides the "green" materials) constitutes the balance 50% of the mix for backyard composting for simulating this scenario. Thus, a diversion rate of 14% for yard waste and 14% of food scraps are assumed to simulate backyard composting.

The baseline modeling scenario assumes collection of 50% of the community's yard waste for composting. Therefore, to simulate the community's change to implementing backyard composting, the amount of yard waste going to community composting and the landfill is reduced. Additionally, the amount of food scraps going to the landfill is reduced. It is assumed that 50% of the yard waste to be backyard composted comes from yard waste that was originally being sent to community composting via curbside collection of yard waste, and the other half of yard waste is from yard waste that is collected with the mixed MSW stream and disposed of in the landfill in the default scenario.

To compare the impacts of a more aggressive backyard composting program, a scenario is modeled assuming diversion of 50% of yard waste and 50% of food scraps to backyard composting. Table 4-4 summarizes the proportions of yard waste and food scraps managed in the baseline and backyard composting scenarios. Both of these scenarios otherwise follow the global assumptions of the default scenario. Figure 4-16 below provides a general visual representation of the materials flow for the backyard composting scenario. Approximately 2,307 and 2,474 MTs of yard waste and food scraps, respectively, are managed by backyard composting for the average scenario. Approximately 8,240 and 8,836 MTs of yard waste and food scraps, respectively, are managed by backyard composting for the aggressive scenario.

Table 4-4. Yard Waste and Food Scraps Diversion Rates Used for Backyard Composting Scenario

Material Management Method	Yard Waste (%)			Food scraps (%)		
	Baseline	**Average**	**Aggressive**	**Baseline**	**Average**	**Aggressive**
Landfill	50	43	25	100	86	50
Community composting	50	43	25	0	0	0
Backyard composting	0	14	50	0	14	50
Total	100	100	100	100	100	100

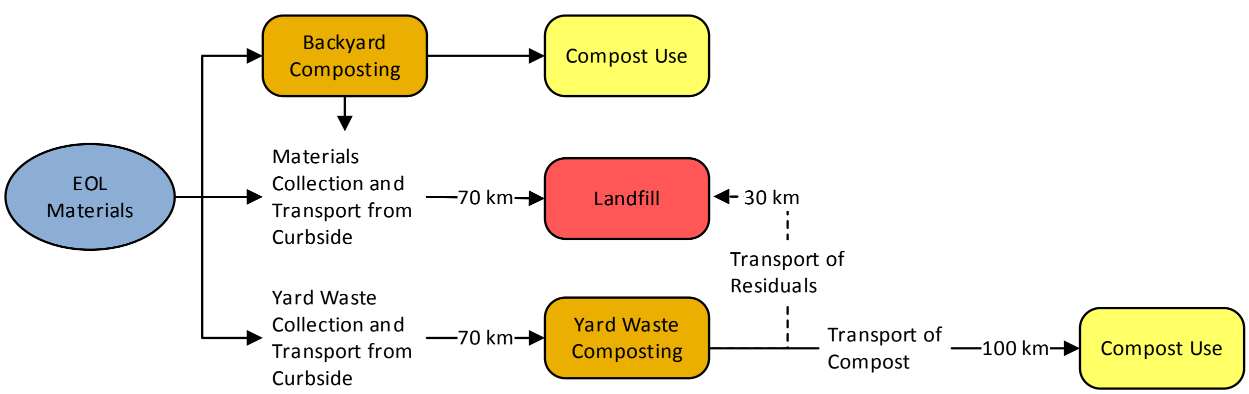


Figure 4-16. EOL Materials Flow with Backyard Composting of a Fraction of Source-Separated Organics

It should be noted that several of the tools, including SWOLF, MSW-DST, and EASETECH, define the system boundary as the point where waste must be handled by the local community. Using this system boundary, backyard composting as well as other in-home activities such as, for example, rinsing containers prior to placement in a recycling bin, are excluded. The emissions associated with backyard composting include the emissions from the production, operation, and EOL management of the composting vessel; any additives to the composting process; and process-specific emissions such as methane and nitrogen oxide emissions from the SSO biodegradation. One limitation of all of the tools except WRATE is the inability to simulate backyard composting process that accounts for all these emissions. WRATE is the only tool that includes a process to simulate impacts of backyard composting. For the other four tools, backyard-composted yard and food scraps were simulated by removing the diverted food scraps and yard waste from the system boundaries of the tool (in the previously described scenario-specific proportions). For tool evaluation purposes, it was assumed that the backyard compost pile is managed to avoid anaerobic conditions and associated methane generation. Potential costs and emissions of the actual backyard composting process could not be, accurately, analyzed by these tools.

4.7.2 Results and Discussion

As expected, a backyard composting program results reduces GHG emissions from the landfill due to the diversion of SSOs from the landfill (Figure 4-17). The effect for the 14% diversion rate are difficult to perceive on the graph, but the reduction in GHG emissions for the 14% diversion scenario range from 3% with WRATE to 16% with EASETECH. It should be noted that WARM, MSW-DST, SWOLF, and EASETECH simulations were conducted by removing the diverted food scraps and yard waste from the EOL materials stream, which is equivalent to assuming that no emissions occur from SSOs managed via backyard composting. In reality, emissions have been reported from backyard composting of these materials (Amliner et. al. 2008). The actual GHG emission would, therefore, be greater than those estimated using WARM, MSW-DST, SWOLF, and EASETECH. The objective of using these tools that do not include backyard composting as a process for simulating this scenario was to assess the upper range of reduction in emissions associated with a decrease in the amount of SSOs collected and transported to landfill (or composting facility) and avoidance of methane generation from SSOs diverted from landfill.

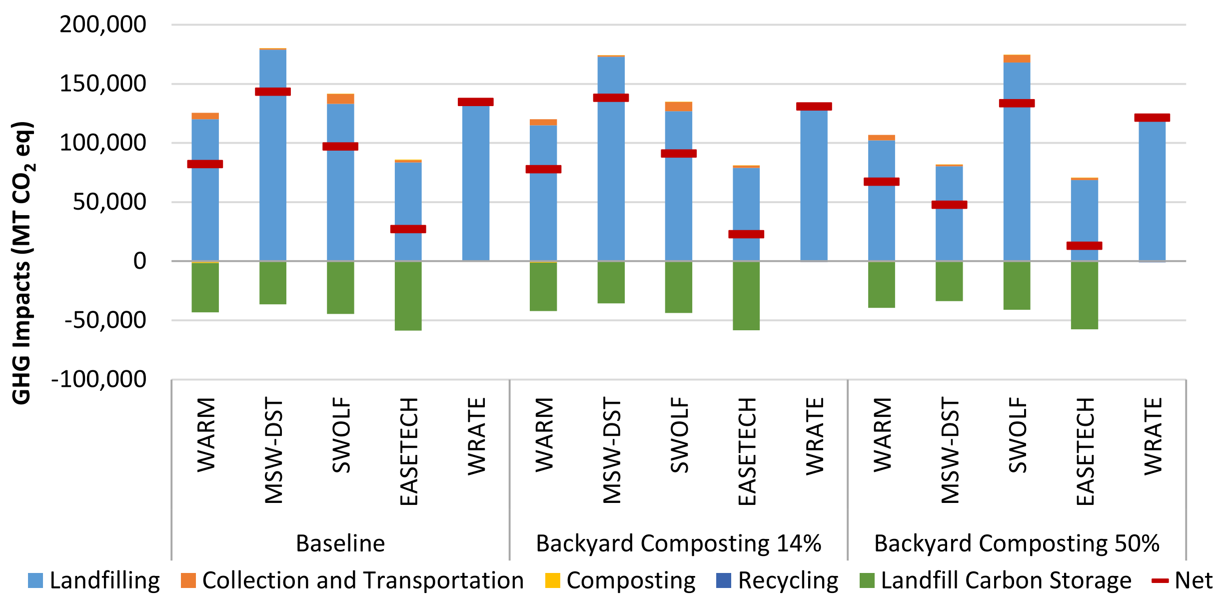


Figure 4-17. Comparison of LCA Tools' GHG Emission Estimates for Backyard Composting

Figure 4-18 compares the annual EOL materials management cost for systems with and without backyard composting. As expected, both MSW-DST and SWOLF estimate a decrease in the landfilling as well as collection and transport cost with implementation of backyard composting. The decrease in collection and transport cost is more significant than that for landfilling. The cost presented in Figure 4-18 do not include compost bin cost and the cost to promote and implement the program.

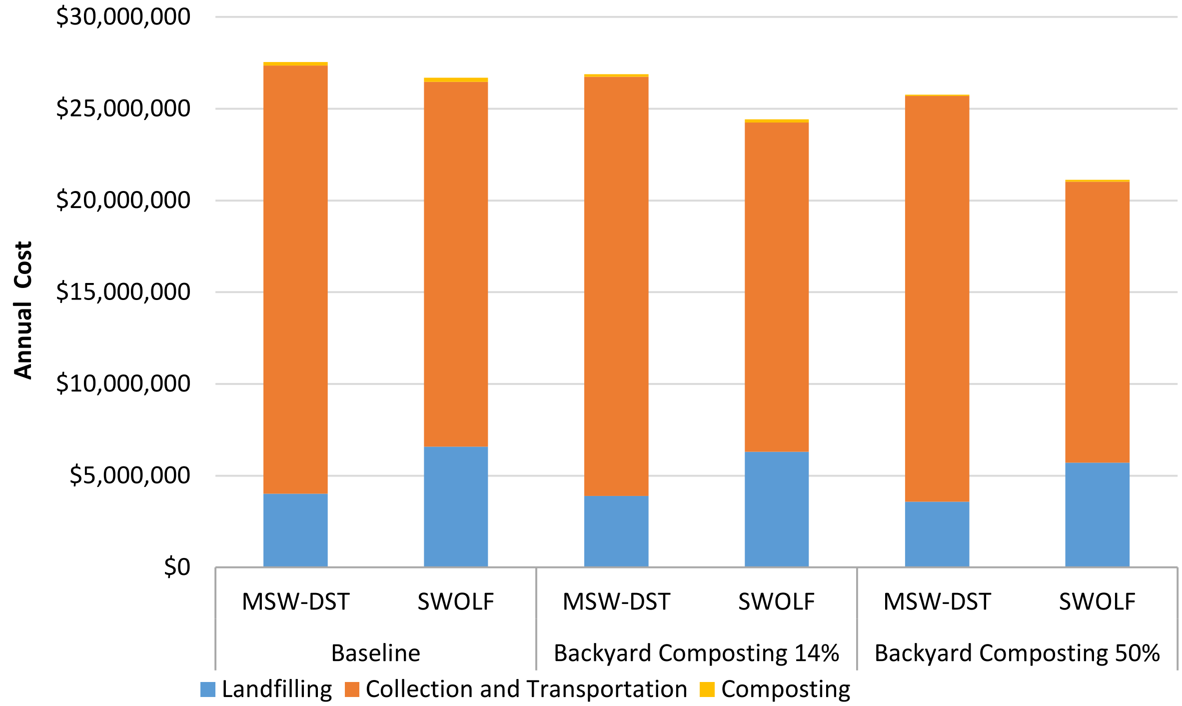


Figure 4-18. Comparison of LCA Tools' Total Annual Cost Estimates for the System with Backyard Composting

4.8 Impact of Materials Recovery

4.8.1 Scenario Description and Assumptions

The community would like to assess the economic and environmental impacts of enhancing materials recovery by instituting a curbside recyclable collection program and building a complementary MRF. The community would like to assess the impacts of the following MRF options: single-stream, dual-stream, and mixed waste MRF. Four cases are compared in this analysis: the baseline scenario (which does not include an MRF), a single-stream MRF, a dual-stream MRF, and a mixed-EOL-materials MRF. The type of MRF implemented is assumed to affect the recycling participation rate, the material recovery rate, and the residual rate (i.e., fraction of contaminated or unrecyclable materials) at an MRF. It is assumed that the overall recycling rate achieved through dual-stream and single-stream collection is the same at 30%, but the capture rate (i.e., the amount of recyclables sent to the MRF due to community participation) and MRF residual rates differ. The following equation presents the relationship among the recycling rate, the capture rate, and the residual rate.

Recycling Rate = Capture Rate × (1-Residual Rate)

The values of these parameters used for each scenario are shown in Table 4-5. Figures 4-19 and 4-20 below provide a general visual representation of the materials flows for the single-stream/dual-stream and mixed-waste MRF scenarios.

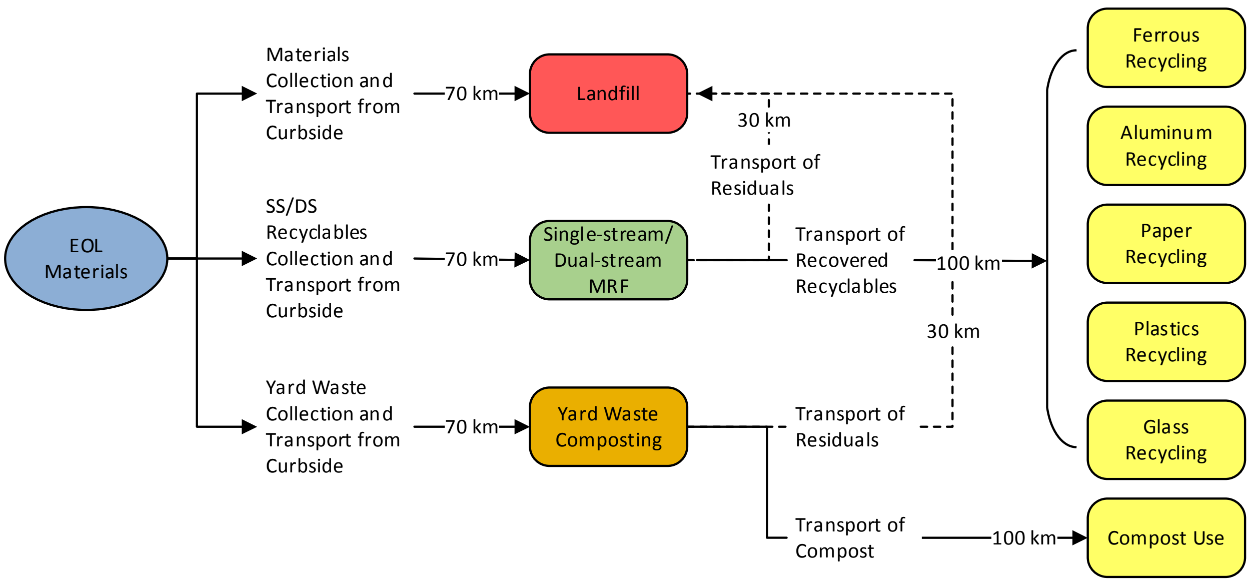


Figure 4-19. EOL Materials Flow with Materials Recovery via a Single/Dual-Stream Recycling Program

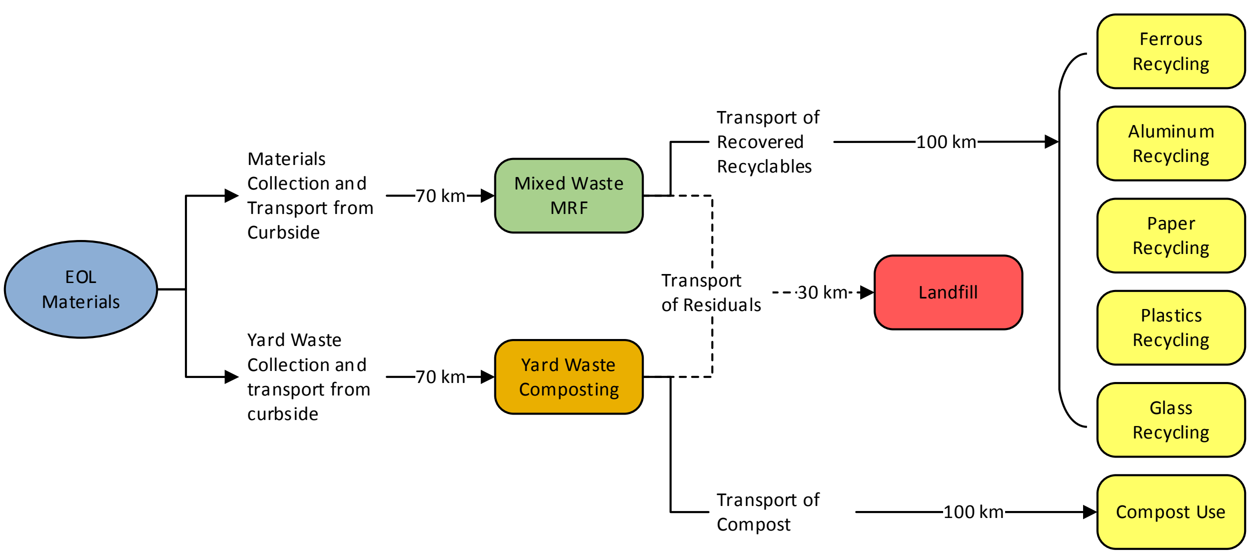


Figure 4-20. EOL Materials Flow with Materials Recovery via a Mixed-Materials Recycling Program

Table 4-5. Material Capture Rate, Residual Rate, and Recycling Used for the MRFs Analyzed.

Recovery Stream	No MRF	Dual Stream MRF	Single Stream MRF	Mixed EOL Materials MRF
Capture rate	0%	32%	34%	100%
Residual rate	0%	6%	12%	80%
Recycling rate	0%	30%	30%	20%

It should be noted that, except for SWOLF, there are major limitations in modeling EOL material management scenarios using different MRF technologies/recyclable collection strategies. WARM does not account for the emissions associated with MRF operation; GHG emissions resulting from the implementation of different MRF options were estimated through the fractionation of specific material categories to recycling and landfilling based on the capture rates. EASETECH only includes a paper MRF; this MRF was modified for all scenario options. A mixed-EOL materials and a separate-stream MRF can be selected in MSW-DST, but the residual rate of the separate-stream MRF cannot be adjusted; because the separate-stream MRF residual rate is set at 10%, the emissions resulting from the use of this facility are only included in the single-stream results. WRATE has multiple MRF options that can be selected, but the capture/residual rates cannot be adjusted from tool default values. Only SWOLF has MRF processes with adjustable capture/residual rates for dual-stream and single-stream recyclable collection, as well as mixed-EOL materials recyclable recovery.

EASETECH has no general "recycling" process, but has a set of specific remanufacturing processes. All recyclable materials in EASETECH are sent to the most appropriate process, though some are not identical. For instance, the plastics in EASETECH are not identified by resin, but the two recycling processes available for plastic are specific to either PE-based resins or PP-based resins. An additional plastic recycling process handles multiple resins but it is specific to Sweden. The material re-use process is identified by resin, but the plastics categories are identified by type, i.e. "soft plastic," "hard plastic," "drink bottles", etc. It is not possible to direct the appropriate resin to the appropriate remanufacturing process. Since PE-based resins represent the largest component of the recyclable plastics stream (US EPA, 2014), all recycled plastics have been modeled as being directed to the PE remanufacturing process.

4.8.2 Results and Discussion

Figure 4-21 compares GHG emission for three MRF scenarios along with the baseline scenario for each tool. All tools' results suggest GHG emission reduction with enhanced materials recovery. The tools estimate that any type of material recovery has a lower GHG emission than no material recovery. The only exception is that WRATE predicts a higher impact from a mixed-EOL-materials MRF than from not recovering materials. This is because of the impact WRATE attributes to processing a large material stream and recovering only 20% of the material for recycling. Some of the additional GHG impact that WRATE estimates comes the energy required to move residuals twice - once from the collection point to the MRF and then again from the MRF to the landfill. EASETECH report nearly identical performance from either dual-stream or single-stream recycling schemes. All tools estimate an increased impact due to additional material transportation, but in all cases this is more than offset by the impact of recycling. SWOLF predicts the most significant increase in collection and transportation impacts. The version of SWOLF evaluated had an error in the dual stream process which created erroneous results, and is excluded from GHG impacts results.

For three of the five tools (WARM, MSW-DST, and EASETECH), single- and dual-stream MRFs showed a lower impact than a mixed-EOL-materials MRF due to the higher overall recycling rate. However, SWOLF predicts a lower impact for a mixed-waste MRF, which may be due to the increased complexity of source-separated recycling collection systems, which may require additional vehicles, drivers, and routes.

Figure 4-22 presents the annual EOL materials management system cost estimates by MSW-DST and SWOLF for each of the MRFs assessed. Because source separation increases the number of collection vehicles/routes, collection for single-stream and dual-stream MRFs is higher than for mixed-EOL materials and no-recycling collection. Both tools estimate an increase in the materials management system cost due to the increase in costs associated with additional materials processing and transport. The benefit offered by the sale of recyclables is not adequate to offset the added cost. It should be noted that the tools' default market price for recyclables was used for the simulations. The prices of some of the commodities (e.g., PET) are much higher than the MSW-DST defaults. For example, the MSW-DST default market price for PET is $17/ton, whereas recycled PET (baled) price in the US in February 2015 was $270 per ton. The estimated benefit from the sale of recyclables is much lower than that based on current market pricing. MSW-DST and SWOLF allows the user to specify the market price of various commodities.

The commodity prices vary greatly depending on factors beyond the control of the solid waste community and have a significant impact on the materials recovery and recycling economics. For example, recent decline in crude oil price has been reported to result in significant decline in recyclables market value and their use in remanufacturing. For a given materials stream and commodities market prices, these tools can be used to assess the MRF construction and operating and maintenance cost above which materials recovery would not be economically viable.

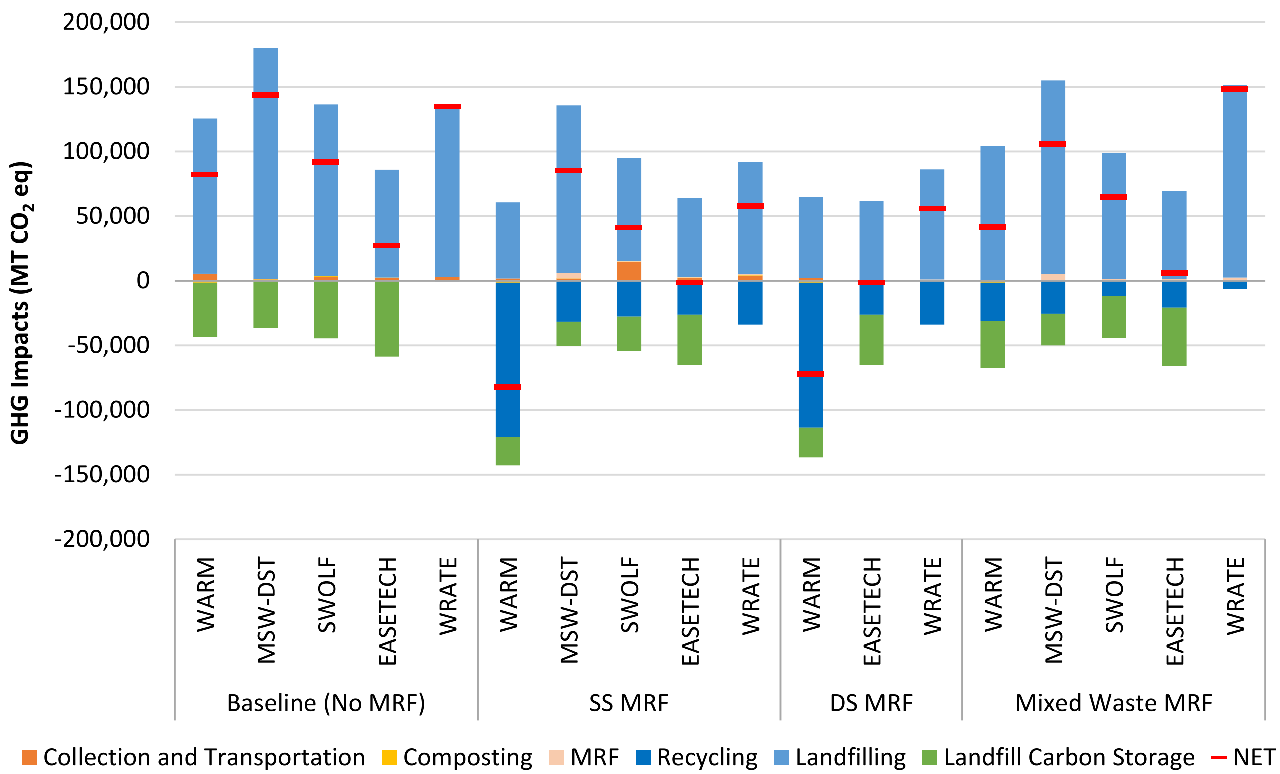


Figure 4-21. Comparison of LCA Tools' GHG Emission Estimates for Different Materials Recovery Options

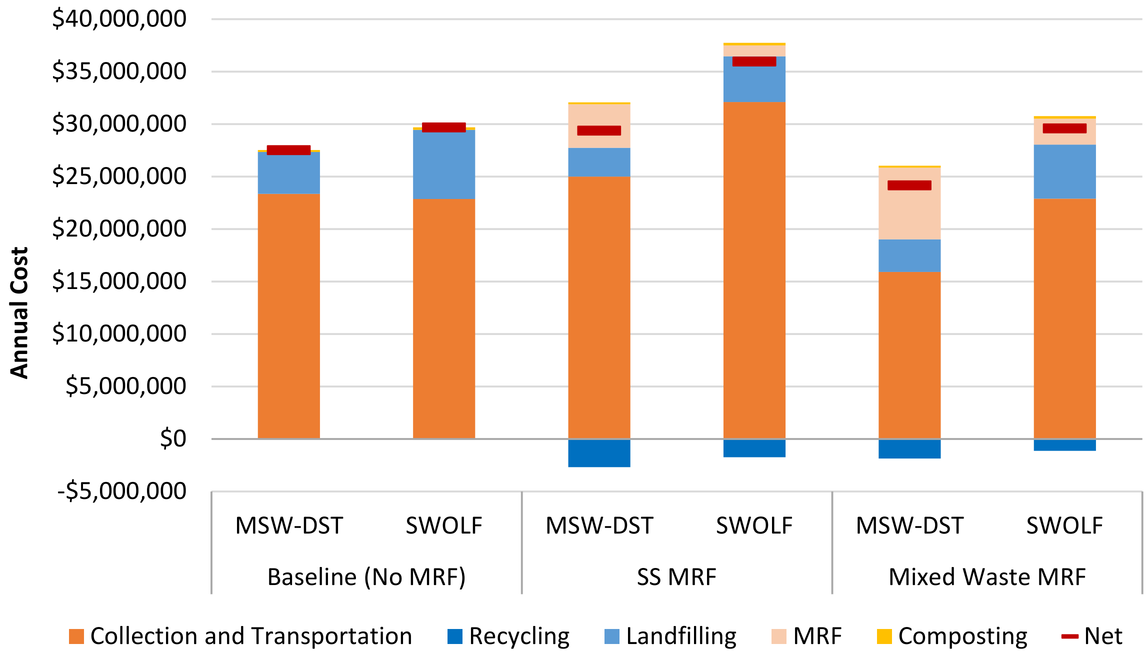


Figure 4-22. Comparison of LCA Tools' GHG Emission Estimates for Different Materials Recovery Options

4.9 Impacts of MRF Automation

A municipality would like to compare the economic and environmental impacts of different levels of MRF automation. Specifically, the community would like to compare the impacts of using only manual sorting with using the highest level of automation available. The community believes that automatic sorting may reduce costs by reducing the labor cost at the facility, reducing occupational exposure potential, and increasing processing rate. The community is also concerned about potentially higher contamination rates due to greater levels of automation.

This scenario could not be readily simulated using any of the five LCA tools under consideration at this time. SWOLF does have options to adjust the level of automation of a MRF, but the version evaluated did not have this MRF component fully implemented and does not output different results based on different levels of automation.

4.10 Impacts of Recycling Plastics vs Recycling Glass

4.10.1 Scenario Description and Assumptions

A community would like to understand the relative environmental and economic benefits of recycling different materials, such as plastic and glass, to improve its recycling outreach program. Plastic is generally more valuable to recycle and acquiring the raw materials used in plastic production has a greater environmental impact than acquiring those used to produce glass. However, the community wants to compare the overall GHG benefit of increasing plastic recycling vs increasing glass recycling.

To capture the effects of recycling plastic vs glass, two scenarios are compared, one in which 121,000 MTs of plastic are recycled and one in which 121,000 MTs of glass are recycled. The scenario is outlined in Figures 4-23 a and b. EOL materials collection is modeled with 100% capture rates, and the same 12%

residual rate is applied from each single-stream MRF scenario modeled. The EOL materials stream for the plastic scenario includes only recyclable plastics in the same relative proportions as the default scenario. The glass stream is modeled as 100% clear glass. Figure 4-23 presents a visual representation of the flow of materials in the plastics and glass recycling scenarios, respectively.

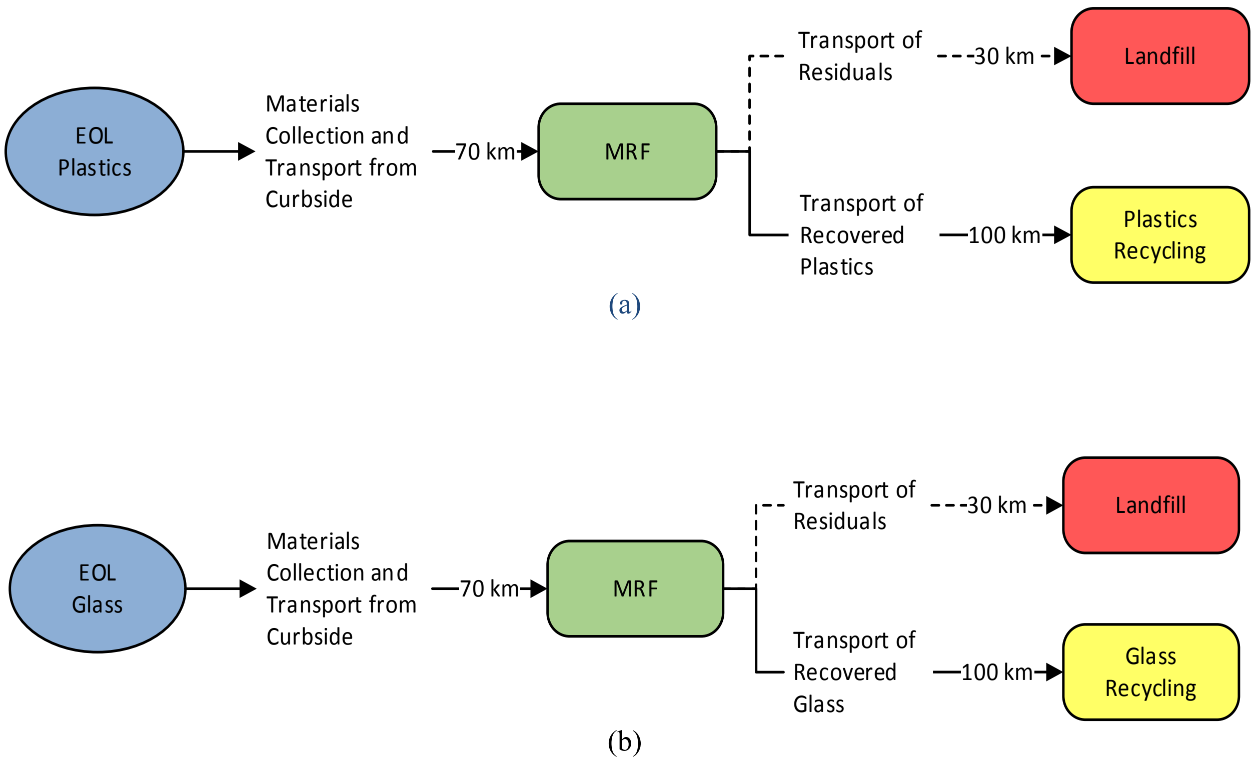


Figure 4-23. EOL Materials Flow for (a) Plastics and (b) Glass Recycling Scenario

While glass types are consistently modeled across all tools, limitations with plastics categorization in some of the tools have been described previously. The goal of the plastic scenario is to only analyze recyclable plastic, but this is difficult to designate in EASETECH and WRATE, which include plastic categories that may include a mixture of both recyclable and unrecyclable plastic (see the types of plastic categories presented in Appendix A for each of these tools). A best effort was made to include recyclable fractions in proportions that represent the US EOL materials stream.

As is mentioned in other scenarios, MSW-DST cannot set a residual rate for the MRF process, so the capture rate is adjusted to reflect the 12% of plastics and glass that are not captured by the MRF. This may result in differences in transport emissions since MSW-DST models these EOL materials as if they are collected in a mixed-EOL materials collection stream rather than with other recyclables. It should be noted that the tool MRF limitations described in the "MRF Types" scenario are applicable to this scenario as well. Because WRATE does not allow the adjustment of the MRF residual/recovery rates, no MRF was included in WRATE model runs for this scenario.

4.10.2 Results and Discussion

Figure 4-24 compares GHG emission estimates for plastic and glass recycling for various tools. As expected, the reduction of GHG emission with recycling plastic is far greater than with recycling the same mass of glass. Crude oil extraction, refining, and eventual plastic manufacturing are more resource intensive than are the same processes leading to glass manufacturing. The "other" categories are mainly comprised of GHG emissions from material collection and transportation and MRF operation, but also include emissions resulting from the landfilling of MRF residuals. The "other" category is higher for plastic recycling than glass recycling with the exception of EASETECH (which does not account for the density of materials). This difference is a result of the bulk density of plastic being lower than that of glass; mass is transported less efficiently, requiring more trucks and creating a higher impact. All tools estimate a larger impact from materials recovery for plastic than for glass.

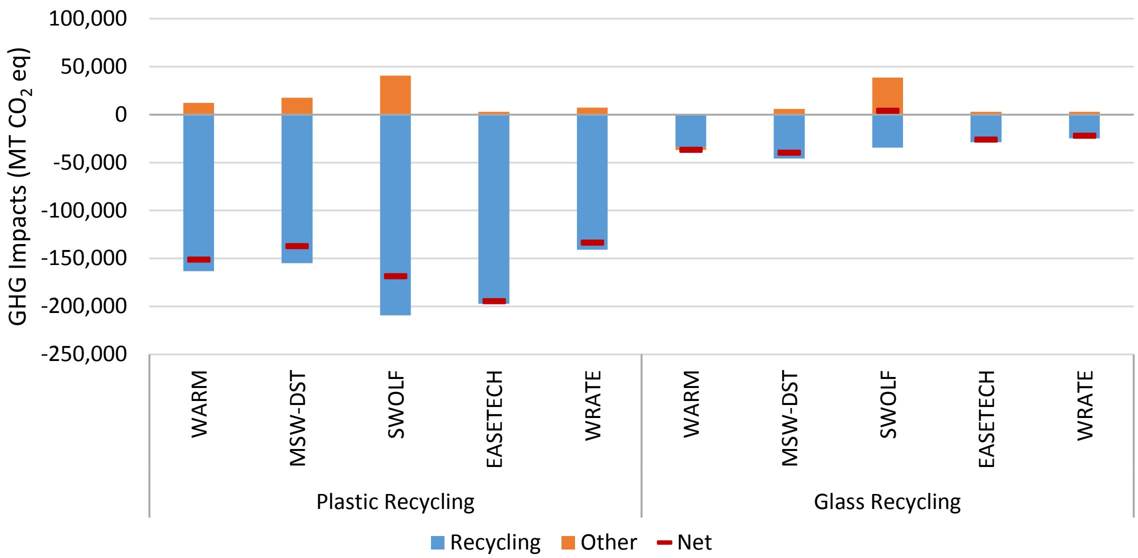


Figure 4-24. Comparison of LCA Tools' GHG Emission Estimates for Plastics and Glass Recycling

It is important to discuss the results from the perspective of the current methods and metrics used by communities to track the sustainability of their EOL materials-management systems. As discussed earlier, communities across the US use recycling rate as the primary metric to assess the sustainability of their EOL materials-management system. The recycling rate is calculated simply based on the amount of the materials recycled and generated. It does not consider the materials-specific properties and or the recycling application. Recycling rate, if used for decision making in this scenario, would suggest that the community would realize the same environmental benefits irrespective of whether it recycled glass or plastics. These results, however, suggest that the recovery of certain materials (e.g, plastics in this case) provides a much larger environmental benefit than those of others (e.g., glass in this case).

The primary reason that the environmental benefits of recycling plastics is much greater than those associated with recycling glass is that the emissions from manufacturing plastic products (from crude oil extraction through consumer products [e.g., plastic containers] manufacturing) are significantly greater than those from manufacturing glass consumer products such as glass containers. Although the tools evaluated in this report primarily focus on the EOL phase of materials management, data used/results of some of these tools (e.g., source reduction feature of WARM) can be used to assess the environmental impacts through all phases of the life cycle of materials. The environmental benefits of reducing the manufacturing plastic products would be greater than those achieved by recycling post-consumer plastics. Using WARM, the GHG emissions reduction achieved by recycling 1 short ton of PET is 1 MT CO_2 eq, whereas that achieved by avoiding (i.e., source reduction) production of 1 short ton of PET is 2 MT CO_2 eq. With their informed choices, consumers can potentially reduce environmental impacts (associated with all the four phases of the life cycle of materials) to a greater extent than those that can be achieved with just the EOL stage of materials management.

Figure 4-25 compares the cost estimates for plastics and glass recycling for SWOLF and MSW-DST. Contrary to expectations, both tools estimate that it economically more favorable to recycle glass than it is to recycle plastic. Based on the mass balance of plastic types and the default prices of plastic, SWOLF suggests a net cost of about $12 per MT of plastic recycled compared to $6 per MT for glass. The tool default market price of recyclable materials was used for simulations. The MSW-DST default market value of many plastics (e.g., $17 per short ton PET) was found to be significantly lower than the current market price ($270 per short ton of PET in February 2015 as published by www.secondarymaterialspricing.com) of these commodities. The MSW-DST default glass price ($14 per short ton for mixed glass) was found to be greater than the current market value of glass (prices published by www.secondarymaterialspricing.com suggest that it cost approximately $17 per short ton in February 2015 to get rid of glass due to lack of demand for recycled glass). Based on the current pricing, recycling plastics would probably be more beneficial economically than recycling glass. As discussed earlier, recycling plastics would have greater environmental benefits than recycling glass. Expending the community's resources on enhancing plastics recovery as opposed to glass recovery would, therefore, be more beneficial economically and environmentally.

A large discrepancy between the MSW-DST default market pricing of materials, which are potentially reflective of market conditions at the time of tool development, and current prices suggests the importance of having tool that dynamically updates cost and price data or at least let users specify this data to reflect the current market conditions for reliable economic-impact assessment.

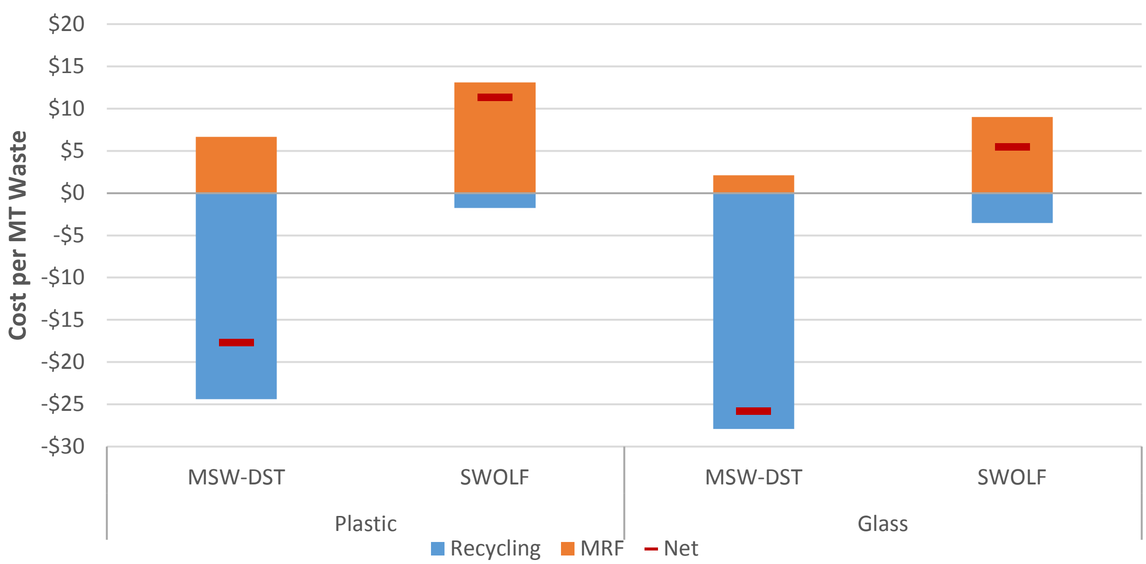


Figure 4-25. Comparison of LCA Tools' Plastics and Glass Recycling Cost Estimates per MT Material Collected

4.11 Impacts of PAYT Program

4.11.1 Scenario Description and Assumptions

A community would like to assess the impacts of implementing a PAYT (PAYT) program. In a PAYT program, residents are charged based on the amount of mixed EOL materials they discard as waste for disposal, incentivizing generating less mixed EOL materials through recycling, composting, reuse, and source reduction. The results of implementing a PAYT system are variable, but tend to increase recycling and decrease EOL materials generation, pushing total EOL materials diversion up from 30% to an average of 50% (Folz and Giles, 2002).

Figure 4-14 below shows the materials flow for the PAYT scenario, showing the beginning point where EOL materials are generated, transported, and managed. To model the effects of implementing a PAYT program, two options are evaluated in this scenario: before and after PAYT. Before PAYT differs from the baseline scenario in that it has a recycling program in place with single-stream collection and a single-stream MRF, since municipalities considering PAYT likely already have a recycling collection program in place. The program assumes a capture rate of 50% of recyclable materials. This results in an overall diversion rate of approximately 30%. Implementing PAYT is assumed to drive the diversion of recyclables and yard waste up to 90%, bringing the overall diversion rate to 50%. The specific diversion rate of recyclables and yard waste and the overall EOL materials stream before and after PAYT are summarized in Table 4-6. The MRF is modeled as a single-stream MRF and therefore includes the tool MRF limitations discussed in the MRF Types scenario.

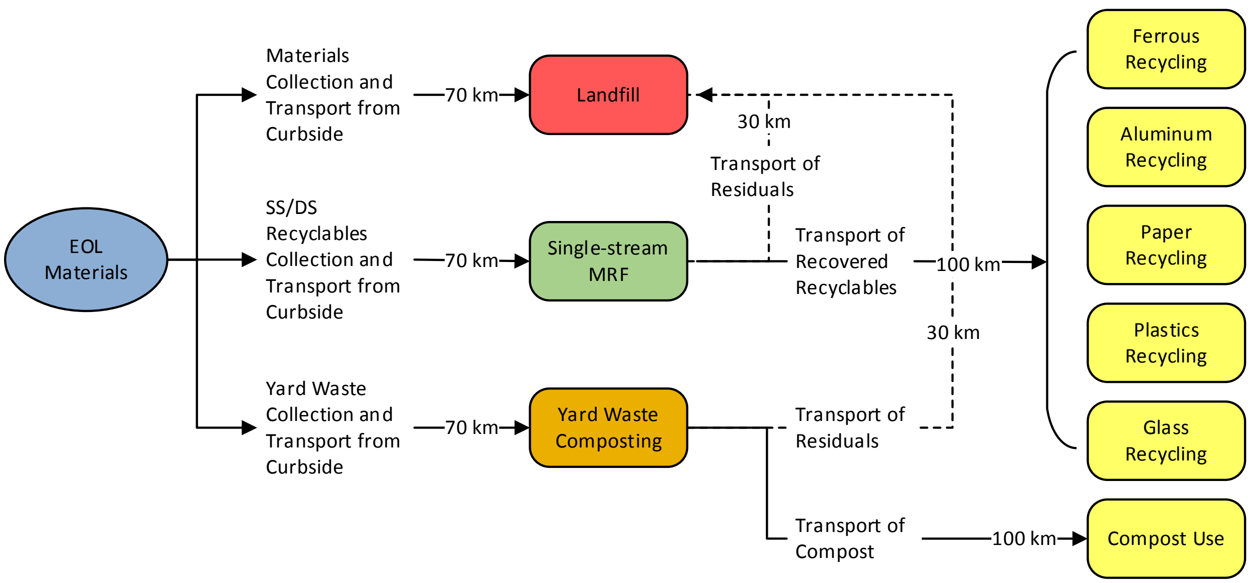


Figure 4-26. EOL Materials Flow with a PAYT Program Implemented with a Single/Dual Stream Materials Recovery Program

Table 4-6. Materials Diversion Rates Assumed for the PAYT Scenario.

	Before Implementing PAYT	After Implementing PAYT
Diversion of recyclables and yard waste	50%	90%
Total waste stream diversion	30%	50%

None of the tools offer a built-in option to implement PAYT, so the results are modeled by altering material capture rates. It should be considered that implementing PAYT requires a method of metering EOL materials disposal, either through purchasing tags to place on the collection containers, limiting the volume of waste container available (e.g., through providing different container sizes), or directly weighing the

EOL material before it is collected. There are cost associated with PAYT program implementation, which are important decision-making considerations for communities considering PAYT. None of the tools include the cost of implementing PAYT or offer flexibility for user to specify these cost. Although the impact of these cost can be simulated indirectly by altering the materials collection or transportation cost, such adjustments are expected to be beyond the technical expertise of users with limited LCA experience.

4.11.2 Results and Discussion

Figure 4-27 compares GHG emission estimates from different tools before and after the PAYT implementation. As expected and in all cases, increasing diversion due to PAYT decreased total GHG emissions by increasing the emissions averted as a result of recycling. Carbon storage decreased due to a decrease in landfilled organics (e.g., paper and vegetative waste), but this reduction in carbon storage is not as great as the increase in recycling-averted emissions offsets.

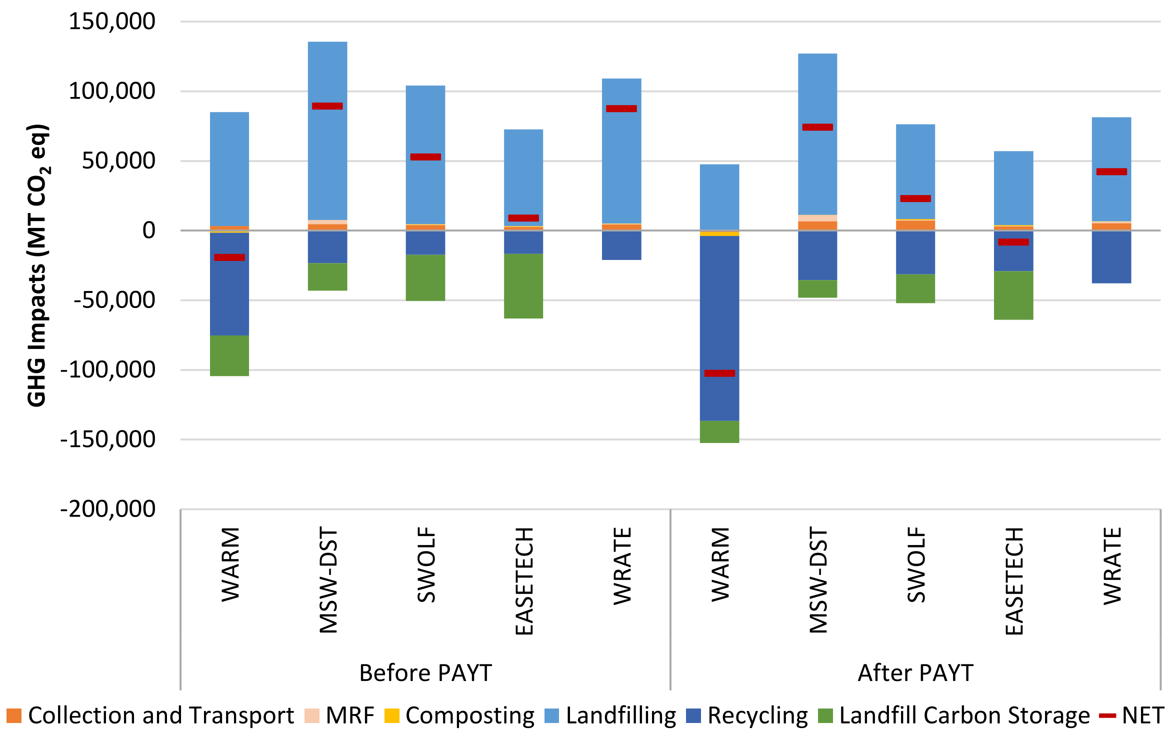


Figure 4-27. Comparison of LCA Tools' GHG Emission Estimates for the System with and without PAYT Program

4.12 Impacts of CDD Recycling

4.12.1 Scenario Description and Assumptions

A community would like to compare the economic and environmental impact of recycling and landfilling CDD materials. CDD is typically disposed of in a CDD landfill, often without LFG collection or a composite liner. These materials, such as concrete, wood, and bricks, are often readily recycled either onsite or following processing at a CDD MRF. Some communities require a certain quantity of CDD recycling for major construction and demolition projects.

To model this scenario, an EOL materials stream is developed that only includes CDD materials, since this material stream is typically separately managed from the MSW stream. The CDD composition assumed for simulating this scenario is presented in Figure 4-28. Figure 4-29 (a) and (b) presents the materials flow for the CDD landfilling and recycling scenarios, respectively.

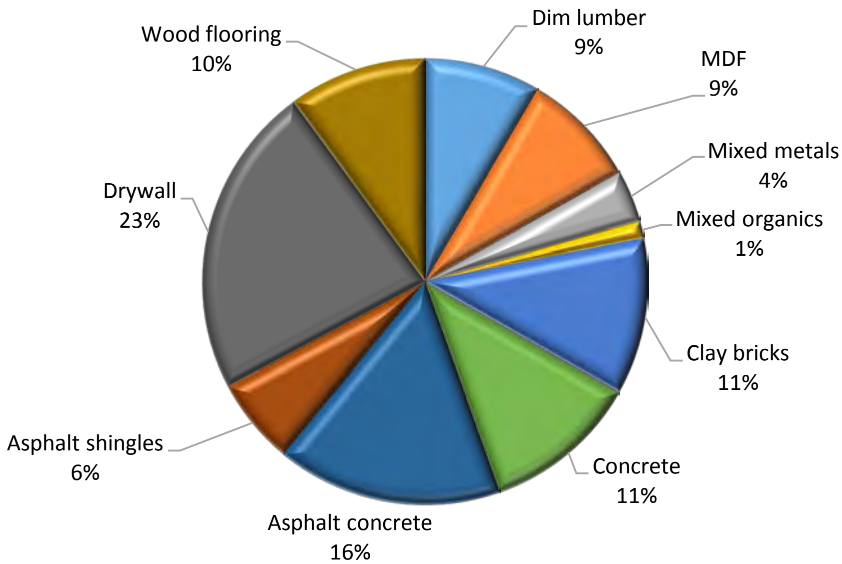
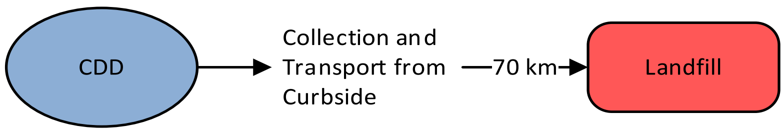
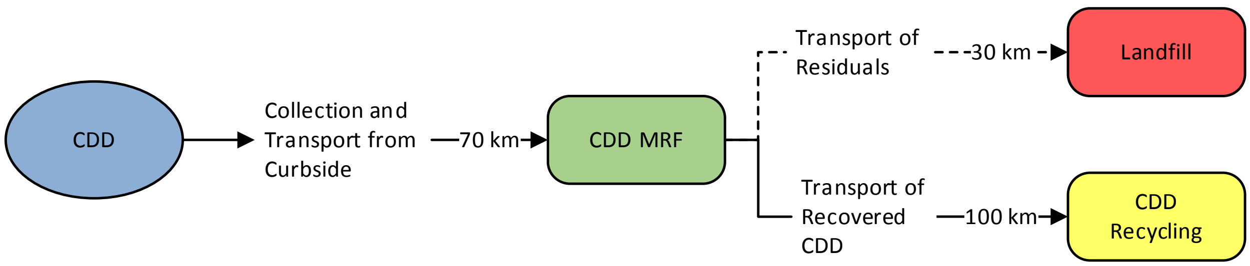


Figure 4-28. CDD Materials Composition assumed for CDD Recycling Scenario



(a)



(b)

Figure 4-29. EOL Materials Flows for CDD (a) Disposal, and (b) Recycling Scenarios

WARM is the only tool that includes multiple CDD materials and models the recycling of CDD materials, so it is the only tool used to analyze this scenario. This scenario compares the effect of landfilling and recycling CDD that has been processed by a CDD MRF, and no residual is assumed from the recycling process. All recycled material is assumed to be reused. The transport distances to a CDD landfill and a CDD MRF are the same as the distances to an MSW landfill and an MSW MRF, respectively, as depicted in previous scenarios. It should be noted that WARM does not include the emissions associated with CDD MRF operation. Also, WARM does not provide the option to recycle wood flooring or mixed organic material, although mixed organic material can be composted in WARM.

4.12.2 Results and Discussion

Figure 4-30 compares GHG emissions for CDD landfilling and recycling estimated using WARM. WARM predicts a substantial savings due to recycling this material, compared to the relatively small benefit resulting from landfilling CDD. This increased benefit results from the avoidance of emissions released from virgin material production, whether the specific CDD material is used to offset its own virgin production (e.g., asphalt concrete recovered and incorporated into a pavement mix to offset the production of asphalt concrete created from virgin material) or the virgin production of another material (e.g. crushed concrete used to offset virgin aggregate production).

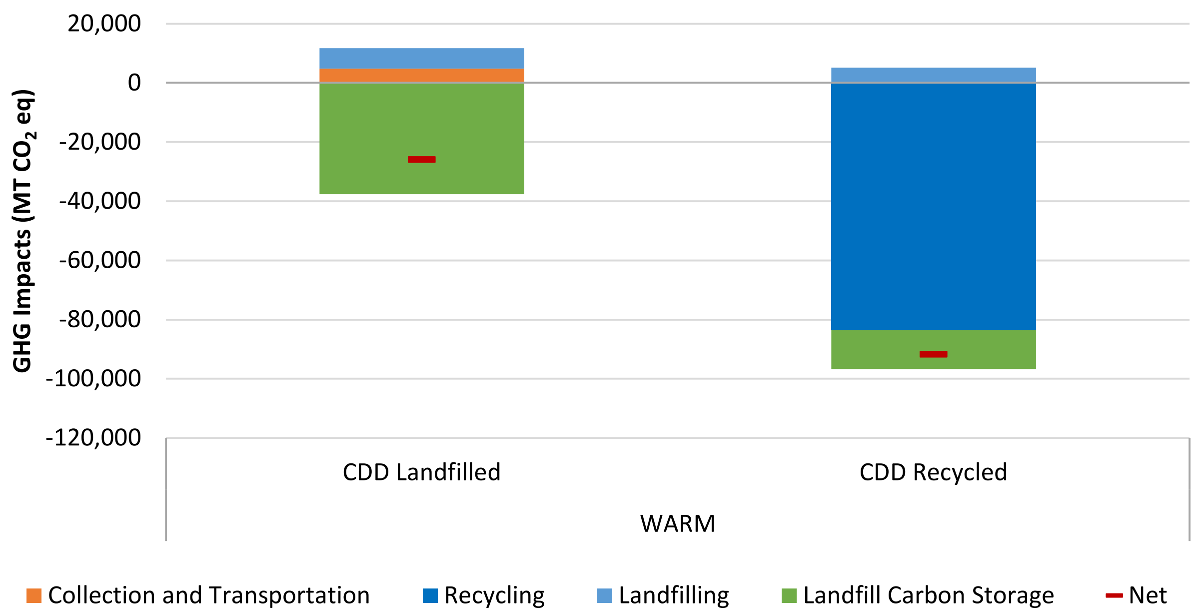


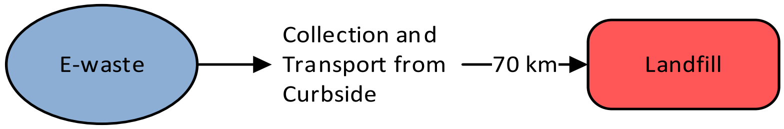
Figure 4-30. Comparison of WARM GHG Emission Estimates for the CDD Landfilling and Recycling Options

4.13 Impacts of E-Waste Collection and Recycling

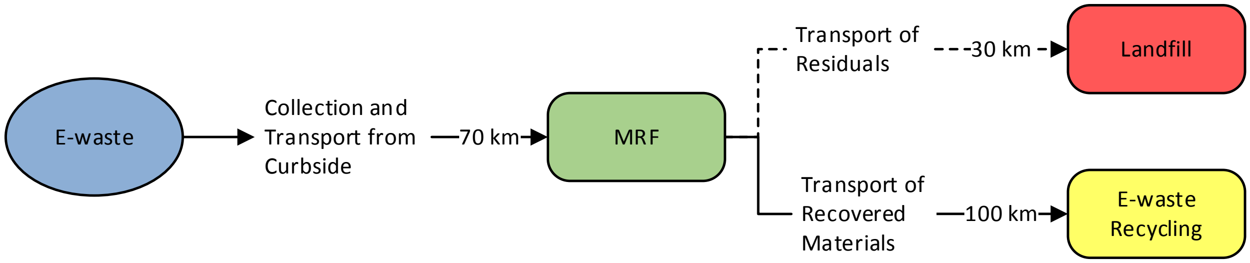
4.13.1 Scenario Description and Assumptions

A community would like to evaluate the economic and environmental impacts of instituting an e-waste curbside collection system to capture e-waste that is not otherwise captured by drop-off programs. E-waste is generally regarded as a high-value material stream and has been reported to pose a major challenge to the solid waste community (Townsend 2011). Many communities have instituted a variety of drop-off programs to promote e-waste recycling.

Two cases are considered to better understand the benefits and costs of a curbside e-waste collection program. The first case assumes that e-waste is collected with the mixed MSW stream and landfilled. The second case assumes that e-waste is source separated and collected as a separate stream, passing through the closest approximation to a pre-sorted material MRF available in each tool. Figure 4-31 (a) and (b) presents flow diagrams for the e-waste landfilling and recycling scenarios.



(a)



(b)

Figure 4-31. EOL Materials Flow with E-waste (a) Disposal, and (b) Recycling Scenarios

Only WRATE and WARM have categories for modeling e-waste. WARM's "personal computers" category was used to model the e-waste management in this scenario. WRATE has several categories of e-waste. SWOLF has a category for e-waste, but this was not fully implemented at the time of this report. MSW-DST and EASETECH do not have a material category for e-waste and thus cannot be used to analyze this scenario. WARM assumes that all personal computers are sent to a specialized e-waste MRF. Unlike WARM, WRATE does not have a specialized MRF for e-waste, so a "civic amenity center" (equivalent to a presorted drop-off center) is used. WRATE does not include an LCI for recycling e-waste, so for the recycling scenario, landfill emissions were not included for the e-waste diverted from landfilling. WARM accounts for the virgin material manufacturing emissions that are avoided by the recycling and recovery of materials from e-waste.

4.13.2 Results and Discussion

Figure 4-32 shows the results of the LCA analysis for GHG impacts for WARM and WRATE. Both tools show a greater overall impact from e-waste landfilling than e-waste recycling. Since WRATE does not have an LCI for recycling e-waste, the reduction in GHG impacts in the recycling case is much greater for WARM than for WRATE. Other impacts, including collection and transportation, are small compared to the reduction in emissions WARM predicts for recycling e-waste and to the reduction in landfilling emissions that WRATE predicts.

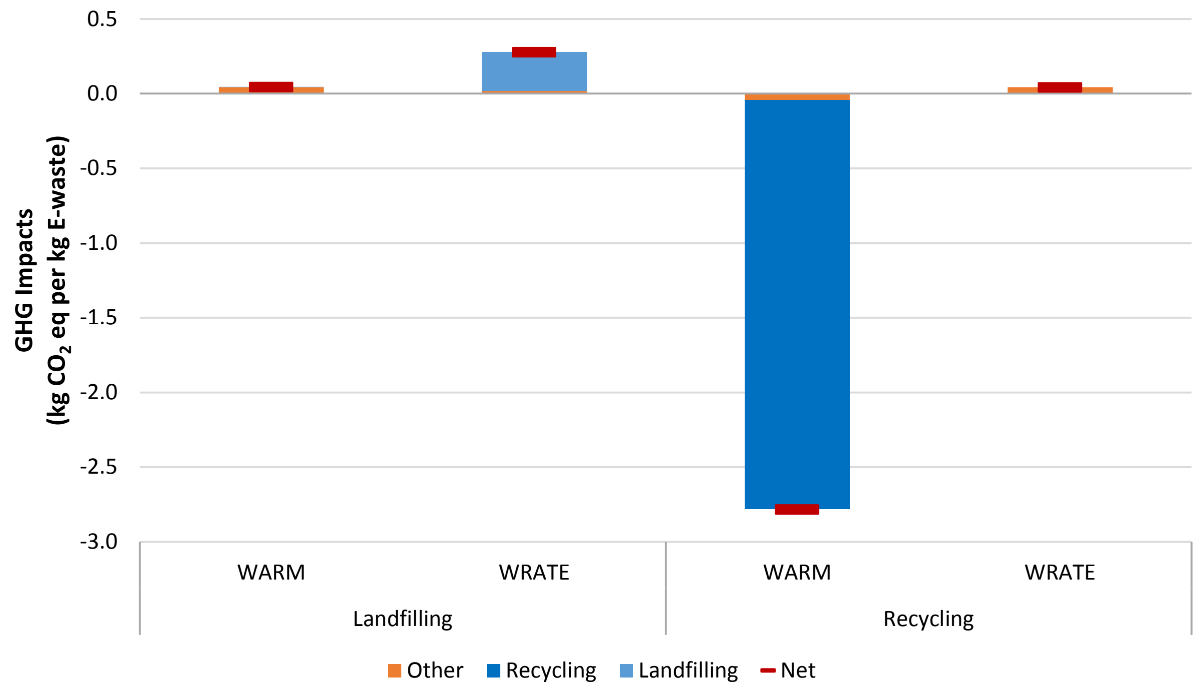


Figure 4-32. Comparison of WARM GHG Emission Estimates for the E-Waste Landfilling and Recycling Options

4.14 *Impacts of Collection Vehicle Fuels Type*

4.14.1 Scenario Description and Assumptions

A community would like to assess the economic and environmental impacts of replacing the existing EOL materials collection fleet with an alternative fuel vehicle fleet. Diesel is the predominant fuel used in collection vehicles. Many municipalities, however, are considering switching to collection vehicles powered with an alternative fuel, such as CNG, in order to reduce fuel expenses and reduce environmental impacts.

Modeling this scenario requires collection and transportation processes which can simulate a variety of fuel types for equivalent or substantially similar vehicle types. Three fuel types - diesel (i.e., the default base case), CNG, and biodiesel - are used to analyze the impacts of fuel-type changes.

Only WRATE has the necessary default functionality to model alternative fuels vehicles. WRATE allows the user to select a diesel-, CNG-, or biodiesel-powered materials collection fleet. Model default vehicle-specific and fuel-specific parameter values were used for the simulation. The tool does not account for any of the economic costs. It appears that SWOLF will ultimately have an option for modeling CNG as a fuel for collection vehicles, but this feature is not yet implemented and could not be included for this simulation. It should be noted that the impact of the fuel types could be evaluated using MSW-DST by modifying the default vehicle emissions to reflect those associated with CNG or biodiesel vehicles. As compilation and modifications of tool-default LCIs data to simulate a scenario like this are likely to be beyond the technical expertise of the targeted audience of this report, this scenario was not modeled using MSW-DST.

4.14.2 Results and Discussion

Figure 4-33 compares the GHG emission estimates for EOL materials collection for three fuel types. The results show that a slight decrease in GHG impacts using CNG as a fuel source over diesel and a 74% decrease in impacts with biodiesel. While CNG does reduce GHG emissions slightly, the carbon emitted is considered fossil carbon, leading to a similar impact as diesel. The impact of switching to biodiesel, which potentially contains and releases equivalent amounts of CO_2 upon combustion amount as diesel, is significant as much of the CO_2 emissions of biodiesel is from biogenic sources. Although GHG emissions can be significantly reduced with the use of a biodiesel fleet, the GHG emissions associated with collection and transportation are relatively insignificant compared to other materials-management processes such as landfilling as shown in several scenarios presented earlier.

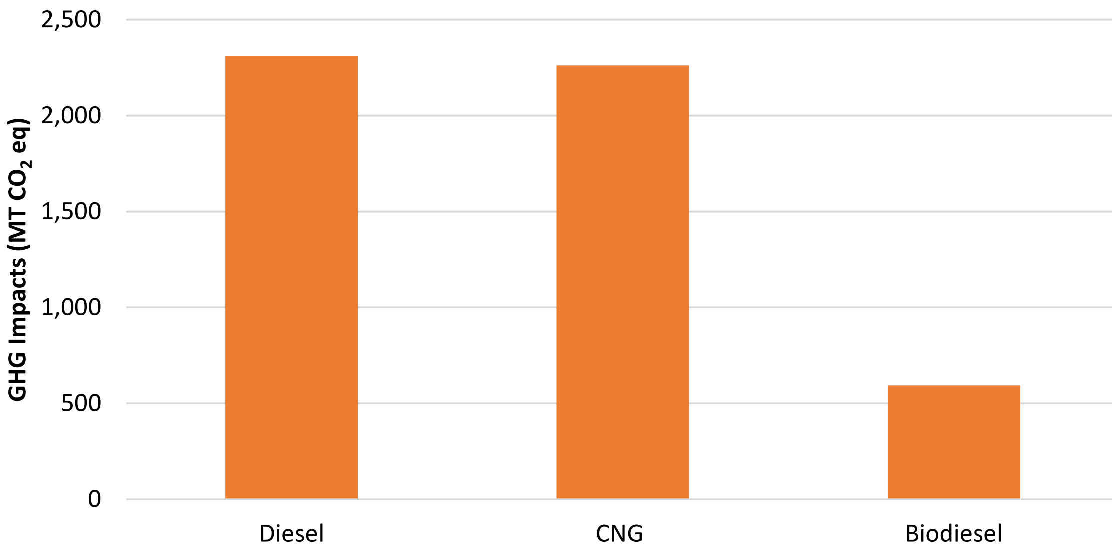


Figure 4-33. Comparison of LCA Tools' GHG Emission Estimates for Different Collection Vehicle Fuels Options

Figure 4-34 shows the acidification emissions predicted by WRATE for the collection vehicle fuels modeled. Unlike the GHG impacts, the acidification emissions for the CNG fuel scenario are an order of magnitude lower than the other fuel scenarios. This appears to be due to the relatively lower amount of acidic gases (e.g., sulfur dioxide) formed by the combustion of CNG compared to diesel or biodiesel fuel. Since WRATE does not have a cost-estimation feature, the economic impacts of switching to a different fuel type for collection vehicles cannot be evaluated using EOL materials LCA tools.

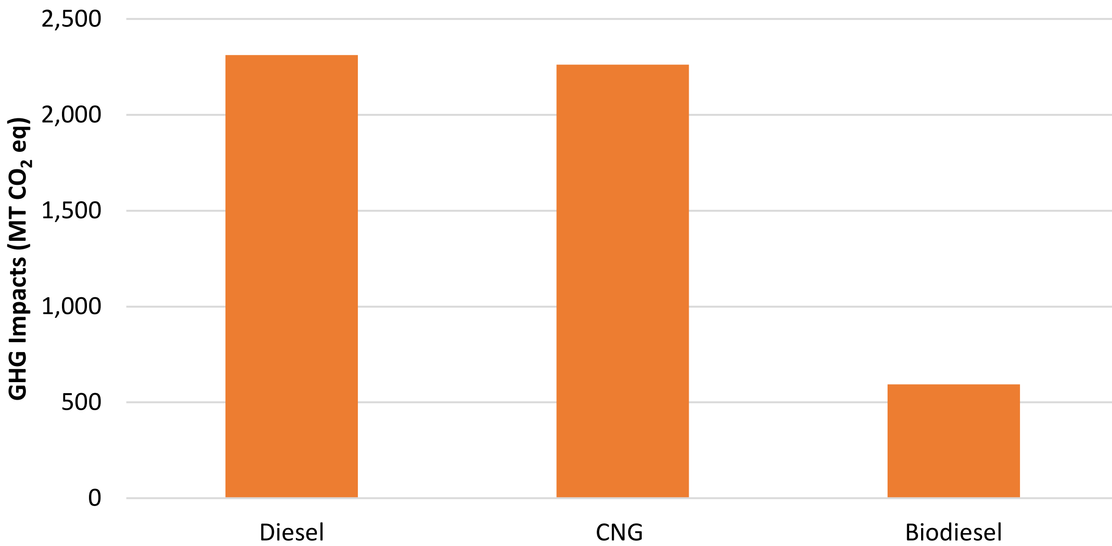


Figure 4-34. Comparison of WRATE's Acidification Impact Estimates for Collection Vehicle Fuels Options

4.15 Impacts of Collection Vehicle Types

The community would like to compare the economic and environmental impacts of using different types of collection vehicles for EOL materials collection. Specifically, the community would like to compare manual collection vs automatic collection of curbside recyclables. Automatic collection vehicles reduce the number of employees required to collect EOL materials while increasing the cost and operational complexity of the collection vehicle, and the community would like to assess the impact of vehicle automation and the associated loss of jobs.

This scenario could not be modeled using any of the five LCA tools under consideration. MSW-DST has several types of collection vehicles available, but it is not clear what the category names in MSW-DST correspond to in the tool's documentation. WRATE includes several vehicle types with manual and mechanized loading options. However, economic impacts, which are the primary objective of this scenario, cannot be evaluated using WRATE. Although user can adjust parameters such as number of workers and vehicle time per house in MSW-DST and SWOLF to simulate the environmental impact and change in materials collection and transport cost associated with collection vehicles used, neither MSW-DST nor SWOLF include options to readily choose commercially-available collection vehicles with varying levels of automation.

4.16 Impacts of a Transfer Station

4.16.1 Scenario Description and Assumptions

The community would like to compare the economic and environmental impacts of constructing a centrally-located transfer station. Depending on the distance between collection routes and the landfill, it is often economical to build a transfer station that allows collection vehicles to tip and transfer EOL materials to more fuel-efficient vehicles for (typically long-distance) transport to the materials-management facility.

To model this scenario, simulations with and without a transfer station were conducted. All baseline scenario, including transportation distances in the case without a transfer station, were used. In the case with a transfer station, the transfer station is assumed to be located 30 km from the center of the city and

50 km from the landfill. This is a total of 80 km compared to 70 km for the baseline case without a transfer station. It is assumed that the additional distance is necessary to accommodate locating the transfer station. It is assumed that a long-haul truck will be used to transport EOL materials from the transfer station to the landfill. Figure 4-35 below shows the material flows for the centrally-located transfer station scenario.

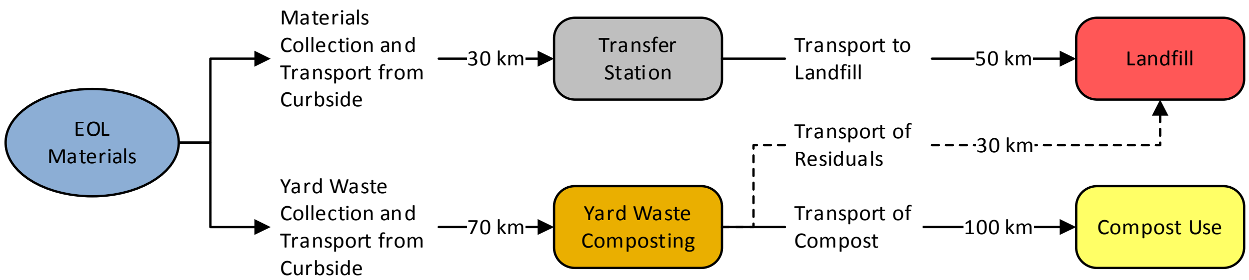


Figure 4-35. EOL Materials Flow for Transfer Station Scenario

WARM does not model variations in the collection process such as a transfer station or alternative vehicles with different fuel efficiencies and thus cannot be used to model this scenario. EASETECH does not have a transfer station process, so the paper-sorting facility is used as a surrogate for a transfer station. DST and SWOLF both have options to include a transfer station and to include different fuel efficiencies for transport vehicles. As stated in the general assumptions, it is assumed that trucks with a capacity of 14 to 20 tons are used for long-range transport. The truck option most closely resembling this capacity is selected in each tool. For SWOLF, a "medium-duty" truck is assumed to be used. MSW-DST automatically assumes a "typical" transport vehicle is used if a transfer station option is selected. The tools' default fuel efficiency was used for simulations.

4.16.2 Results and Discussion

Figure 4-36 shows that all the tools suggest that a centrally-located transfer station reduces GHG emissions associated with EOL materials transportation. Collection and transport emissions overall are reduced, even though the total distance the EOL materials travel is greater, because the vehicles used to transport the materials from the transfer station to the landfill are more fuel efficient. The only processes affected by adding a centrally located transfer station were collection and transportation and the transfer station process. The emissions of the transfer station are small compared to other categories.

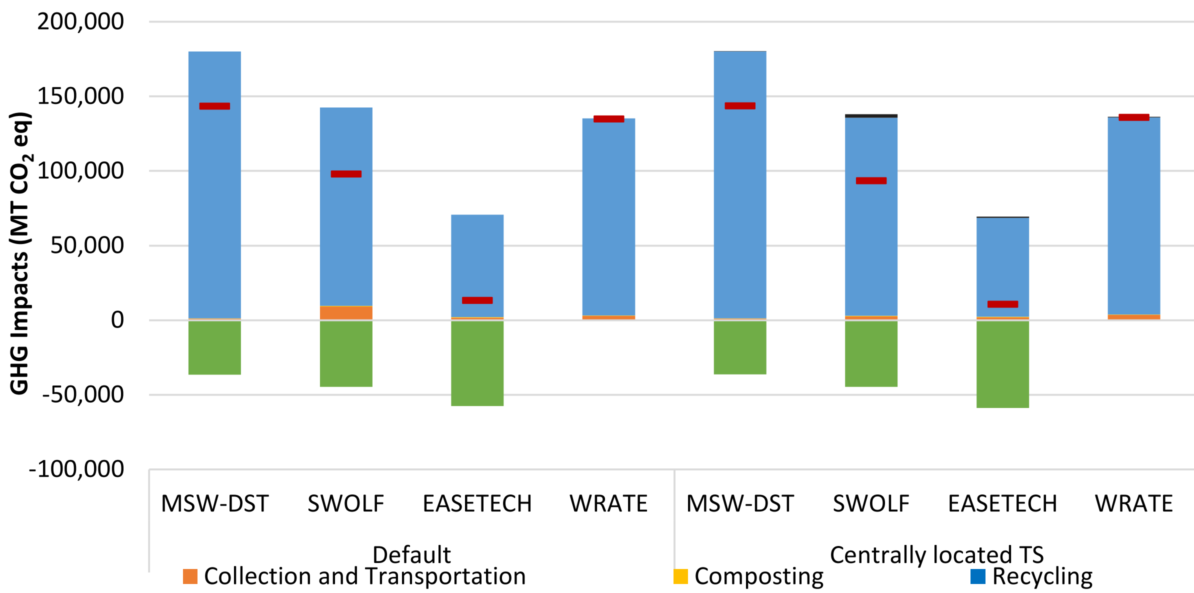


Figure 4-36. Comparison of LCA Tools' GHG Emission Estimates for the System with and without a Transfer Station

Figure 4-37 shows the cost estimated by MSW-DST and SWOLF before and after adding a transfer station. The annualized cost includes the annual operating and maintenance and capital costs, amortized over the life of the facility. Both models estimate a decrease in collection and transport cost with the implementation of a centrally located transfer station. Both models estimate that the savings in collection and transport more than offset the cost of operating the transfer station. SWOLF estimates a larger operating cost than MSW-DST.

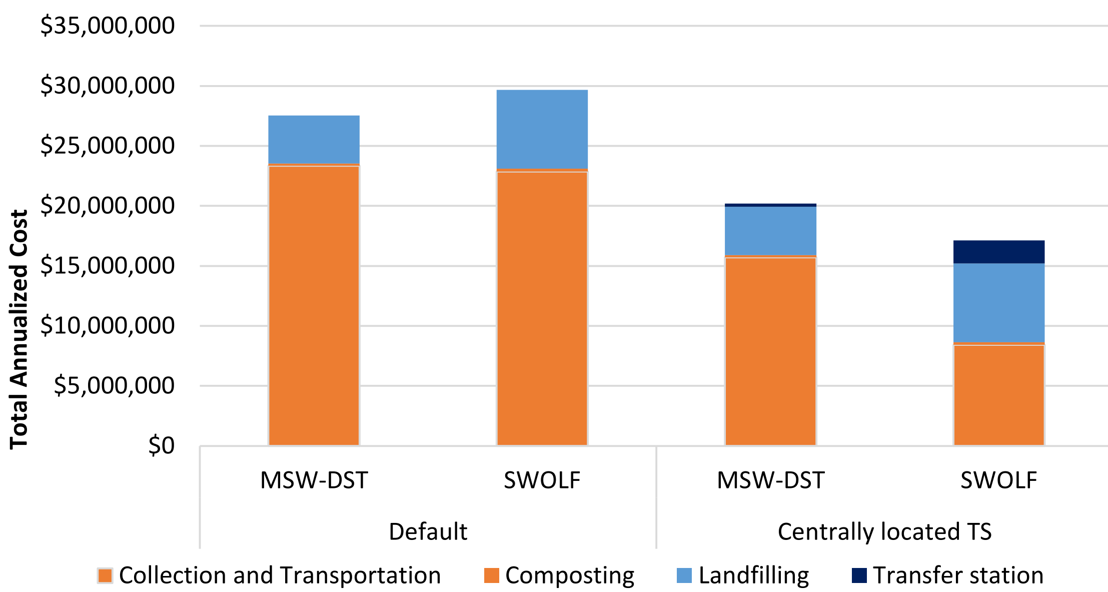


Figure 4-37. Comparison of LCA Tools' Total Annual Cost Estimates for the System with and without Transfer Station

4.17 Impacts of Several Thermal Treatment Options

4.17.1 Scenario Description and Assumptions

The community would like to understand the economic and environmental impacts of different thermal treatment strategies, including traditional incineration (WTE), gasification, and pyrolysis. These processes can recover energy from an EOL materials stream and reduce the mass and volume of EOL materials disposed of in a landfill.

Simulations results from four cases are compared. The first case is the baseline scenario in which all EOL materials except for yard waste are collected in one stream and landfilled. The second case is similar to the baseline scenario, with the exception that the mixed EOL materials stream is incinerated at a WTE facility instead of being placed in an MSW landfill. The ash from this facility is then landfilled in an ash landfill. The third case simply replaces the WTE process with a gasification process. The fourth case replaces the gasification process with a pyrolysis process. The tools default values are used for all energy-recovery parameters such as energy content and electricity conversion. The energy mix displaced by the electricity in this process is the same as the mix presented in the global assumptions. Figures 4-38 and 4-39 represent the materials flow for a WTE process and for a pyrolysis/gasification process for energy recovery, respectively. The main difference between the thermal treatment types is that the pyrolysis and gasification facilities must treat the incoming material stream (e.g., adjust moisture content, remove unsuitable materials) for effective thermal processing. Most mass-burn WTE facilities (currently the most prevalent type of WTE facility in the US) require little to no pre-preprocessing.

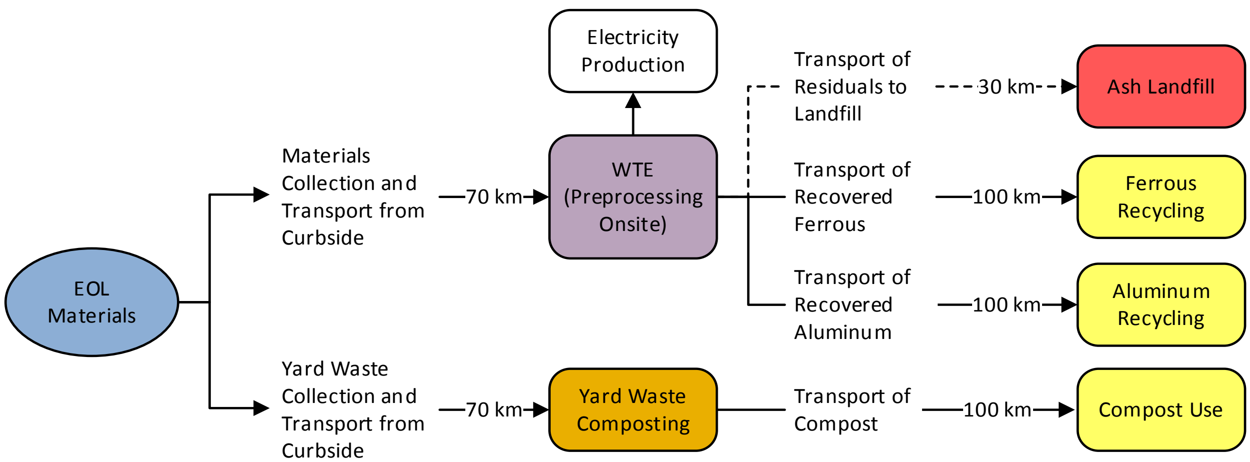


Figure 4-38. EOL Materials Flow for Thermal Treatment Scenario

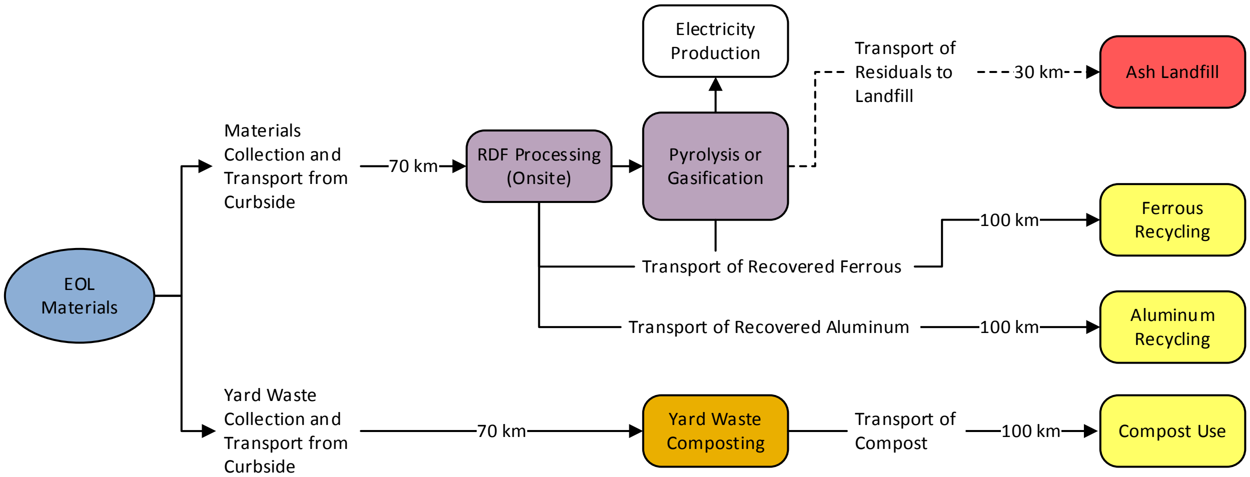


Figure 4-39. EOL Materials for Pyrolysis or Gasification Treatment Scenario

All of the tools can model the default scenario and WTE facility case; however, WRATE is the only tool that can be used to model a gasification and a pyrolysis process. All other assumptions are the same as the default scenario.

4.17.2 Results and Discussion

Figure 4-40 shows the results of the five LCA tools for GHG emissions impacts. All tools estimate a lower impact for WTE processes than for landfilling because the baseline landfilling process does not include LFG collection, resulting in methane emissions. EASETECH estimated an order of magnitude higher emissions savings from operating a WTE facility. WRATE predicts lower GHG emissions for gasification and pyrolysis than for landfilling, but a greater reduction for WTE than for the advanced thermal treatment processes. The GHG emissions for pyrolysis and gasification are greater than WTE mass burn because both gasification and pyrolysis require the materials to be transformed into an RDF more suitable for the process. The RDF production process rejects some of the materials as residual, which is then landfilled where it may generate methane. This leads to a higher GHG emission compared to the WTE mass-burn scenario. Both gasification and pyrolysis produce syngas as a process output. WRATE assumes that the syngas is used for electricity generation. Syngas can also be used for other applications such as vehicle fuel production, which may offer a greater environmental offset than that for electricity generation.

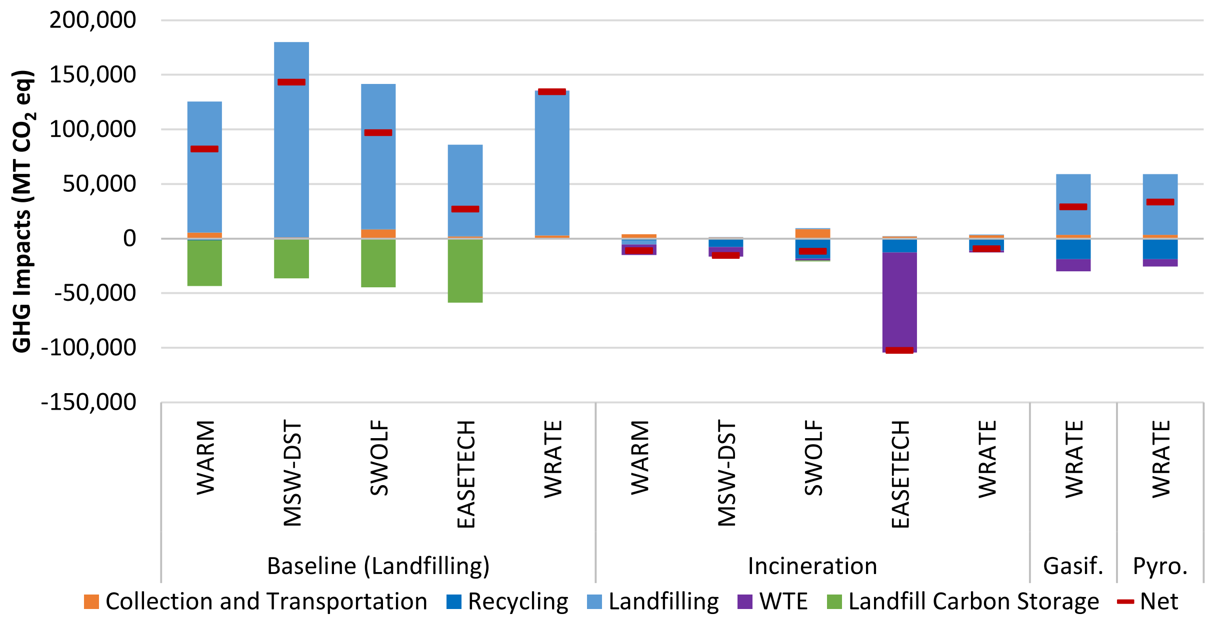


Figure 4-40. Comparison of LCA Tools' GHG Emission Estimates for the Baseline Scenario and Different Thermal Treatment Options

Figure 4-41 presents the annual cost estimated for landfilling and WTE from SWOLF and MSW-DST. It is not clear why MSW-DST estimates lower collection and transportation costs for the incineration case. SWOLF estimates a higher collection and transportation cost, probably to account for the impact of transporting ash and recovered metals twice. MSW-DST estimates a slightly greater revenue through the recovery of metals than SWOLF. MSW-DST estimates a significantly larger cost for operating the WTE incinerator than does SWOLF. Based on the tool development timeline, the cost data used in SWOLF are expected to be more recent and updated than those used in MSW-DST.

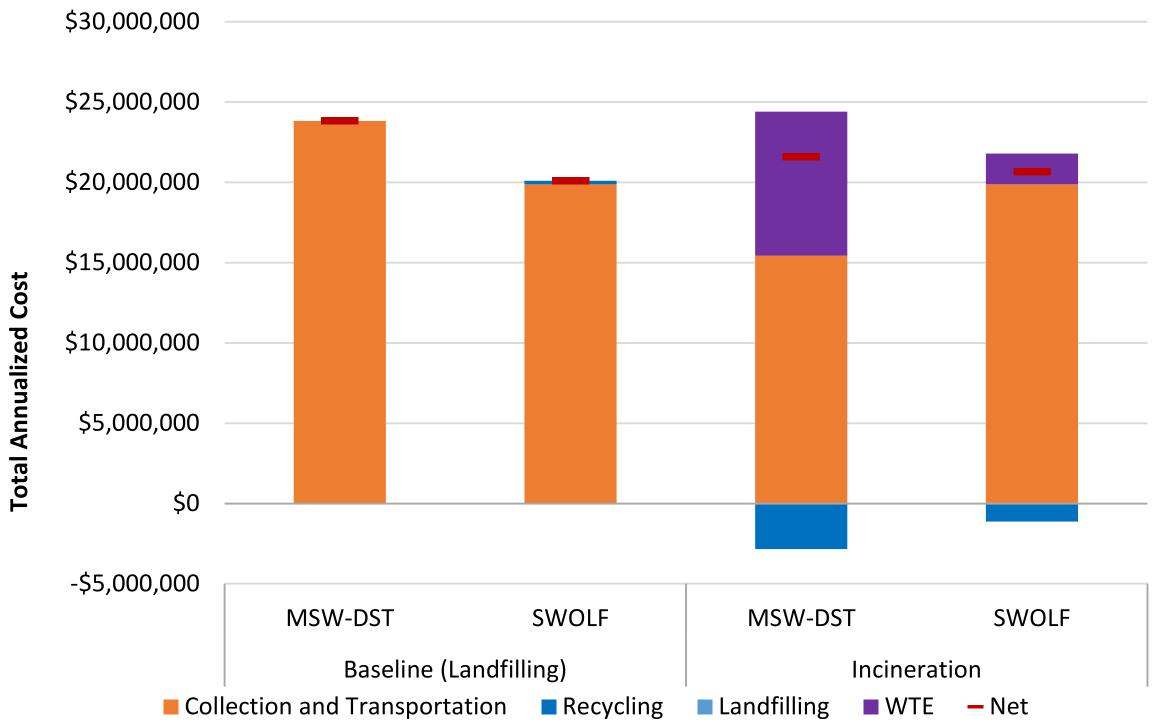


Figure 4-41. Comparison of LCA Tools' Total Annual Cost Estimates for the Baseline Scenario and Different Thermal Treatment Options

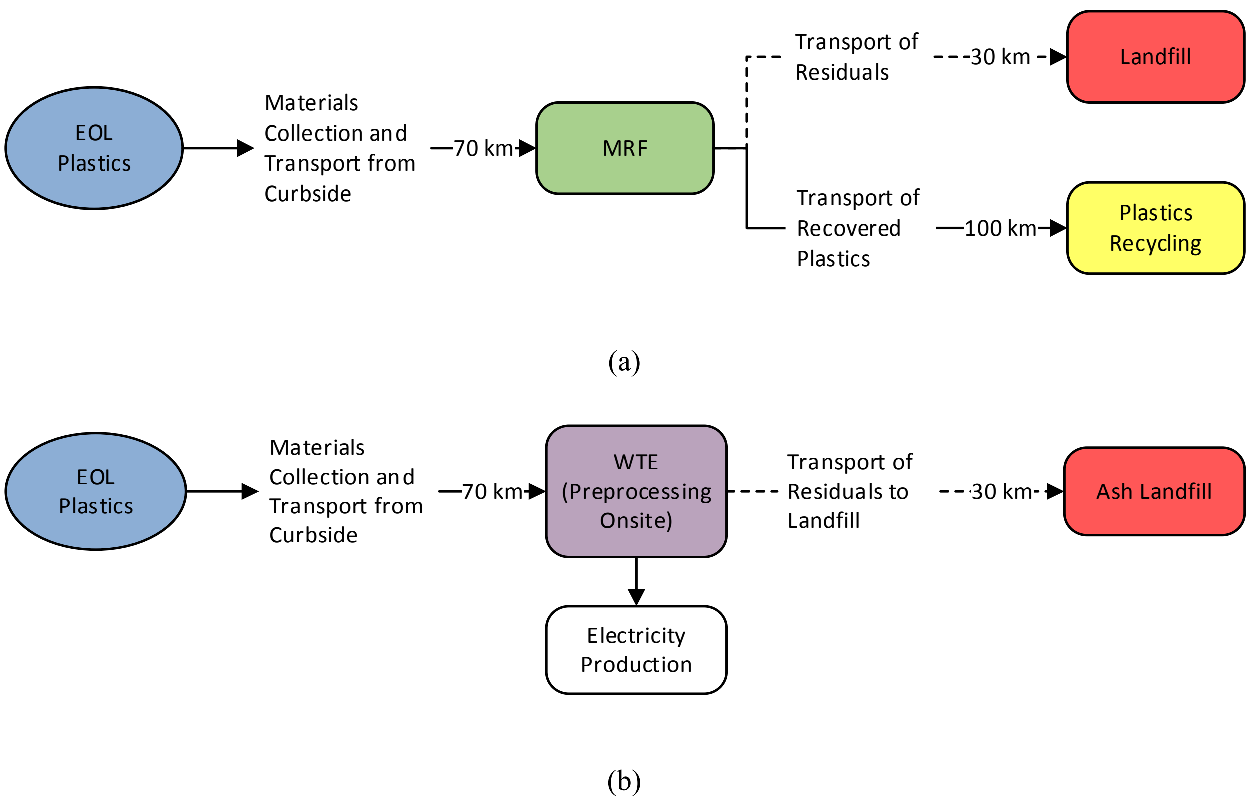
4.18 *Impacts of Plastics Incineration vs Recycling*

4.18.1 Scenario Description and Assumptions

Plastics have a high heating value, making them a valuable fuel for a WTE facility, but they are also a valuable commodity if recycled. The community with a WTE incineration facility would like to understand the economic and environmental impacts of recycling versus incinerating plastics. To analyze the effects of the incineration and recycling of plastic, two scenarios are compared, one in which 121,000 tons of recyclable plastics are combusted with electricity production and one in which 121,000 tons of recyclable plastics are recycled. The EOL materials stream includes only recyclable plastics in the same relative proportions as the default scenario. Electricity produced from WTE plastic incineration displaces the same electricity grid mix specified in the global assumptions section. Figures 4-42 and b represent the material management flows for the scenarios where plastics are recycled and plastics are combusted, respectively.

The goal of this scenario is to model the management of recyclable plastics only, but this is difficult to designate in EASETECH and WRATE, which may include some categories that contain both recyclable and unrecyclable plastic. A best effort is made to include recyclable fractions in proportions that represent the US EOL plastics stream. Also, it should be noted that EASETECH does not have a process that simulates the disposal of fly ash; EASETECH only includes a bottom ash landfill process. This could lead to differences in the results of EASETECH compared to other tools for EOL materials incineration.

As is mentioned in other scenarios, it is not possible to adjust the MSW-DST residual rate for the MRF process, so the MRF capture rate (i.e., the total mass of plastics being sent to the MRF) is adjusted to force the correct amount of plastics being sent to recycling. This could result in substantial differences in transportation emissions, especially considering that MSW-DST models materials as if they are collected in a mixed-EOL materials collection stream rather than with other recyclables. Modeling plastic incineration in SWOLF and WARM was relatively straightforward since the plastics categories are based on resin type, which are consistent with the composition used for this scenario.



(a) (b)

Figure 4-42. EOL Plastics Flow for (a) Recycling, and (b) WTE Scenarios

4.18.2 Results and Discussion

As seen in Figure 4-43, all tools predict a greater GHG emission from incinerating than from recycling plastics. All tools predict a negative net GHG emission for recycling, and only EASETECH predicts a negative net emissions for incinerating plastic. A large variation among tools results for incineration scenario is, probably, a result of differences in the marginal energy mix used for modeling as well as the variation in electricity generation process LCIs among tools. As discussed earlier, 100% coal was assumed as the marginal fuel mix for EASETECH, whereas several fossil fuels were included in the marginal energy mix for the other tools. EASTECH and WRATE electricity generation process LCIs are based on Euorpean data whereas WARM, MSW-DST, and SWOLF LCIs are based on the US-specific data. Because recycling results in additional transportation and processing emisisons compared to incineration, the "other" category is included but is small compared to the impacts of WTE mass burn and recycling. Because plastic is primarily derived from fossil carbon, incineration of plastic releases fossil carbon.

Figure 4-44 shows the economic impact of plastic incineration compared to recycling. Since this scenario models only the plastic part of the EOL materials stream, collection and sorting are not included as the additional landfilled residual amount could not be removed from MSW-DST MRF output. Both tools predict a greater revenue for incineration than for recycling. This is due to the inclusion of lower value plastics such as film plastic and polypropylene, which are considered part of the "non-recyclable-plastic" stream and are not recycled, for WTE. This fraction lowers the net value of the recycled products. However, these non-recyclable plastics have high energy content, which contributes to the electricity generation if incinerated for energy recovery. The SWOLF tool is not fully developed and these costs may be revised in future versions.

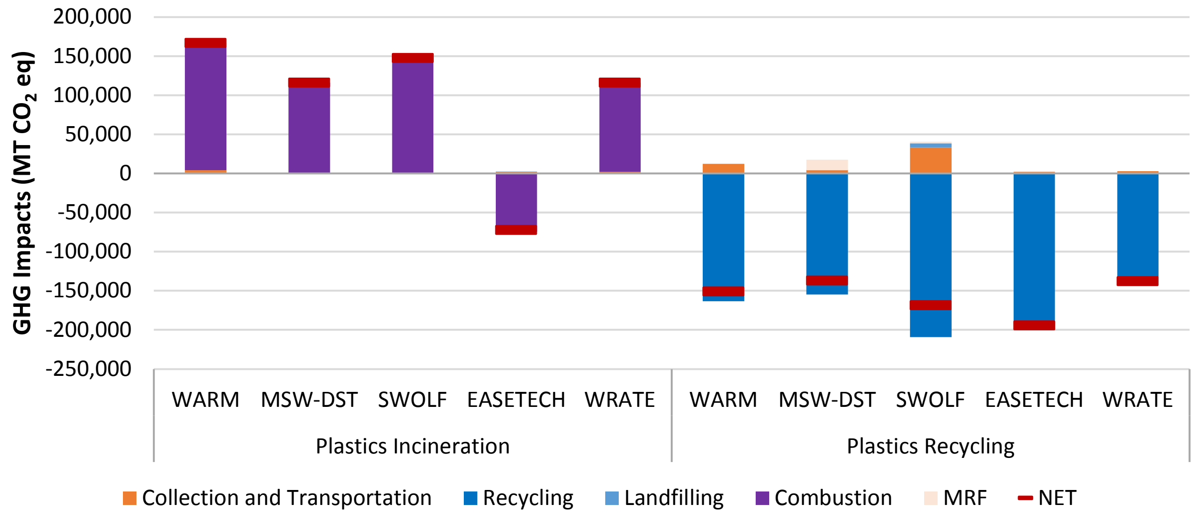


Figure 4-43. Comparison of LCA Tools' GHG Emission Estimates for Plastics Incineration and Recycling

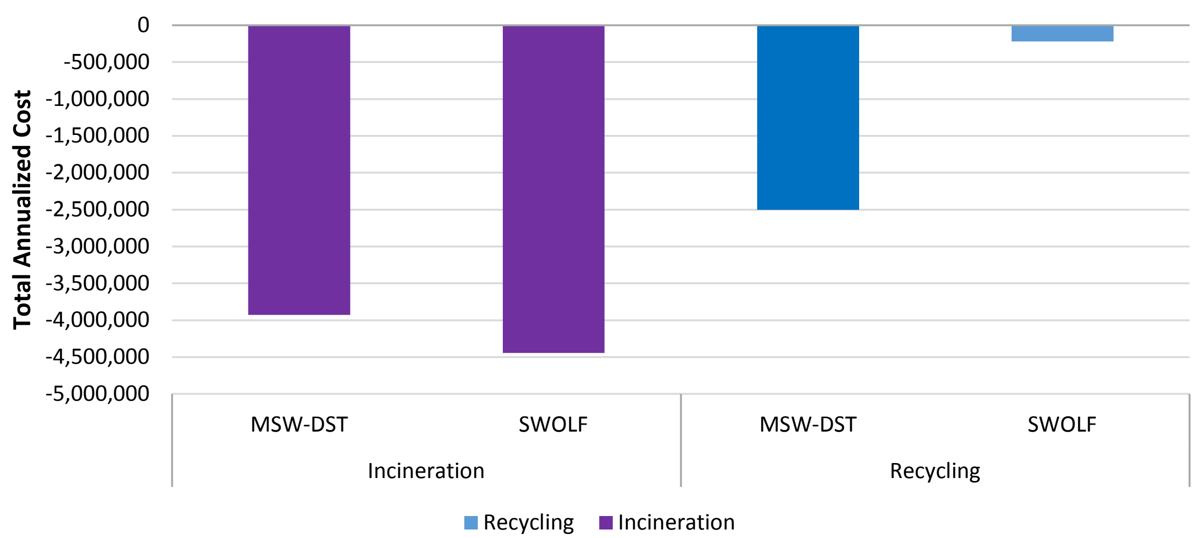
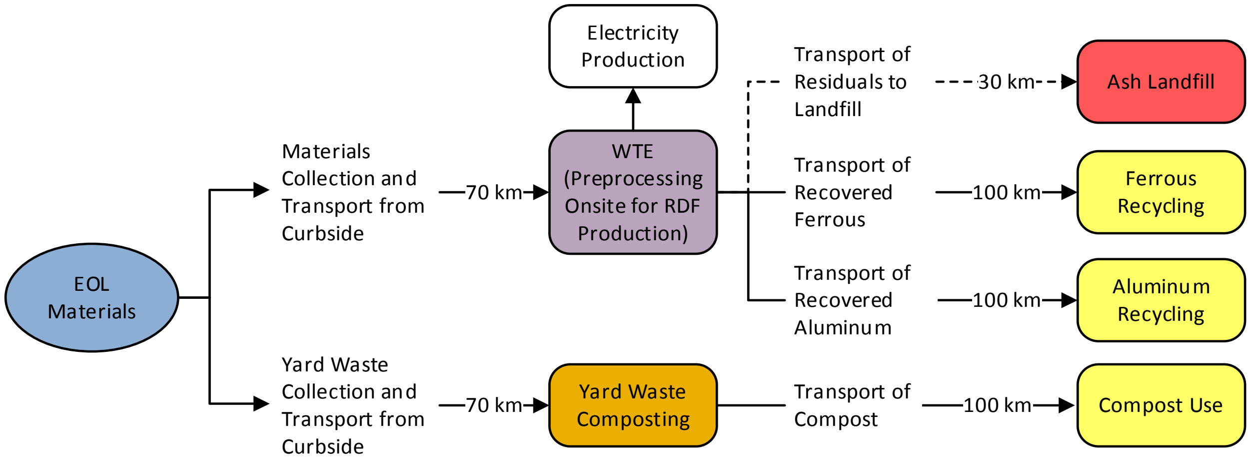


Figure 4-44. Comparison of LCA Tools' Economic Benefits Estimates for Plastics Incineration and Recycling

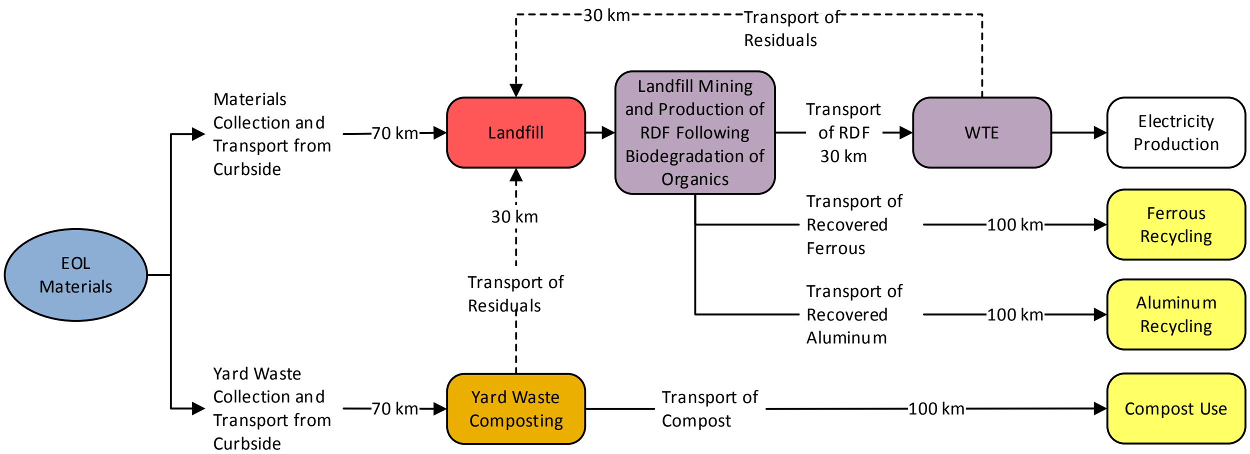
4.19 Impacts of RDF Recovery Before and After Landfilling

The community would like to compare the economic and environmental impacts of RDF production. RDF can be produced from fresh incoming EOL materials or from materials deposited in a closed landfill. Landfill mining is a process that can be used to reclaim older landfill cells to acquire additional landfill airspace or to provide community assets such as parks or land for future development (Jain et al. 2013, Jain et al. 2014). Mining landfill cells and screening out fines can produce an RDF with greater energy content than fresh MSW due to the absence of higher moisture content materials such as food scraps. An additional benefit of RDF production from the mined materials over RDF production from fresh incoming material is that a smaller materials stream would need to be processed as a majority of the biodegradable organics (e.g., food scraps), which have relatively lower energy content, are stabilized.

To model this scenario, two cases are considered. The first case assumes the same EOL materials composition as the baseline scenario, but one which passes through preprocessing at a WTE facility that recovers metals for recycling and produces RDF that is combusted to produce electricity. The rest of the residual material and generated ash is sent to a landfill (Figure 4-45 a). The second case assumes that the EOL materials are deposited in the landfill and mined (after stabilization of biodegradable organics) to produce RDF. It is assumed that the mining process produces three broad categories of materials: those suitable for recovery (i.e., aluminum and ferrous materials), those suitable for RDF production, and residual for landfilling (Figure 4-45 b). RDF is combusted at a WTE facility. In setting up the scenarios to simulate RDF production and landfill mining, it was observed that none of the tools could readily simulate the landfill mining scenario due to a lack of processes specific to landfill mining. Therefore, the RDF production and landfill mining scenarios were not further evaluated. It should be noted that some of these tools can be modified to include landfill mining process LCIs and can be used to model this scenario; Jain et al. (2014) used EASETECH to assess the environmental impacts of landfill mining. As mentioned earlier, process-specific LCIs development and programing to modify the existing tools to include new processes is expected to be beyond the technical expertise of community decision makers.



(a)



(b)

Figure 4-45. EOL Materials Flow with (a) RDF Production before Disposal, and (b) RDF Production after Disposal followed by Landfill Mining

4.20 Summary and Discussion

Table 4-7 presents a summary of scenarios that could be simulated with each tool. Out of total 31 scenarios planning for this evaluation, WRATE readily simulated 25, EASETECH readily simulated 19, MSW-DST and SWOLF simulated 17 each. SWOLF developers plan to add features that would allow it to run 7 additional scenarios. As discussed earlier in this chapter, some of the simulations were conducted by selecting a similar process due to lack of availability of the process of interest in the tool(s), or adjusting/approximating parameters (e.g., diversion rates for PAYT scenario). Such approximations/adjustment may be difficult for a user with limited LCA or technical background, and may also result in an inaccurate assessment. None of the tools except WARM could simulated the impacts of alternative management option for CDD materials. None of the tools except WRATE could simulate impact of alternative fuel vehicle fleet. None of the tools could readily simulate impacts of automation levels of materials collection and recovery operations or impacts of landfill mining. It should be noted that some of these tools can be modified to include process LCIs and can be used to model several of the scenario that could not modeled using features; Jain et al. (2014) used EASETECH to assess the environmental impacts of landfill mining. As mentioned earlier, process-specific development and programing to modify the existing tools to include new processes is expected to be beyond the technical expertise of community decision makers.

Table 4-7. A List of the Scenarios that could be Evaluated Using the LCA Tools

Scenario Title and Section Number	Options	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Baseline Scenario (4.4)	Landfill with no LFG Treatment	✓	✓	✓	✓	✓
Landfill Gas Treatment Options (4.5)	Flaring	✓	✓	✓	✓	✓
	LFG-to-Electricity	✓	✓	✓	✓	✓
	LFG-to-Electricity with Bioreactor	✓	✓	✓	✓	
Source-Separate Organics Processing (4.6)	Collection and Composting	✓		✓	✓	✓
	Collection and AD			✓[a]	✓	✓
Backyard Composting (4.7)	Decreased organics collection due to home composting	✓	✓	✓	✓	✓
Materials Recovery (4.8)	Single stream MRF	✓	✓	✓	✓	✓
	Dual stream MRF	✓		✓[a]	✓	✓
	Mixed waste MRRF	✓	✓	✓	✓	✓
MRF Automation (4.9)	Various levels of manual vs automated work			✓[a]		
Recycling Plastics vs Recycling Glass (4.10)		✓	✓	✓	✓	✓
Pay-as-You-Throw (4.11)		✓	✓	✓	✓	✓
CDD Recycling (4.12)	Landfilling of CDD	✓				
	Recycling of CDD	✓				

Table 4-7 (contd.). A List of the Scenarios that could be Evaluated Using the LCA Tools

Scenario Title and Section Number	Options	WARM	MSW-DST	SWOLF	EASETECH	WRATE
E-waste Collection and Recycling (4.13)	Landfilling of e-waste	✓		✓[a]		✓
	Recycling of e-waste	✓		✓[a]		✓
Collection Vehicle Fuels (4.14)	Diesel	✓	✓	✓	✓	✓
	CNG			✓[a]		✓
	Biodiesel					✓
Collection Vehicle Types (4.15)	Vehicles with different mechanisms for waste collection					
Transfer Station (4.16)	Adding a centrally located transfer station	✓	✓	✓	✓	✓
Thermal Treatment Options (4.17)	Mass burn WTE	✓	✓	✓	✓	✓
	Gasification			✓[a]		✓
	Pyrolysis					✓
Plastic Incineration vs Recycling (4.18)	Plastic incineration	✓	✓	✓	✓	✓
	Plastic recycling	✓	✓	✓	✓	✓
RDF Recovery Before and After Landfilling (4.19)	RDF production from fresh MSW		✓	✓		✓
	RDF production from landfill mining					

[a] Not in the version evaluated, but is expected to be included in future versions.

5 Summary

5.1 Summary of Tools Salient Features Comparison

The decision-making domain of communities in the US typically begins when materials are taken out of the use phase and become a waste to be managed by the community's EOL materials management department or their franchised haulers; the community's decision-makers can indirectly influence processes upstream (e.g., promotion of backyard composting) of the EOL phase. We identified 29 tools that can potentially be used by communities for the LCA of MSW materials. As the decision-making domain of communities includes only the EOL phase of materials collection and management, only the tools that were specific to EOL management of materials in the US or the ones that allow users to customize the tools to simulate US-specific EOL materials management approaches were selected for comparative evaluation. The tools selected for evaluation were WARM, MSW-DST, SWOLF, EASETECH, and WRATE. Only the standard version of WRATE was evaluated in this report; the expert version of this tool offers more flexibility and costs more than the standard version.

These tools were evaluated based on such criteria as LCA scope (e.g., materials and processes included), impacts analyzed (e.g., environmental, social, economic), and other general attributes (e.g., training and tutorials available, documentation thoroughness, ease of use, frequency of update). The tools were evaluated based on a review of tool documentation and use of these tools to simulate the LCA of a variety of materials-management scenarios. These scenarios represent several currently pertinent materials-management-specific challenges that decision makers of US communities must address. These simulations were not only useful in illustrating the applications of LCA in decision making but also helpful in identifying the limitations of these tools.

All the tools evaluated have been developed in the last two decades with WARM being the oldest and SWOLF, which is still under development, being the newest. All these tools (except SWOLF) have been updated since the release of the original version. WARM has been updated most frequently (14 times) since it its initial release in 1998. Table 5-1 compares salient features of these tools. WARM and MSW-DST are available for free while there is an annual licensing fee of £1400 for WRATE and a one-time fee of € 5,000 for EASETECH. The EASETECH license is provided free to the registered user and the training cost (provided by DTU) for consultants, authorities, and developers to become registered users is € 5,000. Fewer than 230 licenses/copies each of EASETECH, MSW-DST, and WRATE have been sold/distributed internationally since their development; there are approximately 300 unique users on the WARM update mailing list. As a point of comparison, there are over 39,000 local governments (counties, municipalities, and townships) existed in the US in 2012 (Hogue, 2013) that may benefit from these tools.

As shown in Table 5-1, all tools included features to compare environmental impacts of the commonly practiced EOL materials (specifically MSW) management options in the US, such as recycling, composting of biodegradable materials, incineration, and landfilling. However, some management options and material streams could only be analyzed with specific tools. For example, only WARM can analyze impacts associated with source reduction and the management of CDD materials; pyrolysis can be analyzed only using WRATE. It should be noted that Table 5-1 includes the process for a tool if it can be readily simulated using the tool even if it is not available as default option. For example, a single-stream MRF is not specifically included in WRATE but it can be modeled using other similar process. Only MSW-DST and SWOLF assess the cost to construct, operate, and maintain a facility.

Tools offered varying degrees of flexibility in simulating slight variations of materials-management options. For example, the impact of progressively expanded LFG collection system can be assessed by varying LFG collection efficiency in MSW-DST; WARM is not suitable for this assessment. Another example of tool-specific flexibility is assessing the impact of replacing a diesel fleet with a CNG fleet for materials collection. This can only be analyzed with WRATE or the future version of SWOLF, as the other tools do not include CNG as a fuel option. The advantage of flexibility is that the user can simulate site-specific conditions, the disadvantage is that a greater number of user-specifiable parameters add tool complexity. In general, EASETECH appeared to be the most flexible and WARM the least flexible in terms of the number of user-specifiable parameters. It should be noted that the standard version of WRATE was evaluated in this study and the expert version is designed to offer greater flexibility.

Tools varied in the scope of emission sources included in process-specific LCIs. For example, WARM's landfill process excludes emissions associated with landfill leachate and landfill construction while WRATE includes emissions associated with these aspects. WARM does not consider emissions associated with facility construction in general. Examples of these emissions include emissions associated with manufacturing/production (including raw materials extraction) of materials (e.g., steel, concrete, geosynthetics, and equipment) and energy (e.g., electricity, diesel) used for materials-management facilities.

Tools varied in the impact categories analyzed and not all tools included the same impact categories, as shown in Table 5-1. For example, WARM only analyzes the GHG impacts, whereas other tools include a wide range of impact categories such as climate change, ecotoxicity, acidification, and eutrophication.

Table 5-1. Comparison of Salient Features of EOL Materials Management LCA Tools

Consideration	WARM	MST-DST	SWOLF	EASETECH	WRATE
Procurement Cost	Free	Free	Free to non-commercial. Cost for commercial use is not yet determined.	€5,000	£1,400/ Year (Std version)
Latest Update	2015	2002	2015	2014	2015
Construction and Operating and Maintenance Cost Estimates	-	✓	✓	-	-
Material Categories					
MSW	✓	✓	✓	✓	✓
CDD	✓	-	-	-	-
Electronic Waste	✓	-	✓[1]	-	✓
Source Reduction	✓	-	-	-	-
Materials Collection					
Bin/cart options	-	✓	✓	-	✓
Drop-off	-	✓	✓	-	✓
CDD Collection	-	-	-	✓	✓
SSO	-	-	✓	-	✓
Materials Transport					
Multiple Fuel Options	-	✓	✓	✓	✓
Multiple Vehicle Options	-	-	-	-	✓
Multiple Modes (e.g., Rail, Ship)	-	✓	✓	✓	✓
Multiple Road Options	-	-	✓	✓	✓
Transfer Station	-	✓	✓	-	✓
MRF					
Single Stream	-	✓	✓	✓	✓
Dual Stream	-	-	✓	-	✓
Mixed EOL materials	-	✓	✓	-	✓
Landfill					
MSW Landfill	✓	✓	✓	✓	✓
Ash Landfill	-	✓	✓	✓	✓
Carbon Storage	✓	✓	✓	✓	-
Leachate	-	✓	✓	✓	✓
LFG- Generation Rate Adjustable	✓	✓	✓	✓	✓
LFG-Flaring	✓	✓	✓	✓	✓
LFG-to-Electricity	✓	✓	✓	✓	✓
LFG Direct Beneficial Use	-	-	-	✓	-

Table 5-1 (contd.). Comparison of Salient Features of EOL Materials Management LCA Tools

Consideration	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Emerging Technologies					
Gasification	-	-	✓[1]	-	✓
Pyrolysis	-	-	-	-	✓
AD	-	-	✓	✓	✓
Incineration					
Mass Burn	✓	✓	✓	✓	✓
Refuse-Derived-Fuel	-	✓	✓	-	✓
Incineration without Energy Recovery	-	-	✓	✓	-
Composting					
Windrow Composting	✓	✓	✓	✓	✓
In-vessel Composting	-	✓	✓	✓	✓
Backyard Composting	-	-	-	-	✓
Tool Output					
Simultaneous Comparison of Multiple Scenarios	-	-	-	-	✓
Process-specific emissions		✓	✓	✓	✓
Impact Categories[2]					
Global Warming	✓	✓	✓	✓	✓
Ozone Depletion	-	-	-	✓	-
Human Toxicity, General	-	-	-	-	✓
Human Toxicity Carcinogenic	-	✓	-	✓	-
Human Toxicity Non-Carcinogenic	-	✓	-	✓	-
Ionizing Radiation	-	-	-	✓	-
Smog Formation	-	✓	✓	✓	-
Eutrophication	-	✓	✓	-	✓
Freshwater Eutrophication	-	-	-	✓	-
Marine Eutrophication	-	-	-	✓	-
Ecotoxicity	-	✓	-	✓	-
Freshwater Aquatic Ecotoxicity	-	-	-	-	✓
Depletion of Abiotic Fossil Fuel Resources	-	-	✓	✓	-
Depletion of Abiotic Non-Fossil Fuel Resources	-	-	-	✓	-
Acidification	-	✓	✓	✓	✓
Terrestrial Eutrophication	-	✓	-	✓	-
PM	-	✓	-	✓	-

[1] planned but not included in version evaluated

[2] SWOLF has an editable impact assessment method section that could add or remove categories. Note EASETECH has multiple impact assessment methods available.

5.2 Observations from the Tools Application for Evaluating Materials Management Options

The following observations were made from the application of the tools for various materials management scenarios simulated using these tools:

1. A majority of the US-specific EOL materials management options could be simulated (with appropriate assumptions in material categories and classification) using WRATE and EASETECH due to the flexibility offered by these tools. Simulating a stream of materials representative of the US (US EPA 2014), which is the dataset the US communities' decision makers are expected to rely upon, was challenging, especially using EASETECH and WRATE due to variation in materials nomenclature. For example, plastics in WRATE and EASETECH are labeled based on use (e.g., drink bottles), and characteristics (e.g., hard plastics in EASETECH), whereas the US EPA Facts and Figure track plastics by resin type (e.g., PET, HDPE). This discrepancy in classification styles is also important because some items (e.g., drink bottles) have compositions that may substantially vary over time.
2. Not all the planned scenarios could be simulated with all the tools. For example, the environmental impact of landfill mining could not readily be analyzed with any of the tools.
3. Several commonly practiced materials management options either are not included in the many of the tools or not referred to by the names used by the EOL materials-management community in the US. For example, none of the tools, except SWOLF, specifically includes single-stream curbside collection and single-stream MRF as options. Although most of the materials-management processes may reasonably be simulated using these tools, use of names inconsistent with industry-standard terminology or processes complicates their use by users with limited LCA background.
4. Due to the wide variation in impact categories analyzed among tools, the only impact category that could be compared among the tools was global warming (i.e., GHG emission). Also, the units for none of the comparable impact categories included in the tools (except WARM) are the same to allow comparison of these impacts among the tools. For instance, the unit for eutrophication in EASETECH is kg P-eq while the unit in MSW-DST for the same category is kg N-eq, making it difficult to quantitatively compare the results across tools.
5. Not all the tools provided process-specific breakdowns of emissions (e.g., materials placement and compaction, LFG) from the major processes (e.g., landfill). The process-specific emissions distributions presented in Chapter 4 were estimated using tool outputs and documentations.
6. LFG and carbon storage had the greatest influence on the overall GHG impact for landfill and remanufacturing credit (i.e., emission offset associated with avoiding virgin materials production due to substitution by recovered materials for product manufacturing has the greatest influence on overall GHG emissions from materials recovery and recycling processes). All the tools, except WRATE, include (or give the user the flexibility to include) carbon storage. Including carbon storage reduces the net GHG emissions estimate for landfill. WARM's remanufacturing credit was significantly greater than the other tools. Due to variations in the magnitude of these parameters, net emissions varied significantly among tools in some scenarios simulated.
7. Although the magnitude of impact varied among tools, the tools results, in general, provided consistent qualitative interpretation of environmental benefits as expected for various materials-management options simulated. For example, although the magnitude of reduction in GHG emission with LFG flaring varied among tools, all the tools, as expected, showed a decline in GHG emissions with LFG collection and flaring.
8. Although the tools evaluated in this report primarily focus on the EOL phase of materials management, data used/results of some of these tools (e.g., source reduction feature of WARM) can be used to assess the environmental impacts through all phases of the life cycle of materials.

5.3 Data Gaps and Considerations for Future Research

Additional research effort is needed to develop approaches and tool(s) that decision makers can use to characterize trade-offs among the environmental, economic, and social impacts of EOL materials management on community sustainability. Some considerations for future revision of the existing tool(s) or new tool development are as follows:

1. As discussed earlier, specifying a material stream representative of the US EPA (2014) was challenging due to variation in materials nomenclature. The materials category nomenclature should be consistent with that used for the US EPA Facts and Figure report and categories/descriptions used by the communities to track EOL materials. The tools should include a description of materials along with examples of materials included in each material category.
2. The tool architecture should allow easy revision to accommodate updated LCIs of individual processes and inclusion of new materials (e.g., electronics) and emerging materials management technology (e.g. pyrolysis) as data become available; pyrolysis in WRATE is based on data from a single facility. Regular updating and maintenance of the LCIs in each tool is needed, as some of the data and assumptions in the tools evaluated appeared outdated. Developing a dedicated web portal (such as http://www.lcacommons.gov/) that allows communities to share data (e.g., cost, process-specific energy and materials usage) that can be used for updating tool(s) inputs (cost, LCIs, and characterization factors) should be considered.
3. The tool(s) should be designed for users with varied educational levels and skill sets. Due to its ease of use, WARM is the most commonly used tool among the tools evaluated in this report. However, WARM offers limited flexibility (e.g., allows specification of only limited number of inputs by the user). A tool that can readily be used by the community decision makers, facility operators, engineers, and regulators at varying level of complexity and flexibility on multiple platforms (e.g., mobile devices, computers, online calculators) would be expected to have more prevalent use and impact on the communities' decision making. As presented above, there are over 39,000 local governments that may benefit from such tools.
4. The tool(s) should consider all phases of a product or process. Although tools specific to EOL management materials were the focus of the evaluation presented in this report, future tools should consider manufacturing and use phases of the materials for use by consumers to assess the impacts of materials consumed and those associated with reduce consumption (i.e., source reduction) or the impacts of consumption. This feature would expand analysis boundary of the current waste LCA tools; only WARM includes manufacturing phase while other tools include only offset for materials remanufacturing using recycled products.
5. None of the selected tools evaluates the social impacts of EOL materials-management options. Only MSW-DST and SWOLF assess the economic impacts of materials management, and these tools only produce an estimated annualized cost. The economic impacts are only limited to the cost of constructing, operating, and maintaining materials-management facilities and do not account for overall economic impacts, such as job creation. Also, the current tools only analyze environmental and economic impacts in isolation and do not account for interaction or trade-off between environmental and economic impacts, e.g., long-term economic benefits from enhanced ecosystem services associated with emission reduction that requires an investment of community resources.

6 References

Amlinger, F., Peyr, S., and Cuhls, C. (2008). Green house gas emissions from compositing and mechanical biological treatment. Waste Management & Research, 2008: 26, 47-60.

Barlaz, M.A. (1998). Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory Scale Landfills. *Global Biogeochemical Cycles*, 12 (2), 373-380.

Berenyi, E.B. (2007). Materials Recycling and Processing in the United States: Yearbook and Directory. 5 Ed. *Government Advisory Associates, Inc.*

Composting Council, (1996). National Backyard Composting Program Training Manual. The Composting Council's National Backyard Composting Program. The Composting Council, Alexandria, VA.

Dumas, R. (1999). Energy Use and Emissions Associated with Electric Energy Consumption as Part of a Solid EOL materials management Life Cycle Inventory Tool. Prepared by Robert D. Dumas Department of Civil Engineering North Carolina State University, July 8, 1999.

Folz, D., and Giles, J. (2002). Municipal Experience with "Pay-as-You-Throw" Policies: Findings from a National Survey. State and Local Government Review, 34(2) (Spring 2002): 105-115.

Gentil, E., Damgaard, A., Hauschild, M., Finneveden, G., Eriksson, O., Thorneloe, S., Kaplan, P., Barlaz, M., Muller, O., Matsui, Y., Li, R., and Christensen, T. (2010). Models for waste life cycle assessment: Review of technical assumptions. Waste Management, 30(2010), 2636-2648.

Hogue, C. (2013). Government Organization Summary Report: 2012, Government Division Briefs, US Census Bureau. http://www2.census.gov/govs/cog/g12_org.pdf accessed on July 5, 2015.

Jain, P., Townsend, T., Johnson, P. (2013) "Case study of landfill reclamation at a Florida landfill site." Waste Management. 33(1):109-116. doi:10.1007/s12665-012-2054-8.

Jain, P., Powell, J., Smith, J., Townsend, T., and Tolaymat, T. (2014). Life-Cycle Inventory and Impact Evaluation of Mining Municipal Solid Waste Landfills. *Environmental Science & Technology,* 2014, 48(5), 2920-2927, **DOI:** 10.1021/es404382s.

Jones, T.W. (2002). *Using Contemporary Archaeology and Applied Anthropology to Understand Food Loss in the American Food System*. Bureau of Applied Research in Anthropology, University of Arizona Tucson, AZ

Oregon DEQ (2014) 2013 Oregon Material Recovery and Waste Generation Rates Report. Environmental Solutions Materials Management Program Oregon Department of Environmental Quality.

Sherman, S., (1996). Backyard Composting: Eight Case Studies. Applied Compost Consulting, Berkeley, CA.

Tchobanoglous, G.; Kreith, F. (2002). *Handbook of Solid EOL Materials Management*, Second Edition. McGraw Hill Inc.

Tchobanoglous, G.; Theisen, H.; Vigil, S. (1993). Integrated Solid EOL materials management-*Engineering Principles and Management Issues;* McGraw-Hill Inc. 79, 293-294.

Townsend, T. (2011). Environmental issues and management strategies of waste electronic and electrical equipment. Journal of Air & Waste Management Association, 61:587-610.

US EPA (1995). *Decision-Maker's Guide to Solid EOL Materials Management*, Volume II. EPA530-R-95-023, August 1995. http://www.epa.gov/osw/nonhaz/municipal/dmg2/

US EPA (1996). New Source Performance Standards for Municipal Solid Waste Landfills. 40 CFR 60 Subpart WWW, 12 March 1996.

US EPA (2009). Sustainable Materials Management: The Road Ahead. EPA530R09009, June 2009. https://www.fas.usda.gov/info/IATR/072011_Ethanol_IATR.pdf.

US EPA (2012a). *Sustainable and healthy communities*. Strategic Research Action Plan 2012-2016. Office of Research and Development, Sustainable and Healthy Communities, United States Environmental Protection Agency, EPA 601/R-12/005, June 2012.

US EPA (2012b). Landfilling. WARM Version 12, Documentation. http://1.usa.gov/UyBqY4. Accessed 21 April 2014.

US EPA (2014*). Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012*. EPA-530-F-14-001, February 2014.

USGS (1998). Materials Flow and Sustainability. USGS Fact Sheet FS-068-98, June 1998.

Winkler, J. and Bilitewski, B. (2007). Comparative Evaluation of Life Cycle Assessment Tools for Solid EOL materials management. *EOL Materials Management*, 27: 1021-1031.

Appendix A

Table A-1. Tool Descriptions and General Attributes

Attribute	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Tool Description	WARM can be used to estimated GHG emissions from various EOL materials management practices—source reduction, recycling, combustion, composting, and landfilling—for a variety of EOL materials constituents. The tool was created to help EOL materials planners and organizations track and voluntarily report greenhouse gas (GHG) emissions reductions associated with the EOL materials management options.	This LCA tool is designed to aid EOL materials planners in evaluating the economic and environmental aspects of integrated MSW management operations including collection, transfer, materials recovery, composting, WTE, and landfill disposal.	This tool is designed for planners and researchers for modeling the economic and environmental impacts of EOL materials management. It includes collection, transport, disposal, reuse, and advanced treatments such as AD, and gasification.	This tool is designed for EOL materials planners for evaluating LCA of integrated EOL materials management operations including transportation, composting, resource recovery, and landfilling based on resources consumption and environmental emissions from these operations for MSW.	WRATE can be used for LCA of integrated MSW management operations including collection, transportation, materials recovery and recycling, composting, combustion, AD, and landfill disposal based on resources consumption and environmental emissions from these operations for EOL materials.
Developed by	US EPA	Developed by RTI, Inc. under a contract from the US EPA	Department of Civil, Construction, and Environmental Engineering at North Carolina State University.	Technical University of Denmark (DTU)	Golder Associates (UL) Ltd and ERM on behalf of the Environment Agency of England and Wales (software owned by Golder Associates)
Year Developed	First released in 1998.	2000	Unreleased	EASE-WASTE was released in 2008. EASETECH began development in 2010.	First released in April 2007
Year of latest update	Last updated June 2014	Current model released June 2015	Unreleased	Current version (2.0.0, Internal Institute Version) released August 2014.	Major update to the tool occurred in 2010, most recently updated in March 2014.
Availability	Online. Web-based	Online	Unreleased. Will be	Must receive training at	Online. After payment

Attribute	WARM	MSW-DST	SWOLF	EASETECH	WRATE
	calculator and Microsoft Excel spreadsheet are available on the US EPA's webpage		available to the public online.	DTU to receive a copy of the program.	the demo version can be activated into the Standard version.
Is there a trial version?	Not applicable as the tool is available online for download for free.	None.	No trial version, tool will be free and available for public download for non-commercial purposes.	None.	Free demo with limited functionality (e.g., only allows five processes for the entire system, limited user-specified inputs, inability save a project or print the report).
Cost	Free	Unknown	Expected to be free for non-commercial uses. There will be a royalty-based fee for commercial uses.	Free for researchers, €5,000 for the course and software for a commercial license.	Standard version annual license costs £ 1,400.
Prevalence of Use	There are 300 users on WARM update mailing list. The US EPA has been contacted by 250-300 unique users in the last 5 years.	Approximately 190 licenses (including 21 for trial version) have been distributed as of July 1, 2015	Unreleased	As of June 2015, 161 licenses have been issued (31 license1 for commercial and 130 for academic users)	From 2008 through 2013 there were 229 annual licenses purchased.
Training	Not available.	Self-guided tutorials.	Developers expect to release online video lectures, and hold an annual training session.	5-days mandatory training course to receive a copy of the tool.	One day of training costs approximately $560; variable training options available on request.
User Support Tools	User guide and documentation available on tool's website; provides detailed information on the tool and background information on processes and materials. In the material tonnage portion of the tool, the user is alerted if mass	Walk through tutorial, informational tips at the top of each page of the tool. User guide and extensive documentation are available on tool's website. Available documentation primarily presents background data used for the tool.	Unreleased. The developers plan to release a user's guide for each module, online courses, and in-person training.	Support from tool developers (up to 5 hours for commercial users). EASETECH Documentation Manual. 7 example training exercises. Access to additional tool versions as they are released. As part of the mandatory training, users are taken	Electronic copy of user manual, access to training (subject to additional fee), help desk access (for users that have attended training), and "Help contents" look up within the tool. The 264 page user manual and the "Help

Attribute	WARM	MSW-DST	SWOLF	EASETECH	WRATE
	balances are unequal for the two scenarios being compared. The tool documentation provides detailed explanation for how the tool assesses impacts.			through the example exercises in order to gain hands-on experience.	contents" within the tool both provide tool screen captures, labels, and descriptions on how to operate the software and set up and run scenarios. The tool's built in error detection calls attention to and identifies errors so the user can easily troubleshoot.
Number of User Specific Inputs (as an indicator of ease of use) – assuming the most simplified EOL materials management scenario is landfilling	The user must enter the tonnage of material under the appropriate management method for a baseline and a comparative scenario of material management.	In the case of modeling residential EOL materials, the tool can be run without any user specific inputs since all default values are provided. If a second residential stream or commercial EOL materials stream were to be modeled, the population, generation rate (lbs/person-day), and collection points, or density (people/house) are necessary inputs. For multi-family dwellings, only the population and generation rate are needed.	The user must enter tonnage and designate the processes modeled. Default values for all processes are provided.	The user must enter the tonnage of the material handled in the modeling scenario. Default values can be used for all the other parameters However, the user must create the specific EOL materials management scenario being modeled by specifying material flows through the process(es) of interest.	At a minimum, the user must enter the name of the EOL materials flow, EOL materials quantity, number of EOL materials containers, and transportation distance to the EOL materials management/treatment facility. The user must specify material flows through the process(es) of interest, and depending on the EOL materials management scenarios chosen there may be additional user inputs that must be entered.
System requirements	The web-based tool requires one of the following browsers: Firefox (version 3 or higher), Chrome, Safari, or Internet Explorer (version 6 or higher).	There is no published list of system requirements for the current version of MSW-DST. Past versions requirements are: Pentium II PC compatible machine with at least a 16 GB hard drive, 512 of	The version evaluated in this report is not the final version of the tool and does not include a published set of system requirements. The version evaluated runs on the Microsoft Excel	The tool user manual and documentation does not provide a description of the minimum system requirements necessary. Separate software packages are provided for 32- and 64-bit operating	The tool was developed to run on IBM PC computers and under Microsoft Windows 7, the speed of the microprocessor should be at least 1 GHz with 1 GB of RAM, and a

Attribute	WARM	MSW-DST	SWOLF	EASETECH	WRATE
	The excel-based tool (Version 13) requires the Microsoft Excel application version 2003, 2007, or 2010.	RAM, 400MZ processor. Machines with less memory or processing capacity may be used but will result in slower run times for the MSW-DST.	application (believed to be compatible with Excel versions 97 and later).	systems.	minimum of 100 MB of hard drive space is necessary to run the software.

Table A-2. Tool Documentations Details

Tool Documentation	WARM	MSW-DST	SWOLF	EASETECH	WRATE
Thoroughness of documentation	Background data clearly documented. Twenty-nine (29) (388 pages) documents describing the data for individual materials and management practices - available on the US EPA WARM website for the user to review.	The most recently updated version of the tools background documentation provides a detailed explanation of the tool's LCI development; however, there are instances when the documentation is inconsistent with the current tool version.	Unknown, the documentation is not yet available to evaluate.	Data used are clearly documented. Each process in the tool program has a documentation tab which provides information on the date the process was created, the date it was updated, the name of the process developer, process data quality index scores and descriptions, a general technology description and references to where the data was obtained. However, not all process documentation tabs are complete. Additional information on some of the more complex processes is found in the tool documentation manual.	The background data are clearly documented. Information such as data sources and contact information, type of data collected (e.g., averages), a data quality indicator are viewable by the user. Additional background documentation details on the process, assumptions made, calculations, and references are available for some processes. There are some instances when documentation is not available due to broken hyperlinks.
Transparency – Qualitative Data	Data typically derived from process-specific field data or secondary research of multiple similar processes.	Data typically derived from process-specific field data or secondary research of multiple similar processes.	Unknown, the documentation is not yet available to evaluate.	Data typically derived from process-specific field data or secondary research of multiple similar processes.	Data typically derived from process-specific field data or secondary research of multiple similar processes.
Transparency –Quantitative Data	User can observe and verify most equations used to determine modeling results from calculations presented in tool documentation.	User can observe and verify most equations used to determine modeling results.	Unknown, the documentation is not yet available to evaluate. The current spreadsheet version makes all inputs and assumptions visible, and the final version is expected to do the same.	User can observe and verify all equations used to determine modeling results. All processes can be opened and the equations and parameters edited.	User can observe and verify most equations used to determine modeling results.
Documentation of degree of	Documentation identifies partial or	The documentation acknowledges that	Unknown, the documentation is not yet	Each process has a documentation tab which	A data quality indicator associated with each

Tool Documentation	WARM	MSW-DST	SWOLF	EASETECH	WRATE
data uncertainty	proxy data, if used. Tool and documentation do not provide a qualitative or quantitative measure of data uncertainty.	results are not 100% precise. Tool and documentation do not provide a qualitative or quantitative measure of data uncertainty.	available to evaluate.	allows the provisions of data quality indicators scores for reliability, completeness, temporal correlation, geographic correlation and technological correlation. However, a significant number of the processes do not include data quality indicator scores.	process is available in WRATE. The indicator is a visual bar that shows the level of completeness and quality of the dataset.

Table A-3. MSW Type Materials Included in Tool Scope

MSW Materials Included				
WARM	**MSW-DST**	**SWOLF**	**EASETECH**	**WRATE**
Paper				
Corrugated containers, magazines/third-class mail, newspaper, office paper, phonebooks, textbooks, mixed paper (general), mixed paper (primarily residential), mixed paper (primarily from offices)	Newspaper, office paper, corrugated cardboard, phone books, books magazines, third class mail, other paper (#1-5), paper - non-recyclable.	Corrugated cardboard, newsprint, office paper, magazines, office paper, 3rd class mail, non-recyclable paper, mixed paper, folding containers, paper bags	Newsprints, magazines, advertisements, books/phone books, office paper, other clean paper, paper and carton containers, dirty paper, dirty cardboard, other clean cardboard.	Paper and card: unspecified paper, newspapers, magazines, recyclable paper, other paper, card packaging, other card
Plastic				
HDPE, LDPE, PET, LLDPE, PP, PS, PVC, PLA, mixed plastics	HDPE - translucent, HDPE - pigmented,PET, other plastic (#1-5), plastic, non-recyclable	Film plastics, translucent HDPE, pigmented HDPE, PET containers, plastic - non-recyclable, Plastic - other #1 polypropylene	Soft plastic, plastic bottles, hard plastic, non-recyclable plastic, plastic products (toys, hangers, pens).	Plastic film: unspecified plastic film, bags, packaging film, and other film plastics; Dense plastic: unspecified dense plastic, drinks bottles, other bottles, other packaging, other dense plastic
Textiles				
NA	NA	Textiles, rubber/leather	Textiles, shoes/leather	Unspecified textiles, artificial textiles, natural textiles
Metals				
Aluminum cans, aluminum ingot, steel cans, copper wire, mixed metals	Ferrous metal: Ferrous cans, ferrous metal, Ferrous - non-recyclables Aluminum: Aluminum, other-aluminum (#1-2), Aluminum - non-recyclable	Ferrous Cans, Ferrous Metal – Other,, Aluminum Cans, Aluminum – Foil, Aluminum – Other, Ferrous - Non-recyclable, Al - Non-recyclable	Beverage cans (aluminum), aluminum foil and containers, food cans (tinplate/steel), plastic-coated aluminum foil, other metals.	Ferrous metal: unspecified ferrous metal, steel food and drink cans, other ferrous metal; Non-ferrous metal: unspecified non-ferrous metal, aluminum drinks cans, foil, other non-ferrous metal
Glass				
Glass	Glass – Clear, Glass – Brown, Glass – Green, Glass – non-recyclable.	Glass – Brown, Glass – Green, Glass – Clear, Mixed Glass, Glass - Non-	Clear glass, green glass, brown glass, non-recyclable glass.	Unspecified glass, packaging, non-packaging glass, green bottles, clear

MSW Materials Included				
WARM	**MSW-DST**	**SWOLF**	**EASETECH**	**WRATE**
		recyclable		bottles, brown bottles, jars
		Organics		
Food scraps (non-meat), grains, bread, fruits and vegetables, dairy products, yard trimmings, grass, leaves, branches, mixed organics	Yard waste: grass, leaves, branches. Food scraps	Yard Trimmings, Leaves; Yard Trimmings, Grass; Yard Trimmings, Branches; Food scraps – Vegetable; Food scraps - Non-Vegetable	Vegetable food scraps, animal food scraps, yard waste/flowers, animal excrements and bedding (straw), wood, many types of garden waste.	Unspecified organic, garden waste, food scraps, organic pet bedding/litter, other organics
		Electronics		
Personal computers	NA	E-waste	Batteries	Waste electrical and electronic equipment: Unspecified WEEE, white goods, large electronic goods (excluding CRT TVs and monitors), CRT TVs and monitors, other WEEE
		Tires		
Tires	NA	Rubber/Leather	Rubber	Non-MSW Waste: Tires,
		Other		
Mixed recyclables; mixed MSW	Residential: Miscellaneous combustible, Miscellaneous non-combustible. Commercial: Combustible compostable recyclable, Combustible Non-compostable recyclable, Non-combustible non-compostable recyclable, Combustible compostable non-recyclable, combustible non-compostable non-recyclable, Non-Combustible Non-compostable, non-recyclable.	Misc. Organic, Misc. Inorganic, wood, wood – other, Diapers and tampons, Aerobic Residual, Anaerobic Residual, Bottom Ash, Fly Ash	Milk cartons (carton/plastic), Juice cartons (carton/ plastic /aluminum). kitchen towels, other combustibles, vacuum cleaner bags, cigarette butts, ceramics, cat litter, other non-combustibles.	Absorbent hygiene products: unspecified absorbent hygiene products, disposable nappies, other (sanpro and dressings); Combustibles: unspecified combustibles, shoes, furniture, other combustibles; Non-combustibles: unspecified non-combustibles, inorganic pet litter, other non-combustibles
		Hazardous household waste		
NA	NA	NA	NA	Specific hazardous household: unspecified hazardous household,

MSW Materials Included				
WARM	**MSW-DST**	**SWOLF**	**EASETECH**	**WRATE**
				clinical waste, paint/varnish, oil, garden herbicides and pesticides
CDD Materials Included				
Dimensional lumber, medium-density fiberboard, wood flooring, clay bricks, concrete, drywall, asphalt shingles, asphalt concrete, fiberglass insulation, vinyl flooring, carpet	NA	Wood, Wood Other	Wood, stones/concrete, soil, small stuff (May-July garden waste), garden waste/soil/stones and foreign objects, small stuff (Aug garden waste), small stuff (Sept-Apr garden waste), branches, plants, grass and leaves, tree, grass, (these may also be considered as MSW organics), stone	Wood (unspecified wood, wood packaging, non-packaging wood); non-combustibles: bricks, blocks, plaster (all one category), fine material <10mm: unspecified fine material; non-combustibles: soil; combustibles: carpet/underlay
Other materials included				
Industrial waste/ processed materials				
Fly ash	No	Aerobic Residual, Anaerobic Residual, Bottom Ash, Fly Ash	Ash	Processed materials: compost PAS 100, compost APEX, home compost, other compost, RDF, fiber, stabilite, bottom ash, bottom ash ferrous, bottom ash non-ferrous, air pollution control residue; Non-MSW waste: waste oils, wheat straw, meat and bone meal, AWDF (rendered hoofs, bones, blood, etc.), untreated willow
Biosolids				
No	No		Biowaste	Non-MSW waste: sewage sludge (dry basis)

Table A-4. US EPA (2014) Materials Composition with the Most Similar Category Found in Each LCA Tool

2012 US Facts and Figures Category	%	WARM	DST	SWOLF	EASETECH	WRATE	Recyclable
Paper & paperboard	-	-	-		-	-	-
Nondurable	-	-	-		-	-	-
Newspaper/mechanical papers	3.34	Newspaper	Newspaper	Newsprint	Newsprints	Newspapers	y
Books	0.34	Textbooks	Books	Office paper	Books, phone books	Other paper	y
Magazines	0.59	Magazines/3rd class mail	Magazines	Magazines	Magazines	Magazines	y
Office-type papers	1.89	Office paper	Office paper	Office paper	Office paper	Recyclable paper	y
Standard mail	1.44	Magazines/3rd class mail	3rd class mail	3rd class mail	Advertisements	Other paper	y
Other commercial printing	1.06	Magazines/3rd class mail	Magazines	3rd class mail	Magazines	Unspecified paper	y
Tissue paper and towels	1.4	Mixed papers (primary residential)	Paper-nonrecyclable	Non-recyclable paper	Dirty paper	Unspecified paper	n
Paper plates and cups	0.51	Mixed papers (primary residential)	Paper-nonrecyclable	Non-recyclable paper	Dirty paper	Unspecified paper	n
Other non-packaging paper	1.6	Mixed papers (general)	Combustible compostable recyclables (commercial stream)	Mixed paper	Other clean paper	Other paper	y
Disposable diaper tissue	0.02	Mixed papers (primary residential)	Paper-nonrecyclable	Diapers and sanitary products	Diapers, sanitary towels, tampons	Disposable nappies	n
Container & packaging	-	-	-		-	-	-
Corrugated boxes	11.75	Corrugated containers	Corrugated cardboard	Corrugated cardboard	Cardboard	Card packing	y
Gable top/aseptic cartons	0.22	Mixed papers (primary residential)	Combustible compostable recyclables (commercial stream)	Folding containers	Milk cartons (carton/plastic)	Unspecified paper	y

2012 US Facts and Figures Category	%	WARM	DST	SWOLF	EASETECH	WRATE	Recyclable
Folding cartons	2.19	Mixed papers (primary residential)	Combustible compostable recyclables (commercial stream)	Folding containers	Milk cartons (carton/plastic)	Unspecified paper	y
Other paperboard packaging	0.03	Mixed papers (general)	Combustible compostable recyclables (commercial stream)	Mixed paper	Other clean cardboard	Other card	y
Bags and sacks	0.38	Mixed papers (primary residential)	Combustible compostable recyclables (commercial stream)	Paper bags	Other clean paper	Unspecified paper	y
Other paper packaging	0.58	Mixed papers (general)	Combustible compostable recyclables (commercial stream)	Mixed paper	Other clean cardboard	Other card	y
Glass		-	-		-	-	-
Durable goods	0.87	Glass	Glass-clear	Glass-clear	Clear glass	Non-packaging glass	y
Container & packaging	-	-	-		-	-	-
Beer and soft drink bottles	2.2	Glass	Glass-clear	Glass-clear	Clear glass	Clear bottles	y
Wine and liquor bottles	0.74	Glass	Glass-clear	Glass-clear	Clear glass	Clear bottles	y
Other bottles and jars	0.8	Glass	Glass-clear	Glass-clear	Clear glass	Jars	y
Metals		-	-		-	-	-
Durable goods	-	-	-		-	-	-
Ferrous metals	5.81	Steel cans	Ferrous metal	Ferrous metal - other	Metal (non-aluminum)	Unspecified ferrous metal	y
Aluminum	0.61	Aluminum ingot	Aluminum	Aluminum - other	Beverage cans (aluminum)	Other non-ferrous metal	y
Lead	0.57	Mixed metals	Non-combustible non-compostable	E-waste	Other metals	Unspecified ferrous metal	y

2012 US Facts and Figures Category	%	WARM	DST	SWOLF	EASETECH	WRATE	Recyclable
			recyclable (commercial stream)				
Other nonferrous metals	0.23	Mixed metals	Non-combustible non-compostable recyclable (commercial stream)	Aluminum non ferrous	Other metals	Other non-ferrous metal	y
Nondurable goods - aluminum	0.08	Aluminum ingot	Aluminum	Aluminum - other	Beverage cans (aluminum)	Other non-ferrous metal	y
Containers & packaging	-	-	-		-	-	-
Steel-cans	0.74	Steel cans	Ferrous cans	Ferrous cans	Food cans (tinplate/steel)	Steel food and drink cans	y
Steel-other steel packaging	0.15	Steel cans	Ferrous metal	Ferrous cans	Food cans (tinplate/steel)	Other ferrous metal	y
Al-beer and soft drink cans	0.52	Aluminum cans	Aluminum	Aluminum cans	Beverage cans (aluminum)	Aluminum drink cans	y
Al-other cans	0.05	Aluminum cans	Aluminum	Aluminum cans	Beverage cans (aluminum)	Aluminum drink cans	y
Foil and closures	0.18	Aluminum ingot	Aluminum	Aluminum - foil	Aluminum foil and containers	Foil	y
Plastics		-	-		-	-	-
Durable goods	-	-	-		-	-	-
PET	0.14	PET	PET	Pet containers	Hard plastic	Other dense plastic	y
HDPE	0.49	HDPE	HDPE (50/50 translucent/pigmented)	HDPE - translucent/pigmented	Hard plastic	Other dense plastic	y
PVC	0.09	PVC	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
LDPE/LLDPE	0.79	LDPE & LLDPE (50/50)	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
PP	1.56	PP	Plastic nonrecyclable	Plastic - other #1, polypropylene	Hard plastic	Other dense plastic	n
PS	0.28	PS	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n

2012 US Facts and Figures Category	%	WARM	DST	SWOLF	EASETECH	WRATE	Recyclable
Other resins	1.22	Mixed plastics	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
Non-durable goods-plates and cups	-	-	-		-	-	-
LDPE/LLDPE	0.01	LDPE & LLDPE (50/50)	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
PLA	0.01	PLA	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
PP	0.08	PP	Plastic nonrecyclable	Plastic - other #1, polypropylene	Hard plastic	Other dense plastic	n
PS	0.33	PS	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
Non-durable goods-trash bags	-	-	-		-	-	-
HDPE	0.09	HDPE	HDPE (50/50 translucent/pigmented)	Film plastics	Soft plastic	Bags	y
LDPE/LLDPE	0.32	LDPE & LLDPE (50/50)	Plastic nonrecyclable	Film plastics	Soft plastic	Bags	n
Non-durable goods-all others	-	-	-		-	-	-
PET	0.22	PET	PET	PET containers	Hard plastic	Other dense plastic	y
HDPE	0.21	HDPE	HDPE (50/50 translucent/pigmented)	HDPE - translucent/pigmented	Hard plastic	Other dense plastic	y
PVC	0.09	PVC	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
LDPE/LLDPE	0.46	LDPE & LLDPE (50/50)	Plastic nonrecyclable	Plastic - non-recyclable	Soft plastic	Other film plastic	n
PLA	0.01	PLA	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
PP	0.48	PP	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
PS	0.08	PS	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n

2012 US Facts and Figures Category	%	WARM	DST	SWOLF	EASETECH	WRATE	Recyclable
Other resins	0.22	Mixed plastics	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other dense plastic	n
Plastic containers & packaging -bottles and jars-PET	1.11	PET	PET	PET containers	Plastic bottles	Drink bottles	y
Plastic containers & packaging – natural bottles-HDPE	0.31	HDPE	HDPE (50/50 translucent/pigmented)	HDPE - Translucent	Plastic bottles	Other bottles	y
Plastic containers & packaging-other containers	-	-	-		-	-	-
HDPE	0.56	HDPE	HDPE (50/50 translucent/pigmented)	HDPE - translucent/pigmented	Hard plastic	Other packaging	y
PVC	0.02	PVC	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other packaging	n
LDPE/LLDPE	0.02	LDPE & LLDPE (50/50)	Plastic nonrecyclable	Plastic - non-recyclable	Soft plastic	Other packaging	n
PP	0.11	PP	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other packaging	n
PS	0.03	PS	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other packaging	n
Plastic containers & packaging-bags, sacks, wraps	-	-	-		-	-	-
HDPE	0.28	HDPE	HDPE (50/50 translucent/pigmented)	Film plastics	Soft plastic	Bags	y
PVC	0.02	PVC	Plastic nonrecyclable	Film plastics	Soft plastic	Packaging film	n
LDPE/LLDPE	0.91	LDPE & LLDPE (50/50)	Plastic nonrecyclable	Film plastics	Soft plastic	Packaging film	n
PP	0.26	PP	Plastic nonrecyclable	Film plastics	Soft plastic	Packaging film	n
PS	0.06	PS	Plastic nonrecyclable	Film plastics	Soft plastic	Packaging film	n

2012 US Facts and Figures Category	%	WARM	DST	SWOLF	EASETECH	WRATE	Recyclable
Plastic containers & packaging-other packaging	-	-	-	Film plastics	-	-	-
PET	0.33	Pet	Pet	Pet containers	Hard plastic	Other packaging	y
HDPE	0.27	HDPE	HDPE (50/50 translucent/pigmented)	HDPE - translucent/pigmented	Hard plastic	Other packaging	y
PVC	0.13	PVC	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other packaging	n
LDPE/LLDPE	0.43	LDPE & LLDPE (50/50)	Plastic nonrecyclable	Plastic - non-recyclable	Soft plastic	Other packaging	n
PLA	0	PLA	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other packaging	n
PP	0.38	PP	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other packaging	n
PS	0.12	PS	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other packaging	n
Other resins	0.15	Mixed plastics	Plastic nonrecyclable	Plastic - non-recyclable	Hard plastic	Other packaging	n
Rubber and leather		-	-		-	-	-
Rubber in tires	1.2	Tires	Miscellaneous combustible	Rubber/leather	Rubber	Tyres	n
Other durables	1.4	Carpet	Miscellaneous combustible	Rubber/leather	Combustible	Carpet/underlay	n
Clothing and footwear	0.31	Tires	Miscellaneous combustible	Rubber/leather	Shoes, leather	Shoes	n
Other nondurables	0.1	Tires	Miscellaneous combustible	Rubber/leather	Combustible	Other combustibles	n
Textiles	5.71	Carpet	Miscellaneous combustible	Textiles	Textiles	Unspecified textiles	n
Wood	6.31	Dimensional lumber	Combustible compostable recyclables (commercial stream)	Wood	Wood	Unspecified wood	n
Other	1.83	Tires	Miscellaneous combustible	Misc. Organic	Combustible	Other combustibles	n

2012 US Facts and Figures Category	%	WARM	DST	SWOLF	EASETECH	WRATE	Recyclable
Other wastes-food	14.52	Food scraps (non-meat)	Food scraps	Food scraps - vegetable & and animal (90/10)	Vegetable food scraps & animal food scraps (90/10)	Food scraps	n
Other wastes-yard trimmings	13.54	Yard trimmings	Grass, leaves & branches (50/30/20)	Yard trimmings - leaves, grass, branches (50/30/20)	Leaves and grass & branches (80/20)	Garden waste	n
Other wastes-miscellaneous inorganics	1.55	Clay bricks	Miscellaneous non-combustible	Misc. Inorganic	Noncombustible	Unspecified non-combustibles	n