ABSTRACT

LEVIS, JAMES WILLIAM. A Mathematical Programming Life-Cycle Assessment Model for Solid Waste Management Decision Making. (Under the direction of Dr. Ranji S. Ranjithan and Dr. Morton A. Barlaz.)

Solid waste management (SWM) is an integral component of civil infrastructure and the broader U.S. economy and policy makers have taken an increasing interest in reducing environmental impacts associated with SWM. In the future, greenhouse gas (GHG) mitigation policies that affect the U.S. energy mix as well as the cost of energy and emissions could significantly impact the strategic direction of SWM. As such, SWM systems must proactively adapt to changing waste composition, policy requirements, and an evolving energy system to cost-effectively and sustainably manage future solid waste.

SWM life-cycle assessment (LCA) models integrated into an optimization framework can simultaneously consider all possible waste collection and treatment alternatives to find the combination of technologies that optimizes environmental and economic objectives. Such a framework must be able to represent multi-stage decisions to consider the changes to the SWM system over time.

The objectives of this research are: to develop the Solid Waste Optimization Life-cycle Framework (SWOLF); to illustrate the use of the framework to analyze the economic and environmental impacts and trade-offs associated with SWM systems based on future changes to waste generation, waste composition, and energy projections; and to analyze the illustrative results to understand how variations in the energy system, GHG policy, and SWM policy affect optimal SWM decisions. SWOLF uses a mixed integer linear programming model to determine optimal SWM strategies while considering the interdependencies among processes in the SWM system. SWOLF is generalizable to include numerous SWM treatment facilities and collection options, and solves in less than two hours using readily available hardware and software.

Two case studies were developed that represent the first applications of an optimizable dynamic life-cycle assessment framework for SWM. The applicability of SWOLF to provide insights into a realistic SWM system was shown through a case study of a hypothetical suburban city over the next 30 years. The results indicated that GHG emissions can increase with increased diversion, which suggests that diversion targets and material disposal bans

may be counterproductive towards reducing GHG emissions in some instances. Relatedly, the model found that SWM strategies designed to reduce GHG emissions were more cost effective at reducing GHG emissions than SWM strategies designed to increase diversion, which indicates that SWM decision makers should focus on the environmental impacts they wish to reduce, instead of using potentially problematic proxies such as landfill diversion. The case study provided numerous insights that were only possible through the use of a stage-wise life-cycle optimization framework. For example, both the diversion maximizing and GHG minimizing scenarios showed stage-wise switching of anaerobic digestion (AD) and composting throughputs based on changes to waste composition and generation.

The model was then used to investigate the effects of energy, GHG, and SWM policies on optimal SWM strategies. This case study required integrating SWOLF with energy system modeling results to investigate how changes in GHG policy and the energy system affect SWM system performance. Minimum cost SWM strategies with GHG emission and diversion targets were affected by a carbon policy. Specifically, the model found that relative GHG benefits of WTE (and other electricity generating technologies) were dependent on waste composition (e.g., percent of paper and plastic) and electricity GHG intensity (e.g., relative contribution of coal, natural gas and renewables). These dynamic interdependencies can only be analyzed through the use of a multi-stage optimization framework. The analyses showed that it is critical for SWM decision makers to systematically consider changes to waste composition and generation, SWM policy, the U.S. energy system, and potential future GHG mitigation policies when develop.

A Mathematical Programming Life-Cycle Assessment Model for Solid Waste Management Decision Making

by
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DEDICATION

For my grandmother.

BIOGRAPHY

James William Levis was born and raised in Elyria, Ohio. He received a Bachelor of Science degree in Mechanical Engineering in 2004 from Carnegie Mellon University in Pittsburgh, Pennsylvania. After graduation he worked as a quality engineer for Westinghouse Electric Company in Columbia, South Carolina for two years. In August 2006, he became a graduate student in the Department of Civil Engineering at North Carolina State University in Raleigh, North Carolina. He received his Master of Science degree in Civil Engineering in 2008. His graduate course work and research has focused on the systemic analysis of solid waste management alternatives under the direction of Drs. Barlaz and Ranjithan.

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Letting your mind play is the best way to solve problems. -Bill Watterson

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SYMBOLS USED

$\alpha_{wm\_in,wm\_out,ws,tp}$	Mass of *waste material wm_out* exiting *treatment process tp* in *waste stream ws* per incoming mass of *waste material wm_in*. Used to represent the separation efficiency in MRFs and ash fraction in WTE processes.
$\beta_{wm,t}$	The proportion of *waste material wm* in the generated waste in stage *t*. $\sum_{wm \in WM} \beta_{wm,t} = 1 \ \forall \ t = 1,2 \ldots FTP$.
$\gamma_{cs,cp,tp}$	Indicator coefficient that equals 1 if *treatment process tp* is the *collection destination* for *collection process cp* in *collection scheme cs*, and equals 0 otherwise.
$\varepsilon_{tp,wm}$	The utilization cost coefficient for *waste material wm* in *treatment process tp* (\$/Mg).
$\varepsilon_{cs,wm,cp}$	The utilization cost coefficient for *waste material wm* in *collection scheme cs* and *collection process cp* (\$/Mg).
$\xi_{i,proc,wm,t}$	The emission factor for pollutant or impact *i* for *waste material wm* from process *proc* in stage *t* (kg/Mg or MJ/kg).
ρ_{cap}	The expansion cost coefficient for capital *treatment process cap* (\$/Mg·yr^{-1}).
σ_{cap}	The build cost coefficient for capital *treatment process cap* (\$/Mg·yr^{-1}).
$\varphi_{wm,scp,t}$	The maximum collection separation efficiency of *waste material wm* collected via *specific collection process scp* in stage *t* ($0 \leq \varphi_{wm,scp,t} \leq 1$).
$\tau_{ts,tp,tp\_up,ws}$	Indicator coefficient that equals 1 if *waste stream ws* is sent *to treatment process tp* from upstream *treatment process tp_up* in *treatment scheme ts*, and equals 0 otherwise.
A/P	Economic conversion factor from a present payment to a series of annual payments.
$actCap_{cap\_e}$	The amount of existing capacity in the initial stage for existing capital *treatment process cap_e* (Mg/yr).
$B_{cap\_n,t}$	A binary variable that equals 1 if *treatment process cap_n* is built in stage *t* and 0 otherwise.
$buildCost_{cap\_n,t}$	The build cost of new capital *treatment process cap_n* in stage *t* (\$).
cap	The capital *treatment process* index.
CAP	The set of capital *treatment processes*. A subset of *TP* and the union of *CAP_E* and *CAP_N*.
cap_e	The existing capital *treatment process* index.

CAP_E	The set of existing capital *treatment processes* and a subset of CAP. In the illustrative example in Chapter 2 CAP_E = {MRF_E}.
cap_n	The new capital *treatment process* index.
CAP_N	The set of new *treatment processes* and a subset of CAP. In the illustrative example in Chapter 2 CAP_N = {MRF_N, WTE}.
$capCost_{proc}$	The total capital cost for *treatment process proc* ($).
cp	The *collection process* index.
CP	The set of *collection processes* and a subset of $PROC$. In the illustrative example in Chapter 2 CP = {MWC, CRC, RWC}.
CP_{cs}	The set of *collection processes* in *collection scheme cs* and a subset of CP. In the illustrative example in Chapter 2 $CP_{mwc\text{-}lf}$ and $CP_{mwc\text{-}wte}$ = {MWC}; and $CP_{rwc\text{-}lf}$ and $CP_{rwc\text{-}wte}$ = {CRC, RWC}.
cs	The *collection scheme* index.
CS	The set of *collection schemes*. In the illustrative example in Chapter 2 CS = {{(MWC-LF)}, {(MWC-WTE)}, {(RWC-LF), (CRC-MRF)}, {(RWC-WTE), (CRC-MRF)}}.
$D_{cap,t}$	A binary variable that equals 1 if capital *treatment process cap* is decommissioned in stage t and 0 otherwise.
$divTarget_t$	The diversion target in stage t.
$E_{cap,t}$	A binary variable that equals 1 if capital *treatment process cap* is expanded in stage t and 0 otherwise.
$expandCost_{cap,t}$	The total expansion cost of capital *treatment process cap* ($).
FTP	The final stage. In the illustrative example in Chapter 2 $FTP = 3$.
$F_{cap,t}$	A binary variable that equals 1 if capital *treatment process cap* has a currently active expansion and is not expanded in stage t and equals 0 if there is an expansion in stage t.
i	The pollutant and environmental impact index.
I	The set of pollutant and environmental impacts. In the illustrative example in Chapter 2 I = {GWP}.
$initT$	The initial stage.
lf	The landfill *treatment process* index.
LF	The set of landfill *treatment processes*. In the illustrative example in Chapter 2 LF = {ALF, LF}.
$life_{cap}$	The number of stages for which capital *treatment process cap* is active.

M	A sufficiently large positive constant.
$minbldcap_{cap\_n}$	The minimum possible capacity that can be built for new capital *treatment process cap_n* (Mg/yr).
$minexpcap_{cap}$	The minimum possible capacity that can be expanded for capital *treatment process cap* after it has been built (Mg/yr).
$Mass_{t}$	Total mass of waste generated in stage t (Mg).
$mwcp$	The *mixed waste collection process* index in *collection scheme cs*.
$MWCP_{cs}$	The set of *mixed waste collection processes* in *collection scheme cs* and a subset of CP_{cs}. In the illustrative example in Chapter 2 $MWCP_{mwc\text{-}lf}$ = MWC; $MWCP_{mwc\text{-}wte}$ = MWC; $MWCP_{rwc\text{-}lf}$ = RWC; and $MWCP_{rwc\text{-}wte}$ = RWC.
$opCost_{proc}$	The total operating cost for capital *treatment process proc* ($).
P/A	Economic conversion factor from a series of annual payments to a single present payment.
P/F	Economic conversion factor from a single future payment to a single present payment.
$proc$	The process index.
$PROC$	The set of all processes. The union of CP and TP. In the illustrative example in Chapter 2 $PROC$ = {MWC, RWC, CRC, MRF_E, MRF_N, WTE, LF, ALF}.
$procAlive_{cap,t,T}$	An indicator coefficient that equals 1 if $t + life_{cap} \leq T$, and 0 otherwise.
$procExist_{cap\_e,T}$	An indicator coefficient that equals 1 if $initT + remLife_{cap\_e} \leq T$, and 0 otherwise.
r	The discount rate used in economic conversion factors. In the illustrative example in Chapter 2 $r = 0.05$.
$remLife_{cap\_e}$	The remaining number of stages for which an existing capital *treatment process cap_e* is active without an expansion.
$rptCost_{cap}$	The net present cost of repeated builds of capital *treatment process cap* in perpetuity ($).
scp	The *specific collection process* index.
SCP_{cs}	The set of *specific collection processes* that collect *waste streams* other than the mixed waste (e.g., recyclables or organics) in *collection scheme cs* and a subset of CP_{cs}. In the illustrative example in Chapter 2 $SCP_{mwc\text{-}lf}$ and $SCP_{mwc\text{-}wte} = \emptyset$; and $SCP_{rwc\text{-}lf}$ and $SCP_{rwc\text{-}wte}$ = CRC.
t	The stage index.

T	The stage index and an alias for *t*.
totCost	The net present cost of the system ($).
$totEmis_i$	The total emissions of pollutant or impact *i* (kg or MJ).
tp	The *treatment process* index.
TP	The set of *treatment processes* and a subset of *PROC*. In the illustrative example in Chapter 2 *TP* = {ALF, LF, MRF_E, MRF_N, WTE}.
tp_up	The upstream *treatment process* and an alias for *tp*.
TP_{ts}	The set of *treatment processes* in *treatment scheme ts* and a subset of *TP*. In the illustrative example in Chapter 2 TP_{L--} ={LF}; TP_{W-A} ={WTE, ALF}; TP_{W-L} ={WTE, LF}; TP_{LL-} ={LF, MRF}; TP_{LWA} ={LF, MRF,WTE,ALF}; TP_{LWL} ={LF, MRF,WTE}; TP_{WLA} ={LF, MRF,WTE,ALF}; TP_{WLL} ={LF, MRF,WTE}; TP_{WWA} ={MRF,WTE,ALF}; TP_{WLA} ={LF, MRF,WTE}.
ts	The *treatment scheme* index.
TS	The set of treatment schemes. In the illustrative example in Chapter 2 *TS* = {L--, W-A, W-L, LL-, LWA, LWL, WLA, WLL, WWA, WWL}.
TS_{cs}	The set of *treatment schemes* in *collection scheme cs* and a subset of *TS*. In the illustrative example in Chapter 2 TS_{mwc-lf} = {*L*--}; $TS_{mwc-wte}$ = {W-A, W-L}; TS_{rwc-lf} = {LL-, LWA, LWL}; and $TS_{rwc-wte}$ = {WLA, WLL, WWA, WWL}.
$utilCap_{cap}$	The minimum percent utilization for capital *treatment process cap*. In the illustrative example in Chapter 2 $utilCap_{wte} = 0.8$.
wm	The *waste material* index.
WM	The set of *waste materials*. In the illustrative example in Chapter 2 *WM* = {Rec, NRec}.
wm-in	The incoming *waste material* index and an alias for *wm*.
wm-out	The exiting *waste material* index and an alias for *wm*.
$W_{cap\_n,t}$	A binary variable that equals 1 if new capital *treatment process cap_n* has active capacity from a previous stage in stage *t* and 0 otherwise.
ws	The *waste stream* index.
WS	The set of *waste streams* exiting *treatment processes*. In the illustrative example in Chapter 2 *WS* = {Ash, Recyclables, Residual}.
$x\_bcap_{cap\_n,t}$	The capacity of new capital *treatment process cap_n* built in stage *t* ($\text{Mg}\cdot\text{yr}^{-1}$).

$x\_curActCap_{cap,t}$	The currently available capacity of capital *treatment process cap* in stage *t* (Mg·yr^{-1}).
$x\_ecap_{cap,t}$	The capacity of capital *treatment process cap* expanded in stage *t* (Mg/yr).
$x\_repcap_{cap,t}$	The capacity of capital *treatment process cap* replaced by an expansion in stage *t*.
$x\_rptcap_{cap,t}$	The capacity of capital *treatment process cap* built or expanded in stage *t* that will be active beyond the decision horizon and will thus need to be rebuilt at the end of life indefinitely.
$x\_util_{wm,tp,t}$	The mass of *waste material wm* processed through *treatment process tp* in stage *t* (Mg).
$x\_util_{cs,wm,cp,t}$	The mass of *waste material wm* collected by *collection process cp* as part of *collection scheme cs* in stage *t* (Mg).
$x_{cs,t}$	The mass of waste processed through *collection scheme cs* in stage *t* (Mg).
$x_{cs,ts,t}$	The mass of waste processed through *collection scheme cs* and *treatment scheme ts* in stage *t* (Mg).
$x_{cs,ts,wm,mwcp,t}$	The mass of *waste material wm* processed through *collection scheme cs* and *treatment scheme ts* and *mixed waste collection process mwcp* in stage *t* (Mg).
$x_{cs,ts,wm,scp,t}$	The mass of *waste material wm* processed through *collection scheme cs* and *treatment scheme ts* and *specific collection process scp* in stage *t* (Mg).
$x_{cs,ts,wm,t}$	The mass of *waste material wm* processed through *collection scheme cs* and *treatment scheme ts* in stage *t* (Mg).
$x_{cs,ts,wm,cp,t}$	The mass of *waste material wm* processed through *collection scheme cs* *treatment scheme ts*, and *collection process cp* in stage *t* (Mg).
$xtpcol_{ts,wm,tp,t}$	The collected mass of *waste material wm* delivered to *treatment process tp* as part of *treatment scheme ts* in stage *t* (Mg).
$xtpin_{ts,wm,tp,t}$	The mass of *waste material wm* entering *treatment process tp* as part of *treatment scheme ts* in stage *t* (Mg).
$xtpout_{ts,wm,tp,ws,t}$	The outgoing mass of *waste material wm* in *waste stream ws* from *treatment process tp* as part of *treatment scheme ts* in stage *t* (Mg).
YPP	The number of years in each stage. In the illustrative example in Chapter 2 YPP = 10 yrs.

1 INTRODUCTION

Proper management of solid waste is essential to minimize risks to human health and the environment. Solid waste contains significant quantities of recoverable materials and can be used for energy recovery, making solid waste management (SWM) a highly visible and potentially high-impact target for enhancing environmental sustainability. Greenhouse gas (GHG) mitigation policies that affect the U.S. energy mix as well as the cost of energy and emissions could significantly alter the cost and strategic direction of SWM. As such, SWM systems must proactively adapt to changing waste composition, policy requirements, and an evolving energy system to cost-effectively and sustainably manage solid waste.

The goal of this research is to develop a quantitative framework to provide insights into the following question: How should SWM systems adapt in the face of changes to waste composition and generation, SWM policy, the U.S. energy system, and potential future GHG mitigation policies? Given the complexity and heterogeneity of SWM systems, rigorous analysis of system response under a GHG policy requires a modeling framework that links detailed process-level life-cycle assessment (LCA) models into an integrated SWM system and to the larger energy system.

LCA is a framework for estimating the environmental impacts associated with products, processes, or systems. SWM LCA models estimate the environmental impacts of various waste management alternatives, and can facilitate "what-if" scenario analyses to quantify the environmental effects of incremental changes to the integrated system. While these models are an essential foundation for systematic integrated analysis of SWM systems, an integrated LCA-based optimization framework is required to systematically generate and analyze potential SWM strategies. Previous research has generally focused on single-stage analyses that assume static systems, although real-world SWM strategies must adapt to population and policy changes as well as changes to waste generation and composition, which necessitates the use of a stage-wise optimization framework.

A stage-wise life-cycle optimization framework should also be capable of considering changes to energy infrastructure in response to evolving environmental policy and technological innovation that may affect the performance of SWM. Since SWM infrastructure is often in operation for decades, it is essential that integrated SWM models provide useful insights into how such changes may affect SWM. The generalized modeling framework for this research is shown in Figure 1-1.

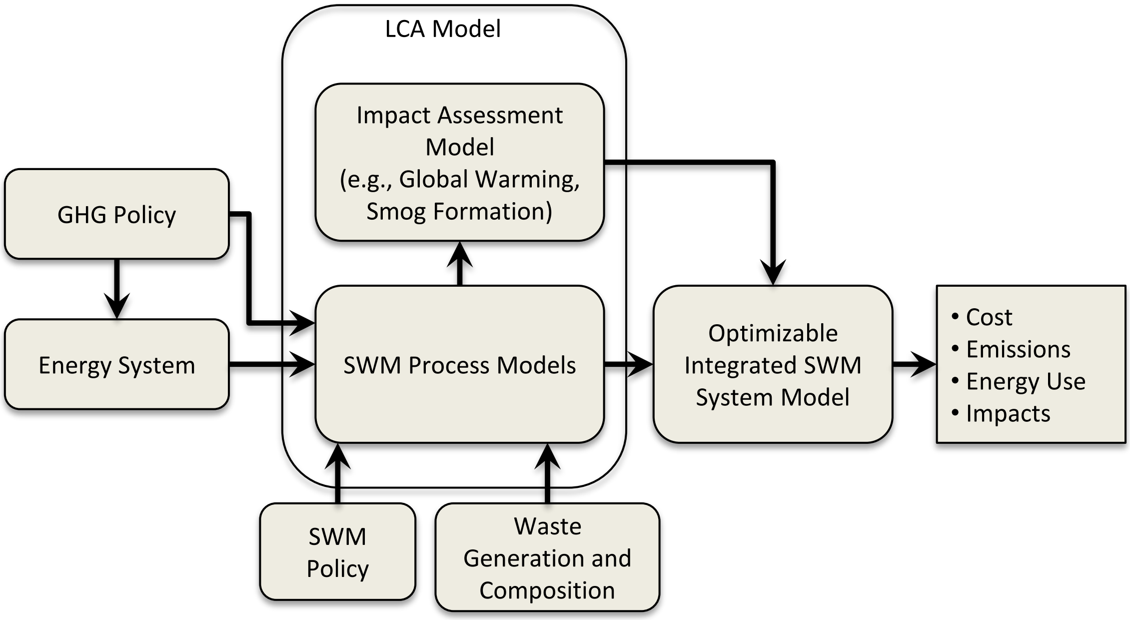

Figure 1-1 Generalized modeling framework showing how energy system modeling is connected to LCA models for a SWM system, and how the outputs of these models are then used as inputs into an optimizable LCA framework to systematically analyze future SWM.

The research goal will be met through the following research objectives:

1) Develop a generalized mathematical programming model capable of identifying SWM strategies that minimize cost or environmental impacts subject to other policy constraints (Chapter 2);
2) Use the optimization model to analyze the economic and environmental impacts and trade-offs associated with SWM strategies that consider future changes to waste generation, waste composition, and energy projections (Chapter 3); and
3) Analyze how variations in the energy system, GHG policy, and SWM policy affect optimal SWM decisions (Chapter 4).

Chapters 2, 3 and 4 were written as standalone research manuscripts. Chapter 2 describes the mixed integer linear mathematical model that forms the foundation for the framework. Chapter 3 uses the framework outlined in Chapter 2 to analyze, for a hypothetical suburban city with a population of 100,000, the SWM plan over the next 30 years , while considering cost, GHG emissions, and landfill diversion under projected changes to waste generation, composition, and the energy system. Chapter 4 uses the framework described in Chapter 2 and the SWM system described in Chapter 3 to analyze how various energy systems, GHG policy, and SWM policy scenarios affect the optimal SWM plan. Finally, the conclusions that can be drawn from this research are presented in Chapter 5.

2 A MULTISTAGE OPTIMIZATION MODEL FOR LIFE-CYCLE ASSESSMENT-BASED INTEGRATED SOLID WASTE MANAGEMENT

2.1 Introduction

Solid waste management (SWM) is an integral component of civil infrastructure and the broader U.S. economy. In 2010, U.S. municipal solid waste (MSW) systems processed approximately 250 million tons of waste. The direct emissions from landfilling, composting, and combustion of waste resulted in an estimated 123 Tg of CO_2e emissions, representing over 10% of non-energy related greenhouse gas (GHG) emissions. Landfills, which received 54% of MSW in 2010, are currently estimated to be the third largest source of anthropogenic methane in the U.S. (U.S. EPA, 2011 and U.S. EPA, 2012). MSW also contains significant quantities of recoverable materials and can be used for energy recovery, making the SWM system a highly visible and potentially high-impact target for enhancing environmental sustainability. Expected future GHG mitigation policies are likely to impact the cost and strategic direction of SWM. Given the complexity of SWM, even subtle changes to SWM programs pose potential for unintended environmental consequences. The appropriate selection of waste processing technologies and efficient waste management strategies offer opportunities to minimize environmental impacts, particularly through energy and materials recovery. An effective SWM strategy must account for the complex interdependencies and interactions among waste handling processes (e.g., collection, material recovery, biological and thermal treatment, and landfilling) and their effects on competing management objectives (e.g., minimize cost, maximize net energy production, increase waste diversion from landfills, and minimize GHG emissions). The framework presented here is intended to optimize integrated SWM decisions at the solid waste system level (e.g., municipality or county), but the results of these system level analyses could be aggregated to analyze larger jurisdictions (e.g., state, provincial, regional, or national).

Life-cycle assessment (LCA) is a useful tool for systematically estimating the environmental impacts associated with SWM processes and systems (Bjorklund et al., 2010).

Several LCA models have been developed to determine the environmental impacts associated with SWM systems (e.g., Dalemo et al., 1997; McDougall et al., 2001; Haight, 2004; Kirkeby et al., 2006). These models estimate the environmental impacts of various waste management alternatives, and can be used to perform “what-if” scenario analyses to quantify the environmental effects of incremental changes to the integrated system. While these models are an essential foundation that enables a systematic integrated analysis of SWM systems, they cannot simultaneously consider all possible waste collection and treatment alternatives to find the combination of technologies that optimizes environmental and economic objectives.

Only limited research in LCA-based optimization of integrated SWM has been reported (e.g., Harrison et al., 2001; Solano et al., 2002; Shmelev and Powell, 2006; and Hung et al., 2007). Previous research has generally focused on single-stage analyses that assume static systems, although real-world SWM strategies must adapt to population and policy changes as well as changes to waste generation and composition. While some previous research efforts have considered stage-wise decision-making in SWM (e.g., Li et al., 2006; Li and Huang, 2007; and Tan, 2010), they focused on relatively simple systems (e.g., a single or limited number of waste materials, a limited number of waste collection alternatives, little or no waste separation) without consideration of full life cycle emissions, and involved computationally demanding solution procedures (e.g., fuzzy quadratic programming , interval-parameter stochastic integer programming, inexact dynamic programming containing fuzzy boundary intervals). These approaches work well for small illustrative systems, but are not readily generalizable and scalable to larger systems.

Prior work has not addressed changes in energy infrastructure in response to evolving environmental policy and technological innovation that may affect the performance of SWM. Changes in the broader energy system due to changes in the national and regional electricity generation mix will affect the prices of fuel and electricity used in SWM as well as the emissions associated with electricity use. For example, replacing coal-fired electricity generation with natural gas or renewables will change the emissions associated with electricity use. Since SWM infrastructure is often in operation for decades, it is essential that integrated SWM models provide useful insights into how such changes affect SWM. Long-term changes to the energy system, which involve the slow turnover of long-lived capacity, motivate the development of a multi-stage optimization of SWM.

While prior models are useful, a general modeling framework is needed to more realistically represent actual SWM management systems, which include dozens of waste streams, varying generation sector types, dozens of potential collection and treatment processes, and multiple time stages. This paper presents the Solid Waste Optimization Life Cycle Framework (SWOLF), which is suitable for stage-wise decision support under different scenarios. SWOLF is capable of developing integrated SWM strategies that consider existing as well as new SWM infrastructure. This is a major advantage since the reduced incremental costs associated with continued use of existing infrastructure is often an important factor in long-term capital decision making. Section 2.2 describes the modeling framework and includes an illustrative example that demonstrates the capability of the framework to represent complex SWM systems. Section 2.3 describes a simple test system, which is used to help illustrate the mathematical description of the optimization model in Section 2.4. Section 2.5 presents a simple, illustrative analysis using the test system described in Section 2.3, and Section 2.6 draws conclusions from the model formulation and application.

2.2 Integrated Solid Waste Management Modeling Framework

2.2.1 Life cycle assessment framework for solid waste management

The functional unit for this LCA is the total mass of mixed MSW set out at the curb in a SWM system (e.g., municipality or county) over a specified decision horizon. The functional unit does not include items reused or treated by the waste generator (e.g., clothing used as rags, food waste treated in a garbage disposal, onsite composting). The basis of the framework is an LCA of an integrated SWM system that includes unit process models for waste collection, transfer, separation, treatment and disposal processes necessary to properly treat the functional unit. Figure 2-1 shows the inputs and outputs of a generic process model included within the system.

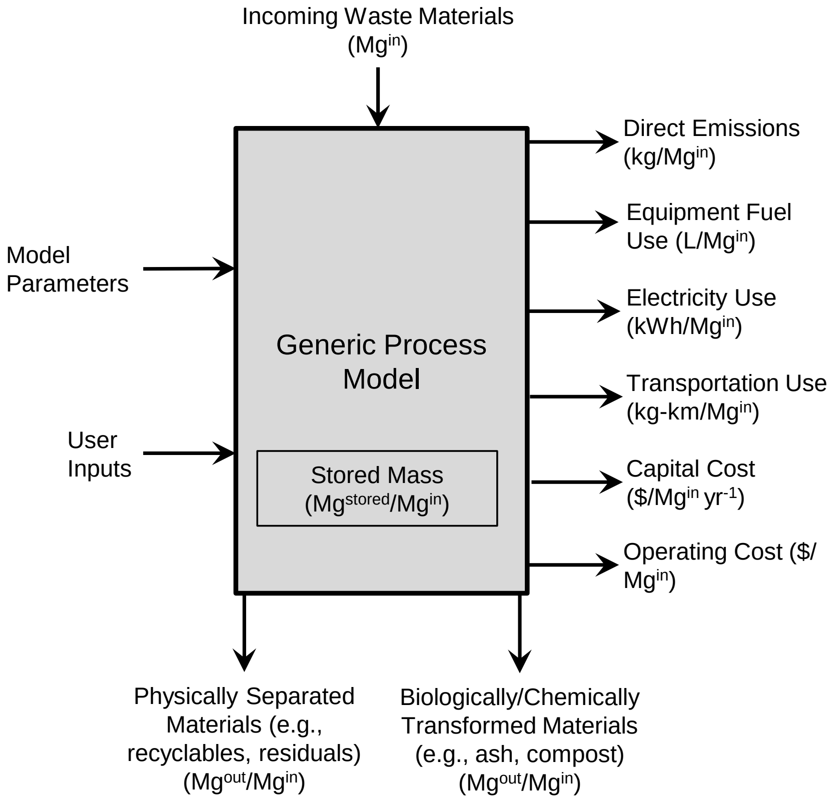

Figure 2-1. Inputs and outputs for a generic waste treatment process model. Input masses and all outputs are specified per unit mass of each waste material. Model parameters and user inputs are used to characterize the transformation of the incoming waste mass as well as the resulting emissions, fuel use, and costs. User inputs represent the model parameters that are system-specific, which need to be specified by users, while default values are available for other model parameters. 1 Mg = 1 metric ton.

Default model parameters are provided, but can also be changed by the user. For example, each piece of equipment in a material recovery facility (MRF) has a separation efficiency in units of Mg separated/Mg^{in} and an electricity use coefficient in units of kWh/Mg^{in}. Based on the incoming waste composition as well as the input and parameter values, each process model calculates the masses of output waste materials, emissions, fuel use, electricity use, capital costs, and operating costs. Emission factors have been developed for the emissions associated with equipment fuel use, transportation, chemical and biological transformations, and electricity use in each process. Life cycle impact factors can then be used with the life cycle inventory results to calculate environmental impacts from the emissions (e.g., global warming potential, acidification potential, or human toxicity). To build an LCA model for an entire waste system, the mass flows from the appropriate combination of these unit processes are linked from waste collection through final disposal or beneficial recovery of material. Detailed documentation of the solid waste unit process models will be published elsewhere.

2.2.2 Mass flow modeling

Once the appropriate process models that constitute a specific SWM system are chosen, it is necessary to estimate the mass flows of each *waste material* through these processes to define an integrated SWM strategy. Table 2-1 presents definitions of terms used in the modeling of mass flows in a SWM system.

Table 2-1. Definition of terms used in the modeling of mass flows in a SWM system.

Term	**Applicable Notation in Section 2.4**	**Definition**
Collection destination	-	A *treatment process* (e.g., transfer station, landfill, composting facility) that accepts a *waste stream* from a *collection process*.
Collection process	CP_{cs}	A process (e.g., mixed waste collection, single stream recyclable collection, separated organics collection) that collects one or more *waste streams* from the curb and delivers each *waste stream* to a *collection destination*.
Collection scheme	CS	A set of *collection processes* that includes a set of *specific collection processes* that each collect unique *waste streams* and a single *mixed waste collection process* to collect the residual mixed waste.
Mixed waste collection process	$MWCP_{cs}$	A *collection process* that can collect all of the *waste materials* (i.e., mixed or residual collection processes). The *mixed waste collection processes* are a subset of the *collection processes* within a *collection scheme*.
Specific collection process	SCP_{cs}	A *collection process* that collects specific subsets of *waste materials* (e.g., recyclable or organics collection). The *specific collection processes* are a subset of the *collection processes* within a *collection scheme*.
Treatment path	-	A set of *treatment processes* that processes all of the *waste materials* in a *waste stream* from a single *collection process* through to final disposal or beneficial recovery.
Treatment process	TP	A process that accepts a set of *waste streams* and may generate separated and/or transformed *waste streams* (e.g., transfer station, waste-to-energy, material recovery facility).
Treatment scheme	TS_{cs}	A set of treatment processes that treats all of the *waste streams* collected by a *collection scheme* and can consist of multiple *treatment paths*.
Waste materials	WM	The set of materials that can be collected, treated and/or disposed of in the system (e.g., food waste, newsprint, steel cans).
Waste streams	WS	A set of *waste materials* that can be collected or treated together in a *collection process* or *treatment process*, respectively (e.g., recyclables, residual, ash).

A direct way to model the mass flow through the system would be to use a network mass flow model that accounts for all of the incoming and outgoing mass for each process in the system. Such an approach is problematic because each *waste material* will have different processing costs and emissions, and will undergo different transformations in each process. For example, landfilling steel cans will have different environmental impacts than landfilling food waste. Recycling aluminum will generate more revenue per ton than recycling glass bottles. The unique responses of each *waste material* to each process require that the mass flow of each individual *waste material* through the system be considered. This is challenging for a network flow model because all of the *waste materials* enter the system as a mixed entity, which reflects the waste composition of the generated mixed waste. For example, if one were to consider the use of a landfill and a waste-to-energy (WTE) facility, the optimal solution from a simple network model could send combustibles to the WTE facility, and the rest of the waste to the landfill, but the individual *waste materials* cannot be separated without the use of a dedicated separation facility. To ensure that *waste materials* are not inappropriately separated in a process, linked ratio constraints that introduce nonlinear expressions would have to be enforced for each *waste material* and process. This would result in a non-linear optimization model. Since the purpose of the model is to derive a readily scalable and generalizable framework, mass is balanced with only linear expressions using *collection and treatment schemes* that account for all mass flows from collection through treatment and final disposal or beneficial recovery.

Collection schemes collect all of the generated *waste materials* and consist of a combination of *collection processes* (e.g., mixed waste collection + single stream recyclable collection + source separated organics collection) as well as the destination (e.g., landfill, material recovery facility, and composting) for each *collection process*. Valid *collection schemes* must include a way to collect all of the generated *waste materials*. For example, single stream recyclable collection combined with source separated organics collection do not make a valid *collection scheme*; a *mixed waste collection process* must be included to collect the non-recyclable and non-source separated organic waste materials. There are also limits on the proportion of each *waste material* that can be collected by each *collection process*. For example, only recyclable *waste materials* can be collected by recyclable *collection processes*, and there is a limit on the proportion of a recyclable *waste material* that can be collected by a given *collection process*. This limit is due to lack of participation and imperfect separation performed at the household level by waste generators (i.e., not everyone recycles, and those who do recycle may not separate consistently).

The mass of waste collected by each *collection scheme* must then be treated. The possible ways for collected waste to be treated are called *treatment schemes*, which vary for each *collection scheme*. An example system that contains numerous potential *treatment schemes* is shown in Figure 2-2. Each collected *waste stream* must have an associated *treatment path* that begins at a *collection destination* (i.e., single stream MRF, mixed waste MRF, composting, WTE, and landfill in this example) and ends in final disposal or beneficial recovery (i.e., remanufacturing or land application). The system shown in Figure 2-2 includes three collected *waste streams* (i.e., mixed waste, single stream recyclables, and organics).

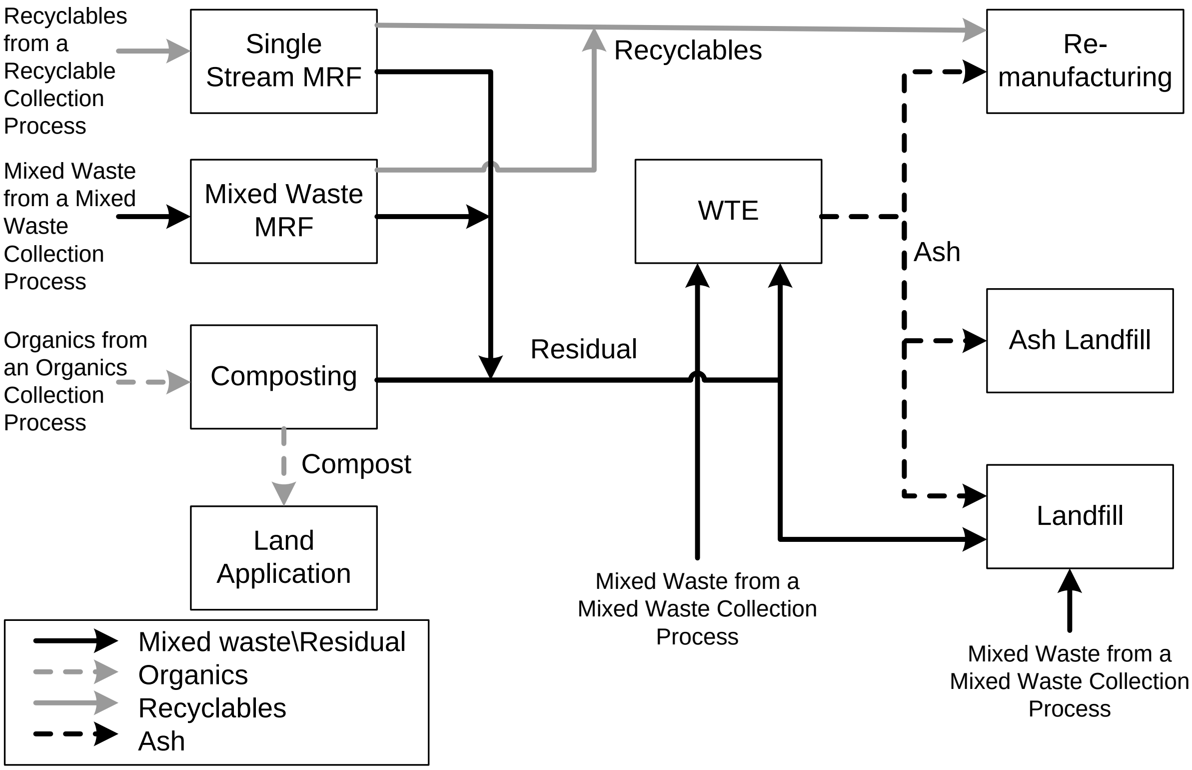

Figure 2-2. An example of a set of *treatment schemes* that shows the potential waste flows for all of the collected waste. The organics and recyclable collection processes are both *specific collection processes.* The single stream MRF, mixed waste MRF, composting, WTE, and landfill are all potential *collection destinations*. In this example system, there are 102 possible *treatment schemes* and each one belongs to at least one *collection scheme*.

Each of these *waste streams* has associated *treatment paths* that are shown in Figure 2-3. Even though only three *waste streams* are collected, reconfigured *waste stream*s are produced by the *treatment processes* (e.g., separated recyclables, compost, ash, and residual waste). The fraction of each *waste material* entering each *treatment process* that goes to each output *waste stream* is determined by both the *treatment process* and *treatment scheme.* For example, a representative *treatment path* consists of single-stream recyclables going to a single stream MRF, the separated recyclables from the single stream MRF going to remanufacturing, the MRF residual going to a WTE facility, and the ash from the WTE facility going to a landfill. In that example, a mixed recyclable *waste stream* is collected, but the MRF produces a separated recyclable *waste stream*, and a residual *waste stream*. The WTE facility then produces an ash *waste stream* when the residual *waste stream* is combusted. The fraction of each *waste material* separated out in the single stream MRF is determined by the specified separation efficiency of the equipment used in the MRF. Similarly, the ash produced by each *waste material* entering the WTE facility is determined by the WTE process model based on the ash content of each *waste material* and the combustion efficiency of the WTE facility. The *treatment scheme* determines the entire material flow from *collection destination* for each *collection process* in the associated *collection scheme* through final disposal or beneficial use. In the example shown in Figure 2-2, a *treatment scheme* would consist of at least one mixed waste *treatment path* and at most one *treatment path* for each of the other *waste streams* (i.e., no more than one path from commingled recyclables and no more than one path from organics can be added to the chosen mixed waste path). This ensures that any *treatment scheme* uniquely and fully defines how all of the incoming waste is treated.

Using this modeling framework, the model solution defines the mass flows through the system in each time stage from the initial period until the end of decision horizon. It is assumed that the mass flows through the system remain constant within each stage, but can change between stages.

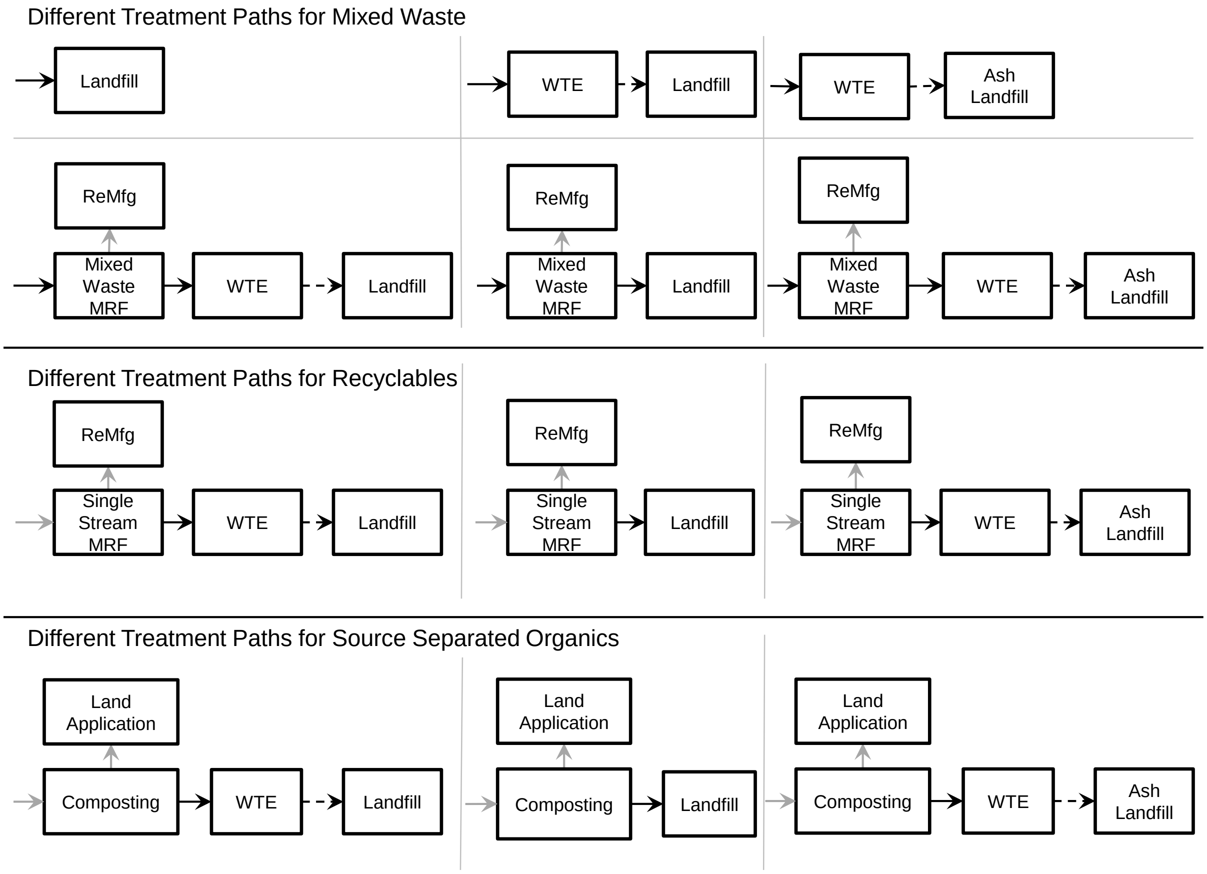

Figure 2-3. All the *treatment paths* for the example shown in Figure 2-2. *Treatment schemes* are produced by combining one mixed waste *treatment path* with at most one of each of the recyclable and source separated organics paths (i.e., more than one of either is not allowed).

2.2.3 Facility capacity modeling

Given the long-lived nature of most SWM processes, it is necessary to consider changes in the SWM system, including the capital investments to build, expand, or replace facilities. Facility capacity can be updated in each stage, and the mass flow through a *treatment process* is limited by the available facility capacity in each stage. The model can consider both existing and new facilities. The ability to include existing facilities allows the model to consider the lower costs often associated with existing infrastructure when determining the optimal solution. Facilities are constrained to a minimum feasible capacity specific to its process type (e.g., composting facilities can be built with smaller throughput capacity than

WTE facilities). Each facility type has a lifetime over which it is active; and when its lifetime ends, its capacity is no longer available to treat waste. During the lifetime of the facility, the capacity of that facility can be expanded. If a facility is expanded, it must be expanded by at least a specified minimum expansion level that considers economies of scale. It is assumed that during expansion the necessary maintenance and repairs are performed to reset the facility life to its original lifetime. To maintain the new level of available capacity, the existing capacity is replaced by the expanded capacity. If the lifetime of a facility extends past the decision horizon, it is assumed to be rebuilt indefinitely at the end of its life to provide equivalent service beyond the decision horizon. This is consistent with other infrastructure planning studies, which assume that equivalent capacity exists indefinitely to meet the continuing service demand. If a facility becomes inactive before the end of the decision horizon, it can be decommissioned. The capacity decisions require the use of binary variables, resulting in a mixed integer linear programming (MILP) modeling framework to find the optimal integrated SWM plan.

2.2.4 Cost modeling

As with all civil infrastructure projects, it is necessary to consider both capital and operating costs. The costs associated with each unit process are provided by the life-cycle process model as shown in Figure 2-1. The capital costs for each process are reported in units of dollars per annual throughput capacity (i.e., $\$/\text{Mg-yr}^{-1}$, 1 Mg = 1 metric ton). Capital costs are generally defined as one-time construction-related costs. Capital costs are associated with building new facilities and expanding facilities in each stage as well as indefinitely rebuilding capacity after the model time horizon for those facilities with active capacity at the end of the decision horizon. Capital costs used to build existing facilities are considered sunk and therefore do not affect future decisions.

In addition to capital costs, operating costs are associated with treating materials through each process. The operating costs of a process are specific to each *waste material* and include direct processing costs such as labor and maintenance costs as well revenue from selling recyclable materials to remanufacturers. Fuel and electricity costs are calculated separately based on their total consumption for processing each *waste material* as well as the fuel and electricity prices in each stage. Separating out the fuel and electricity costs allows the model to consider future changes in prices based on different energy and environmental policy futures.

Remanufacturing, collection, and landfills do not have an explicitly modeled capacity or capital costs (all capital costs are amortized into the operating costs). Remanufacturing covers a diverse array of facilities across a number of industries. The total capacity is essentially infinite when compared to MSW recyclable generation, so remanufacturing costs and emissions are considered on a per unit mass recycled basis. The main capital expenditure for a collection process is the vehicles. The lifetime of collection vehicles is relatively short and the existence of resale markets for such vehicles makes it reasonable to incorporate their upfront cost into the operating costs. Since landfills are essentially continuing construction projects, it is difficult to reasonably differentiate capital and operating costs, and since landfill disposal is readily available in most locations for a flat fee per ton, the lack of capital decisions should not alter optimal solutions found by the model. Landfill lifetimes are also variable based on their utilization, so all landfill construction costs are amortized into their operating costs. Landfills can have cumulative capacity constraints that prohibit the model from disposing of more waste than an individual landfill can hold.

2.2.5 Environmental emissions modeling

Figure 2-4 shows the system boundary for the LCA. All emissions are calculated for each *waste material;* the accounting of *waste material*-specific costs and emissions requires the use of the mass flow framework described in Section 2.2.2. Gross emissions are generated from extracting and processing fuel and raw materials as well as from electricity use. Avoided emissions result from the production of electricity, soil amendments, and recyclables that offset production from virgin sources. The net emissions are equal to the difference between the gross and avoided emissions. Consistent with standard LCA practice, the environmental emissions associated with facility construction are considered to be negligible, so environmental emissions are only associated with processing a *waste material* through a *collection or treatment process*. There are four general types of environmental emissions as shown in Figure 2-1. First, direct emissions occur as a result of physical, chemical, or biological processes, e.g., landfill gas emissions, WTE combustion emissions. Second, there are emissions from equipment fuel use. These emissions result from any diesel, gasoline, compressed natural gas (CNG), or liquefied petroleum gas (LPG) combusted in equipment while processing material, as well as the pre-combustion emissions associated with extracting and producing that fuel. Third, there are electricity-related emissions and offsets associated with electricity use and generation, respectively. These emissions occur offsite and depend on the current electricity generation mix (i.e., the share of coal, natural gas, nuclear, and renewable electricity generation), which can vary by stage and include the emissions associated with extracting and processing the fuels used to generate the electricity. Fourth, transportation related emissions that can vary by vehicle fuel type and fuel efficiency; both of which can also vary by stage. Transportation-related emissions occur during waste collection, transport of waste materials between processes, and transport of necessary secondary materials to *treatment processes* (e.g., transporting soil to a landfill).

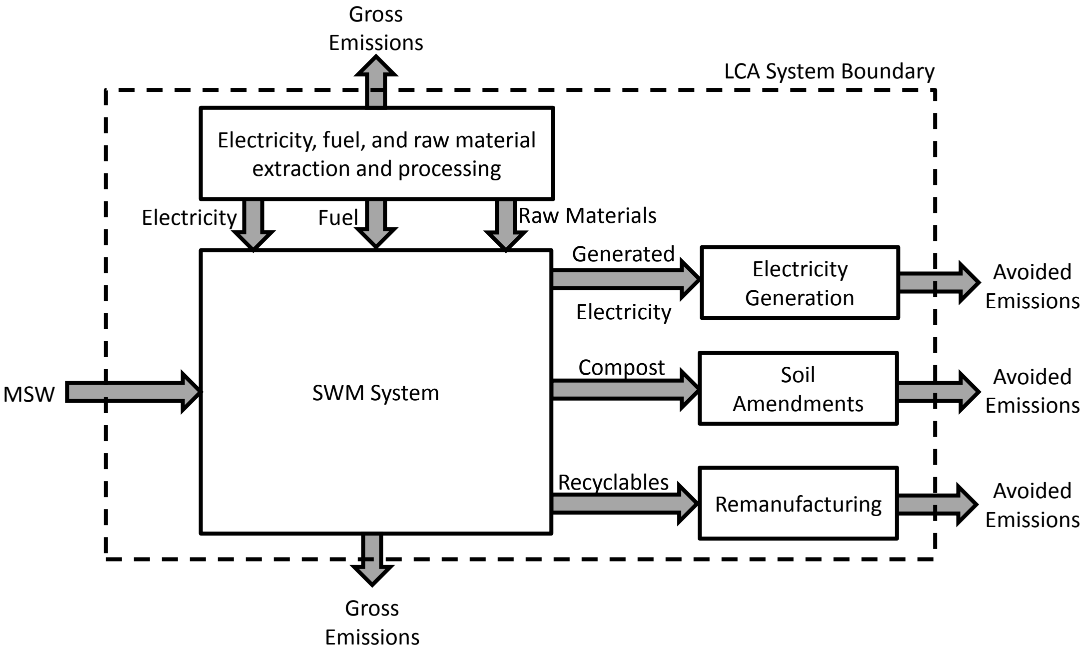

Figure 2-4. System boundary for the SWM life-cycle assessment. Gross emissions are generated through electricity, fuel, and raw material extraction and processing, as well as directly in SWM processes. Emission offsets are produced from avoiding electricity generation, soil amendment production, and virgin material production. Net emissions are equal to the difference between gross and avoided emissions.

2.2.6 Solid waste management policy requirements

User-specified constraints can be added to analyze and explore specific SWM policies. A common consideration for solid waste decision-makers is the need to achieve diversion targets, which require that a specified percentage of waste mass not be disposed in landfills. The purpose of diversion targets is to encourage recycling and/or energy recovery of wastes, which ostensibly increase environmental sustainability. Users can also ban specific materials from entering particular process types. For example, many countries, states, and provinces have bans on sending various degradable waste materials to landfills. Such a policy would be modeled by setting the mass of those materials entering a landfill to zero. To eliminate a treatment process from consideration, either due to a regulatory ban or user preference, the treatment facility capacity can be set to zero. It is also possible to set economic (i.e., budget) constraints while minimizing environmental emissions or maximizing diversion. Users can also specify minimum utilization constraints for certain processes; these constraints ensure that if a facility is built, a minimum specified fraction of its capacity is utilized. For example, such a constraint applies to WTE plants that typically require at least 80% utilization for the plant to operate efficiently.

2.3 Illustrative Integrated Solid Waste Management System

The modeling framework outlined in Section 2.2 and explained with applicable mathematical expressions in Section 2.4 is generic and flexible. Here a specific illustrative example system (Figure 2-5) is used, without loss of generality, to help describe the model structure and the implementation of the mathematical programming model presented in Section 2.4. In this example, the waste is generated in each of the three, 10-year stages (Table 2-2).

Table 2-2. Waste generation for the illustrative SWM system shown in Figure 2-5.

	Generated Waste (Mg)		
	2010-2019	2020-2029	2030-2039
Recyclables	25,000	33,000	45,000
Non-recyclables	25,000	27,000	30,000
Total	50,000	60,000	75,000

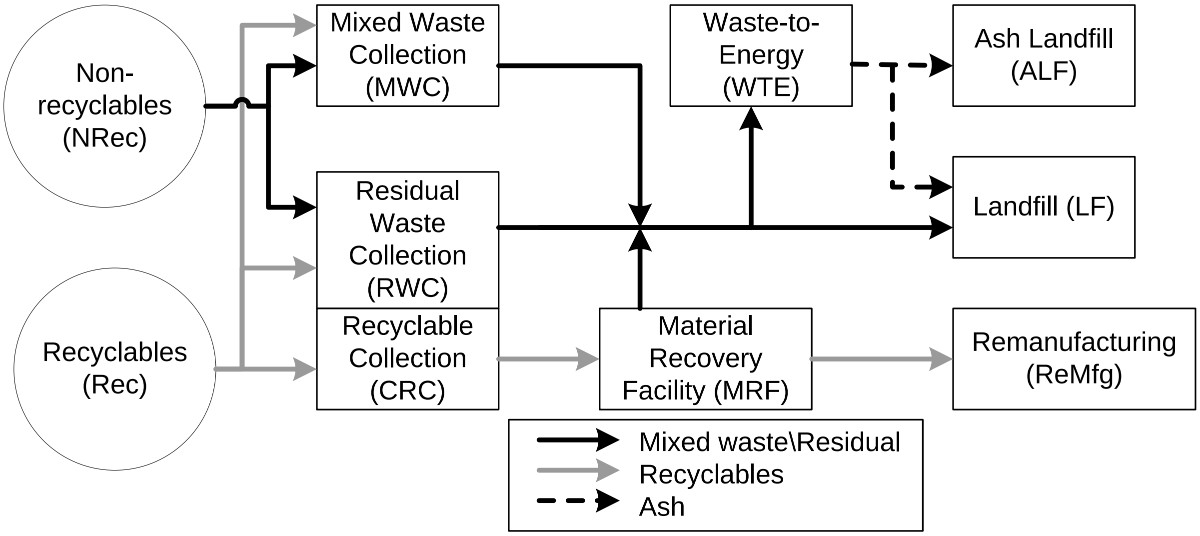

Figure 2-5. System model of potential mass flows for the illustrative example. WTE, LF, and MRF are all potential *collection destinations*. The residual waste collection process collects the waste mass not collected by recyclable collection. Recyclable collection requires residual waste collection to form a valid *collection scheme*.

The model parameter values used to generate the illustrative results can be found in Appendix A. The WTE facility is required to receive at least 80% of its capacity in each stage that it is active.

The illustrative example shown in Figure 2-5 includes two *waste materials*, namely, recyclables (Rec) and non-recyclables (NRec). These materials can be handled by three *collection processes*: mixed waste collection (MWC), commingled recyclable collection (CRC), and residual waste collection (RWC). The RWC process collects the residual waste mass not collected by recyclable collection. The commingled recyclable collection process can collect at most 60% of the generated recyclables due to inconsistent recyclable separation by the waste generators. The possible *collection destinations* for mixed and residual waste are the landfill (LF) and WTE facility *treatment processes*. The only available destination for CRC is the MRF. The illustrative example includes an existing MRF (MRF_E) that has 10 years of remaining life with a capacity of 10,000 Mg/yr in operation during the first stage. A new MRF (MRF_N) can be built in any stage. The MRF_N has an assumed separation efficiency of 90%, compared to 80% for the MRF_E. Recovered recyclables from either MRF are sent to a remanufacturing (ReMfg) process. Residual from either MRF can be disposed in the landfill or the WTE facility. Ash from WTE combustion can be disposed in a dedicated ash landfill (ALF) or a mixed waste landfill. Five percent of the incoming mass to the WTE facility is assumed to exit as ash.

The three *collection processes* are combined to form six *collection schemes*: 1) all generated waste is collected as mixed waste and disposed at the landfill (MWC to LF); 2) all generated waste is collected as mixed waste and processed at the WTE facility (MWC to WTE); 3-4) recyclables are collected as commingled recyclables and the residual waste is collected separately and disposed in the landfill (CRC to MRF_E or MRF_N; and RWC to LF); and 5-6) recyclables are collected as commingled recyclables and the residual waste is collected separately and processed at the WTE facility (CRC to MRF_E or MRF_N; and MWC to LF). Each of the *collection schemes* also has associated *treatment schemes* that are shown in Table 2-3. In this illustrative example, *treatment schemes* are defined by where MRF residuals are treated, and where WTE ash is disposed. The mixed or residual waste *collection destination* is determined by the *collection scheme*.

Table 2-3. *Collection schemes* and their associated *treatment schemes* in the illustrative example. The *treatment scheme* designations are formed from the destinations of mixed waste collection, MRF residuals, and ash. The illustrative system has three *collection processes* with six *collection schemes*, as well as 17 *treatment schemes* (the number of *collection and treatment schemes* that include a MRF are doubled to include the MRF_N and MRF_E alternatives).[a]

		Treatment Schemes		
Collection Scheme	Treatment Scheme Designation[b]	Mixed Waste Destination	MRF Residual Destination	Ash Destination
MWC to LF	L--	{LF	—	—}
MWC to WTE	W-A	{WTE	—	ALF}
	W-L	{WTE	—	LF}
CRC to MRF_N or MRF_E and RWC to LF	LL-	{LF	LF	—}
	LWA	{LF	WTE	ALF}
	LWL	{LF	WTE	LF}
CRC to MRF_N or MRF_E and RWC to WTE	WLA	{WTE	LF	ALF}
	WLL	{WTE	LF	LF}
	WWA	{WTE	WTE	ALF}
	WWL	{WTE	WTE	LF}

[a] MWC – Mixed waste collection, CRC – Commingled Recyclable Collection, RWC – Residual Waste Collection, ALF – Ash Landfill, LF – Landfill, MRF_N – New MRF, MRF_E – Existing MRF, WTE – Waste-to-Energy

[b] The *treatment scheme* designations used in the expressions in Section 2.4.

2.4 *Mathematical Expressions for the Integrated Solid Waste Management Model*

A comprehensive set of expressions is required to appropriately model the SWM system. One set of constraints is used to ensure mass balance in each stage. Another set of constraints is used to assign each facility's available capacity in each stage based on decisions made in preceding stages. Another set of expressions is used to calculate costs and other environmental emissions. Finally, user-defined constraints can be added to meet other objectives (e.g., diversion constraints, utilization constraints). The subsections below provide the mathematical model formulation, and the nomenclature used in the equations is included in the Symbols Used section.

2.4.1 Mass flow expressions

Mass flow constraints ensure that mass is conserved through each process and that waste composition only changes when a *treatment process* alters the composition through physical, chemical, or biological means (e.g., MRFs separate recyclables from non-recyclables, WTE combusts waste and produces ash, composting facilities convert organics to compost). The mass flow constraints for a single stage were developed based on the modeling approach described by Solano et al., (2002), which has been generalized and extended in this paper to accommodate multiple stages. Based on our functional unit of waste at curbside, Eq. 1 ensures that all of the generated waste in each stage is collected by one of the *collection schemes* in each stage. In the illustrative example, FTP = 3, and CS = {{(MWC-LF)}, {(MWC-WTE)}, {(RWC-LF), (CRC-MRF)}, {(RWC-WTE), (CRC-MRF)}}.

$$Mass_t = \sum_{cs \in CS} x_{cs,t} \quad \forall\, t = 1,2 \ldots FTP \qquad \text{Eq. 1}$$

Eq. 2 ensures that all of the waste collected by each *collection scheme* in a stage is assigned to an appropriate *treatment scheme* in that stage. The *treatment schemes* are indexed by *collection schemes* because each *collection scheme* has a set of feasible *treatment schemes*. For the illustrative example, there are 17 *treatment schemes*, as shown in Table 2-3, with their associated *collection schemes*.

$$x_{cs,t} = \sum_{ts \in TS_{cs}} x_{cs,ts,t}$$ Eq. 2

$\forall\, cs \in CS,\ \forall\, t = 1,2 \ldots FTP$

Eq. 3 allocates the entire generated, collected, and treated waste mass to individual *waste materials*. In the illustrative example, *WM* = {Rec, NRec} and the composition of the generated mass found in Table 2-2 is used to calculate $\beta_{wm,t}$ for each material in each stage.

$$x_{cs,ts,wm,t} = \beta_{wm,t} \cdot x_{cs,ts,t}$$ Eq. 3

$\forall\, cs \in CS,\ \forall\, ts \in TS_{cs}, \forall\, wm \in WM, \forall\, t = 1,2 \ldots FTP$

Eq. 4 ensures that all of the collected and treated waste is allocated to a *collection process*. The *collection processes* are indexed by the *collection schemes* to which they belong. In the illustrative example, $CP_{mwc\text{-}lf}$ and $CP_{mwc\text{-}wte}$ = {MWC}; and $CP_{rwc\text{-}lf}$ and $CP_{rwc\text{-}wte}$ = {CRC, RWC}.

$$x_{cs,ts,wm,t} = \sum_{cp \in CP_{cs}} x_{cs,ts,wm,cp,t}$$ Eq. 4

$\forall\, cs \in CS,\ \forall\, ts \in TS_{cs},\ \forall\, wm \in WM,\ \forall\, t = 1,2 \ldots FTP$

While Eq. 4 is used to ensure that the waste mass of each material is collected by a *collection process*, Eq. 5 ensures that *waste materials* are not collected at a proportion greater than the proportion at which they can be separated in a given *specific collection process*. For waste materials that cannot be collected by a given collection process, the maximum collection efficiency is zero (e.g., the maximum collection efficiency for NRec in CRC is zero). In the illustrative example, $SCP_{mwc\text{-}lf}$ and $SCP_{mwc\text{-}wte}$ = {Ø}; and $SCP_{rwc\text{-}lf}$ and $SCP_{rwc\text{-}wte}$ = {CRC}.

$$x_{cs,ts,wm,scp,t} \leq \varphi_{wm,scp,t} \cdot x_{cs,ts,wm,t}$$ Eq. 5

$\forall\, cs \in CS,\ ts \in TS_{cs},\ \forall\, wm \in WM,\ \forall\, scp \in SCP_{cs},\ \forall\, t = 1,2 \ldots FTP$

While Eq. 5 defines the maximum mass of each *waste material* that can be collected by each *specific collection process*, Eq. 6 ensures that waste mass that is not collected in *specific* *collection processes* is collected in a *mixed waste collection process*. In the illustrative example, $MWCP_{mwc\text{-}lf}$ and $MWCP_{mwc\text{-}wte}$ = {MWC}; $MWCP_{rwc\text{-}lf}$ and $MWCP_{rwc\text{-}wte}$ = {RWC}.

$$x_{cs,ts,wm,mwcp,t} = x_{cs,ts,wm,t} - \sum_{scp \in SCP_{cs}} x_{cs,ts,wm,scp,t} \qquad \text{Eq. 6}$$

$$\forall\, mwcp \ \in MWCP_{cs}, \forall\, cs \ \in CS,\ ts \ \in TS_{cs},\ \forall\, wm \ \in WM,\ \forall\, t = 1,2 \ldots\ FTP$$

Eq. 5 and Eq. 6 define the mass of each *waste material* collected through each *collection process* and *treatment scheme*, and Eq. 7 is used to define the total mass of each *waste material* collected via each *collection process* by summing over every *treatment scheme* associated with the *collection scheme* to which the *collection process* belongs.

$$x\_util_{cs,wm,cp,t} = \sum_{ts \in TS_{cs}} x_{cs,ts,wm,cp,t} \qquad \text{Eq. 7}$$

$$\forall\, cs \ \in CS, \forall\, wm \ \in WM, \forall\, cp \in CP_{cs},\ \forall\, t = 1,2 \ldots\ FTP$$

Eq. 8 is used to determine the mass of each *waste material* delivered from each *collection process* to each *treatment process*. In the illustrative system WTE, MRF, and landfill are the *treatment processes* that accept waste from collection, and are thus the *collection destinations.*

$$xtpcol_{ts,wm,tp,t} = \sum_{cs \in CS} \sum_{cp \in CP_{cs}} \gamma_{cs,cp,tp} \cdot x_{cs,ts,wm,cp,t} \qquad \text{Eq. 8}$$

$$\forall\, ts \ \in TS,\ \forall\, wm \ \in WM,\ \forall\, tp \ \in TP_{ts}, \forall\, t = 1,2 \ldots\ FTP$$

Eq. 9 and Eq. 10 are used in conjunction with Eq. 8 to determine the mass of each *waste material* processed through each *treatment process* in each *treatment scheme.* Eq. 9 defines the output mass of each *waste material* in each *waste stream* from each *treatment process* in each *treatment scheme*. In the illustrative system, *WS* = {Ash, Recyclables, Residual}. Eq. 10 defines the incoming mass of each *waste material* into each *treatment process* in each *treatment scheme*. The flow of the *waste materials* in each *waste stream* from *collection* *destination* through to final disposal and/or beneficial recovery is determined by the *treatment scheme* and the characteristics of the *treatment processes* in that *treatment scheme*.

$$xtpout_{ts,wm\_out,tp,ws,t} = \sum_{wm\_in \in WM} \alpha_{wm\_in,wm\_out,ws,tp} \cdot xtpin_{ts,wm\_in,tp,t} \qquad \text{Eq. 9}$$

$$\forall\, wm\_out\ \in WM, \forall\, ts \in TS,\ tp \in TP_{ts}, \forall\, ws\ \in WS, \forall\, t = 1,2 \ldots\ FTP$$

$$xtpin_{ts,wm,tp,t} = xtpcol_{ts,wm,tp,t} + \sum_{tp\_up \in TP_{ts}} \sum_{ws \in WS} \tau_{ts,tp,tp\_up,ws} \cdot xtpout_{ts,wm,tp\_up,ws,t} \qquad \text{Eq. 10}$$

$$\forall\, wm\ \in WM, \forall\, ts \in TS,\ tp \in TP_{ts},\ \forall\, t = 1,2 \ldots\ FTP$$

Eq. 11 sums the incoming mass of each *waste material* through each *treatment process* in each *treatment scheme* to determine the total mass of each *waste material* processed through each *treatment process* in each stage, so that operating costs and process emissions can be assigned to each *treatment process* and *waste material* in each stage.

$$x\_util_{wm,tp,t} = \sum_{ts \in TS} xtpin_{ts,wm,tp,t} \qquad \text{Eq. 11}$$

$$\forall\, wm\ \in WM, \forall\, tp\ \in TP,\ \forall\, t = 1,2 \ldots\ FTP$$

2.4.2 Facility capacity expressions

The preceding mass flow equations are used to ensure that all of the waste mass is collected and treated in every stage, but they do not provide any constraints on what capacity is available to treat the waste. Eq. 12 is used to ensure that the total mass of waste processed through each capital *treatment process* in each stage does not exceed the available capacity for that *treatment process*. In the illustrative example, *CAP* = {MRF_E, MRF_N, WTE}.

$$x\_curActCap_{cap,t} \geq \sum_{wm \in WM} x\_util_{wm,cap,t} \qquad \text{Eq. 12}$$

$$\forall\, cap\ \in CAP, \forall\, t = 1,2 \ldots FTP$$

In addition to limiting the waste flow to each capital *treatment process* by the available capacity, constraints are required to determine the available capacity of each capital *treatment process* in each stage. Eq. 13 is used to determine the available capacity of new *treatment processes* in the initial stage. Since new capital *treatment processes* by definition have no existing capacity in the initial stage, the available capacity is equal to whatever capacity is built in the initial stage. In the illustrative system, *CAP_N* = {MRF_N, WTE}. The set of capital *treatment processes CAP* is the union of the set of new capital *treatment processes CAP_N* and existing capital *treatment processes CAP_E*.

$$x\_curActCap_{cap\_n,t} = x\_bcap_{cap\_n,t} \qquad \text{Eq. 13}$$

$$\forall\ cap\_n \in CAP\_N, \forall\ t = 1,2 \ldots FTP$$

In stages after the initial stage, the available capacity should equal the still active built capacity, unless the capacity has been expanded or decommissioned. Eq. 14 ensures that the available capacity is greater than or equal to the previously built capacity that is still active unless there is an active expansion or the capacity was decommissioned in a previous stage. Eq. 15 ensures that the available capacity is less than or equal to the previously built capacity unless there is an active expansion or the capacity was decommissioned in a previous stage. The equations are non-binding if there is an active expansion or the capacity was decommissioned in a previous stage (*M* is defined as a sufficiently large constant to ensure that the equations are not binding), so together they ensure that the currently available capacity in each stage for new capital *treatment processes* is equal to the still active built capacity unless the facility has been expanded or decommissioned. Eq. 14 and Eq. 15 are representative of a style of paired constraints that are used frequently in the facility capacity modeling. When a combination of binary variables is true, the constraints ensure equality between the left and right hand sides of both equations, and if that combination of binary variables is not true, then the constraints are non-binding. In Eq. 14 and Eq. 15, if there are no active expansions, and the facility has not been decommissioned in a previous stage, then the current capacity is equal to the still active built capacity. If the facility has been expanded or decommissioned, then both of the equations are non-binding.

$$x\_curActCap_{cap\_n,T} + M\sum_{t=1}^{T}\left(procAlive_{cap\_n,t,T} \cdot E_{cap\_n,t} + D_{cap\_n,t}\right) \geq \sum_{t=1}^{T} procAlive_{cap\_n,t,T} \cdot x\_bcap_{cap\_n,t} \quad \text{Eq. 14}$$

$\forall\ cap\_n \in CAP\_N, T = 2,3 \ldots FTP$

$$x\_curActCap_{cap\_n,T} \leq M\sum_{t=1}^{T}\left(procAlive_{cap\_n,t,T} \cdot E_{cap\_n,t} + D_{cap\_n,t}\right) + \sum_{t=1}^{T} procAlive_{cap\_n,t,T} \cdot x\_bcap_{cap\_n,t} \quad \text{Eq. 15}$$

$\forall\ cap\_n \in CAP\_N, T = 2,3 \ldots FTP$

Since existing capacity cannot be built, the capacity of existing facilities in the initial stage is equal to the preexisting capacity unless it is expanded or decommissioned in the initial stage. As in Eq. 14 and Eq. 15, Eq. 16 and Eq. 17 ensure that in the initial stage, the actual capacity of existing capital *treatment processes* equals the existing capacity unless the capacity is expanded or decommissioned.

$$x\_curActCap_{cap\_e,t} \leq actCap_{cap\_e} + M\left(E_{cap\_e,t} + D_{cap\_e,t}\right) \quad \text{Eq. 16}$$

$\forall\ cap\_e \in CAP\_E,\ t = 1$

$$x\_curActCap_{cap\_e,t} + M\left(E_{cap\_e,t} + D_{cap\_e,t}\right) \geq actCap_{cap\_e} \quad \text{Eq. 17}$$

$\forall\ cap\_e \in CAP\_E, t = 1$

Unlike new facilities, existing facilities can be expanded in the initial stage. Eq. 18 and Eq. 19 ensure that the actual capacity of existing capital *treatment processes* in the initial stage equals the amount of expanded capacity if the capital *treatment process* is expanded in the initial stage.

$$x\_curActCap_{cap\_e,t} \leq \; x\_ecap_{cap\_e,t} + \; M\left(1 - \; E_{cap\_e,t}\right) \tag{Eq. 18}$$

$\forall \; cap\_e \; \in CAP\_E, t = 1$

$$x\_curActCap_{cap\_e,t} + M\left(1 - E_{cap\_e,t}\right) \geq \; x\_ecap_{cap\_e,t} \tag{Eq. 19}$$

$\forall \; cap\_e \; \in CAP\_E, t = 1$

Eq. 20 and Eq. 21 perform the same function as Eq. 14 and Eq. 15 for existing facilities by ensuring that the currently active capacity equals the still active initial capacity unless the facility has been expanded or decommissioned.

$$\begin{aligned} x\_curActCap_{cap\_e,T} &+ M\sum_{t=1}^{T}\left(procAlive_{cap\_e,t,T} \cdot E_{cap\_e,t} + D_{cap\_e,t}\right) \\ &\geq \; procExist_{cap\_e,T} \cdot actcap_{cap\_e} \end{aligned} \tag{Eq. 20}$$

$\forall \; cap\_e \; \in CAP\_E, T = 2{,}3 \ldots FTP$

$$\begin{aligned} &x\_curActCap_{cap\_e,T} \\ &\quad \leq M\sum_{t=1}^{T}\left(procAlive_{cap\_e,t,T} \cdot E_{cap\_e,t} + D_{cap\_e,t}\right) \\ &\quad + \; procExist_{cap\_e,T} \cdot actcap_{cap\_e} \end{aligned} \tag{Eq. 21}$$

$\forall \; cap\_e \; \in CAP\_E, T = 2{,}3 \ldots \; FTP$

Both existing and new facilities can be expanded after the first stage. Eq. 22 and Eq. 23 ensure that current capacity equals the active expanded capacity if the capacity has not been decommissioned.

$$x\_curActCap_{cap,T} + M\left(1 - E_{cap,T}\right) + M\sum_{t=1}^{T}\left(D_{cap,t}\right) \geq \; x\_ecap_{cap,T} \tag{Eq. 22}$$

$\forall \; cap \; \in CAP, T = 2{,}3 \ldots \; FTP$

$$x\_curActCap_{cap,T} \leq M\left(1 - E_{cap,T}\right) + M\sum_{t=1}^{T}\left(D_{cap,t}\right) + \; x\_ecap_{cap,T} \tag{Eq. 23}$$

$\forall\ cap \in CAP, T = 2,3 \ldots\ FTP$

Facilities can be expanded multiple times. If a facility has an active expansion, and it has not been expanded in the current stage, then it has the same capacity that it had in the previous stage, unless it has been decommissioned. Eq. 24 and Eq. 25 ensure that current capacity equals the capacity in the previous stage if the capacity was expanded in a previous stage, but not the current one, and the facility was not decommissioned. Eq. 26 and Eq. 27 are used together to ensure that $F = 1$ if there is an active expansion, and there is not an expansion in the current stage, and that $F = 0$ if there is an expansion in the current stage.

$$x\_curActCap_{cap,t} + M\left(1 - F_{cap,t}\right) + M \cdot D_{cap,t} \geq\ x\_curActCap_{cap,t-1} \qquad \text{Eq. 24}$$

$\forall\ cap \in CAP, t = 2,3 \ldots\ FTP$

$$x\_curActCap_{cap,t} \leq M\left(1 - F_{cap,t}\right) + M \cdot D_{cap,t} +\ x\_curActCap_{cap,t-1} \qquad \text{Eq. 25}$$

$\forall\ cap \in CAP, t = 2,3 \ldots\ FTP$

$$M \cdot F_{cap,T} \geq \frac{1}{FTP}\sum_{t=1}^{T}\left(procAlive_{cap,t,T} \cdot E_{cap,t}\right) - E_{cap,T} \qquad \text{Eq. 26}$$

$\forall\ cap \in CAP, \forall\ T = 1,2, \ldots\ FTP$

$$M \cdot (F_{cap,T} - 1) \leq \frac{1}{FTP}\sum_{t=1}^{T}\left(procAlive_{cap,t,T} \cdot E_{cap,t}\right) + \left(1 - M \cdot E_{cap,T}\right) \qquad \text{Eq. 27}$$

$\forall\ cap \in CAP, \forall\ T = 1,2, \ldots FTP$

Decommissioning a facility sets the available capacity to zero in the stage where decommissioning occurs, and every stage after. Eq. 28 ensures that the capacity is zero if the facility has been decommissioned in a previous stage, and Eq. 29 ensures that each facility is only decommissioned once during the model decision horizon.

$$x\_curActCap_{cap,T} \leq M\left(1 - \sum_{t=1}^{T} D_{cap,t}\right)$$ Eq. 28

$\forall\ cap \in CAP, \forall\ T = 1,2, \ldots\ FTP$

$$\sum_{t=1}^{FTP} D_{cap,t} \leq 1$$ Eq. 29

$\forall\ cap \in CAP$

The capacity that is replaced by an expansion is accounted for to ensure that the costs of the expansion are only paid for the added capacity. Eq. 30 and Eq. 31 are used to define the replaced capacity from expansions in each stage as equal to the capacity in the previous stage if the capacity is expanded in the current stage. Only existing facilities can be expanded in the initial stage, and Eq. 32 and Eq. 33 define the replaced capacity for existing facilities in the initial stage.

$$x\_repcap_{cap,t} \leq M\left(1 - E_{cap,t}\right) + x\_curActCap_{cap,t-1}$$ Eq. 30

$\forall\ cap \in CAP, t = 2,3, \ldots\ FTP$

$$x\_repcap_{cap,t} + M\left(1 - E_{cap,t}\right) \geq x\_curActCap_{cap,t-1}$$ Eq. 31

$\forall\ cap \in CAP, t = 2,3, \ldots\ FTP$

$$x\_repcap_{cap\_e,t} + M\left(1 - E_{cap\_e,t}\right) \geq actCap_{cap\_e}$$ Eq. 32

$\forall\ cap\_e\ \in CAP\_E, t = 1$

$$x\_repcap_{cap\_e,t} \leq M\left(1 - E_{cap\_e,t}\right) + actCap_{cap\_e}$$ Eq. 33

$\forall\ cap\_e\ \in CAP\_E, t = 1$

Capacity that exists beyond the decision horizon is rebuilt at the end of its lifetime and is designated repeated capacity. Eq. 34 through Eq. 37 ensure that capacity existing beyond the model decision horizon is rebuilt indefinitely. Capacity that is decommissioned has zero repeated capacity (this is the benefit of choosing to decommission); otherwise the repeated capacity equals the last amount of capacity built or expanded, which means that any capacity that is built or expanded in the final stage is repeated indefinitely.

$$x\_rptcap_{cap\_e,T} \geq procExist_{cap\_e,FTP} \cdot actcap_{cap\_e} - \sum_{t=T+1}^{FTP} x\_rptcap_{cap\_e,t} - M\left(1 - \sum_{t=T}^{FTP} D_{cap\_e,t}\right) \quad \text{Eq. 34}$$

$\forall\ cap\_e \in CAP\_E, T = 1$

$$x\_rptcap_{cap,T} \geq procAlive_{cap,T,FTP} \cdot \left(x\_bcap_{cap,T} + x\_ecap_{cap,T}\right) - \sum_{t=T+1}^{FTP} x\_rptcap_{cap,t} - M\left(1 - \sum_{t=T}^{FTP} D_{cap,t}\right) \quad \text{Eq. 35}$$

$\forall\ cap \in CAP, T = 1,2, \ldots\ FTP - 1$

$$x\_rptcap_{cap,t} \leq procAlive_{cap,t,FTP}\left(x\_bcap_{cap,t} + x\_ecap_{cap,t}\right) \quad \text{Eq. 36}$$

$\forall\ cap \in CAP, t = 2,3 \ldots\ FTP - 1$

$$x\_rptcap_{cap,FTP} = x\_bcap_{cap,FTP} + x\_ecap_{cap,FTP} \quad \text{Eq. 37}$$

$\forall\ cap \in CAP$

Eq. 38 and Eq. 39 ensure that capacity already exists for it to be expanded in new and existing treatment facilities, respectively.

$$\sum_{t=1}^{T-1} procAlive_{cap\_n,t,T} \cdot \left(B_{cap\_n,t} + E_{cap\_n,t}\right) \geq E_{cap\_n,T} \quad \text{Eq. 38}$$

$\forall\ cap\_n \in CAP\_N, \forall\ T = 2,3 \ldots\ FTP$

$$E_{cap\_e,T} \leq procExist_{cap\_e,T} \cdot actcap_{cap\_e} + \sum_{t=1}^{T-1} procAlive_{cap\_e,t,T} \cdot E_{cap\_e,t} \qquad \text{Eq. 39}$$

$\forall\ cap\_e\ \in CAP\_E, \qquad \forall\, T = 2{,}3 \ldots FTP$

Eq. 40 and Eq. 41 are used to control the binary variable W so that it equals 1 if there is existing capacity and 0 otherwise. Eq. 42 then ensures that no new capacity is built if the facility has existing capacity.

$$M \cdot W_{cap\_n,T} \geq \sum_{t=1}^{T-1} procAlive_{cap\_n,t,T} \cdot \left(B_{cap\_n,t} + E_{cap\_n,t}\right) \qquad \text{Eq. 40}$$

$\forall\ cap\_n\ \in CAP\_N, \forall\, T = 2{,}3 \ldots FTP$

$$W_{cap\_n,T} \leq \sum_{t=1}^{T-1} procAlive_{cap\_n,t,T} \cdot \left(B_{cap\_n,t} + E_{cap\_n,t}\right) \qquad \text{Eq. 41}$$

$\forall\ cap\_n\ \in CAP\_N, \forall\ T = 2{,}3 \ldots FTP$

$$B_{cap\_n,t} \leq 1 - W_{cap\_n,t} \qquad \text{Eq. 42}$$

$\forall\ cap\_n\ \in CAP\_N, \forall\ t = 2{,}3 \ldots FTP$

Eq. 43 and Eq. 44 ensure that capacity is built above minimum requirements. Eq. 45 and Eq. 46 ensure that the additional capacity from an expansion (i.e., $x\_ecap_{cap,t} - x\_repCap_{cap,t}$) is above minimum requirements (e.g., ≥1000 Mg/day for WTE).

$$B_{cap\_n,t} \cdot minbldcap_{cap\_n} \leq x\_bcap_{cap\_n,t} \qquad \text{Eq. 43}$$

$\forall\ cap\_n\ \in CAP\_N, \qquad \forall\ t = 1{,}2, \ldots FTP$

$$B_{cap\_n,t} \cdot M \geq x\_bcap_{cap\_n,t} \qquad \text{Eq. 44}$$

$\forall\ cap\_n\ \in CAP\_N, \forall\ t = 1{,}2, \ldots FTP$

$$E_{cap,t} \cdot M \geq x\_ecap_{cap,t} \qquad \text{Eq. 45}$$

$\forall\ cap\ \in CAP, \forall\ t = 1{,}2, \ldots FTP$

$$x\_ecap_{cap,t} + (1 - E_{cap,t})M \geq x\_repCap_{cap,t} + minexpcap_{cap} \qquad \text{Eq. 46}$$

$$\forall\ cap\ \in CAP, \forall\ \ t = 1,2, \dots\ FTP$$

Eq. 47 ensures that capacity can be modified in at most one of three ways in each stage: built, expanded, or decommissioned.

$$B_{cap,t} + E_{cap,t} + D_{cap,t} \leq 1 \qquad \text{Eq. 47}$$

$$\forall\ cap \in CAP, \forall\ \ t = 1,2, \dots\ FTP$$

2.4.3 Cost expressions

As outlined in Section 2.2, costs are split into capital and operating costs, and the total cost is the sum of the amortized capital cost plus the annual operating cost. The cost expression for each treatment and collection process is shown in Eq. 48 and can be used as an objective function or as a budget constraint in the optimization model.

$$totCost = \sum_{proc \in PROC} capCost_{proc} + opCost_{proc} \qquad \text{Eq. 48}$$

Capital costs are associated with building, expanding, and rebuilding facilities indefinitely beyond the model time horizon. Eq. 49 is used to determine the total net present capital cost of each *treatment process* with modeled capacity (the amortized capital costs associated with *collection processes* are included in the operating costs). The (*P/F*,*r*,*t*) factor is used to convert future costs to present costs. The (*A/P*,*r*,$life_{cap}$) factor converts the repeated costs to an annual cost over the life of the facility. The subsequent (*P/A*,*r*,∞) factor converts this infinite annual cost into a single future payment at time $t + life_{cap}$. Finally, the (*P/F*,*r*, $t + life_{cap}$) factor converts this future cost into a present cost. In the illustrative example $r = 0.05$.

$$\begin{aligned} capCost_{cap} = \sum_{1}^{FTP} & \left(buildCost_{cap,t} + expandCost_{cap,t}\right)\left({}^{P}/_{F,\,r,\,t}\right) \\ & + \left(rptCost_{cap,t}\right)\left({}^{A}/_{P,\,r,\,life_{cap}}\right)\left({}^{P}/_{A,\,r,\,\infty}\right)\left({}^{P}/_{F,\,r,\,t\,+\,life_{cap}}\right) \end{aligned} \qquad \text{Eq. 49}$$

$$\forall\ cap \in CAP$$

Eq. 50 is used to calculate the build costs associated with each *treatment process* in each stage by multiplying the amount of capacity built by the build cost coefficient for that process. Similarly, Eq. 51 is used to calculate the expansion costs associated with each *treatment process* in each stage by multiplying the amount of additional capacity by the expansion cost coefficient for that process, and Eq. 52 calculates the indefinite rebuilding costs in the same manner.

$$buildCost_{cap\_n,t} = x\_bcap_{cap\_n,t} \cdot \sigma_{cap\_n} \qquad \text{Eq. 50}$$

$\forall\ cap\_n\ \in CAP\_N, \qquad \forall\ t = 1,2, \dots\ FTP$

$$expandCost_{cap,t} = (x\_ecap_{cap,t} - x\_repcap_{cap,t}) \cdot \rho_{cap} \qquad \text{Eq. 51}$$

$\forall\ cap \in CAP, \forall\ t = 1,2, \dots\ FTP$

$$rptCost_{cap,t} = x\_rptcap_{cap,t} \cdot \sigma_{cap} \qquad \text{Eq. 52}$$

$\forall\ cap \in CAP, \forall\ t = 1,2, \dots\ FTP$

Eq. 53 and Eq. 54 are used to calculate the net present operating cost for *the collection and treatment processes*, respectively. The utilization of each process at the final decision point is assumed to be continued in perpetuity. The (*P/A*,*r*,∞) converts the infinite annual operating costs into a single payment at time *T*. Then the (*P/F*,*r*,*T*) factor converts the future cost at stage *T* into a present cost. The (*P/A*,*r*,*YPP*) converts the annual operating costs in each period into a single payment at time *t*. Then the (*P/F*,*r*,*t*) factor converts the future cost at stage *t* into a present cost.

$$\begin{aligned} opCost_{cp} = \sum_{wm \in WM} \varepsilon_{cs,wm,cp} \Bigg(& x\_util_{cs,wm,cp,T} \cdot \left({}^{P}\!/_{A}, r, \infty\right)\left({}^{P}\!/_{F}, r, T\right) \\ & + \sum_{t=1}^{T-1} x\_util_{cs,wm,cp,t} \left(\frac{P}{A}, r, YPP\right)\left(\frac{P}{F}, r, t\right)\Bigg) \end{aligned} \qquad \text{Eq. 53}$$

$\forall\ cp\ \in CP$

$$opCost_{tp} = \sum_{wm \in WM} \varepsilon_{tp,wm} \left(x\_util_{tp,wm,T} \cdot \left({}^{P}/_{A}, r, \infty\right)\left({}^{P}/_{F}, r, T\right) + \sum_{t=1}^{T-1} x\_util_{tp,wm,t} \left(\frac{P}{A}, r, YPP\right)\left(\frac{P}{F}, r, t\right)\right) \quad \text{Eq. 54}$$

$\forall\ tp\ \in TP$

2.4.4 Environmental emissions expressions

As outlined in Section 2.2, environmental emissions are associated with the utilization of each process. Eq. 55 is used to calculate the total environmental emissions from the system and can be used as an objective or a constraint.

$$totEmis_i = \sum_{t=1}^{FTP} \sum_{proc \in PROC} \sum_{wm \in WM} \xi_{i,proc,wm,t} \cdot x\_util_{proc,wm,t} \quad \text{Eq. 55}$$

$\forall\ i\ \in I$

2.4.5 Solid waste management policy expressions

If a facility requires a minimum level of use, Eq. 56 can be used to ensure that facility throughput is maintained at a minimum level. In the illustrative example, $utilCap_{wte} = 0.80$.

$$x\_curActCap_{cap,T} \cdot utilCap_{cap} \leq \sum_{wm \in WM} x\_util_{cap,wm,t} \quad \text{Eq. 56}$$

$\forall\ cap\ \in CAP, \forall\ t = 1,2, \dots\ FTP$

As explained in Section 2.2, landfill diversion targets are common in SWM operations. Eq. 57 can be used to calculate the percent landfill diversion in each stage and can be used as an objective or a constraint.

$$1 - \frac{1}{Mass_t} \sum_{lf \in LF} \sum_{wm \in WM} x\_util_{lf,wm,t} \geq divTarget_t \quad \text{Eq. 57}$$

$\forall\ t = 1,2 \dots FTP$

2.5 *Results and Discussion*

Three example scenarios were implemented and solved for the illustrative system described in Section 2.3 as a verification exercise and to demonstrate the functionality of the framework. Three 10-year stages were modeled, covering a total of 30 years. The first scenario is called ‘MinCost’ where the objective is to minimize cost without any consideration of environmental issues. The second scenario is called ‘Diversion’ and imposes an increasing diversion constraint in each stage while minimizing cost. A diversion constraint of 10%, 25%, and 50% was imposed in stages 1, 2, and 3, respectively. The third scenario is called ‘GHG’ and minimizes the GHG emissions over the 30-year period, while the total net present cost of the system was constrained to be less than that of the Diversion scenario. The purpose of the GHG scenario is to explore whether there is a more cost effective way to reduce GHG emissions than the use of diversion targets.

2.5.1 Scenario-specific results

Table 2-4 shows the net present cost, GHG emissions and percent diversion in each stage for each scenario. In the MinCost scenario, all of the generated waste was landfilled, resulting in the lowest cost, the greatest GHG emissions, and zero diversion. In the MinCost scenario, all of the generated waste is allocated (through the combination of Eq. 1, Eq. 2, and Eq. **4**) to the MWC to LF *collection scheme* and the landfill *treatment scheme* using the MWC *collection process* because this system leads to the least cost in Eq. 48 with no other policy constraints to consider.

Table 2-4. Net present cost, annual GHG emissions, and diversion results for the three illustrative scenarios. The MinCost scenario costs the least, generates the most GHG emissions, and diverts the least. The Diversion scenario costs the most and diverts the most, while the GHG scenario generates the least GHG emissions.

		Annual GHG Emissions ($MTCO_2e$)[a]			Diversion (%)		
Scenario	Net Present Cost (Million $)	2010	2020	2030	2010	2020	2030
MinCost	48	-250	-849	-1770	0	0	0
Diversion	73	-2200	-7400	-5100	10	25	50
GHG	64	-5600	-8700	-14,000	27	30	32

[a] Negative values indicate net emissions savings from avoided emissions due to material recycling (remanufacturing), energy generation (WTE, landfill) and carbon storage (landfills).

The Diversion scenario costs the most and leads to the most diversion through the use of a relatively high cost WTE facility in the final stage. Figure 2-6 shows the material flows for each stage in the Diversion scenario, and illustrates the utility of using a generalizable multi-stage framework that can incorporate existing infrastructure. In the first stage, 6200 Mg of recyclables are sent to the MRF_E, which produces 1200 Mg of residual and 5000 Mg of recyclables (i.e., 10% diversion) based on the 80% separation efficiency of recyclables in MRF_E (represented by α in Eq. 10). The rest of the waste is landfilled because it is the least costly treatment option. The MRF_E was utilized because it was capable of meeting the 10% diversion target at lower cost than the MRF_N. Without a stage-wise optimization model, a solid waste planner would not be able to see the evolution from MRF to WTE over time as the diversion constraint increases. Such a result highlights the need for a multi-stage optimization framework like SWOLF, which can guide cost- and emissions-efficient infrastructure deployment over time.

In the second stage, a 20,000 Mg/yr MRF_N is built that processes 16,700 Mg of recyclables producing 1700 Mg of residual to landfill and 15,000 Mg of recyclables to remanufacturing, thereby achieving the 25% diversion target. A new MRF (MRF_N) is built rather than expanding the existing MRF (MRF_E) because in the example system expansions are twice as costly per unit capacity than a new facility, so expanding MRF_E by 10,000 Mg/yr and building a 20,000 Mg/yr MRF_N would cost the same, but MRF_N has lower operating cost and higher separation efficiency. The value of systematic consideration between using older, less efficient technology versus building new, higher efficiency processes further illustrates the utility of this framework. MRF_N is built to a capacity of 20,000 Mg/yr because that is the minimum allowable capacity of MRF_N (enforced by Eq. 43 and Eq. 44). In the third stage, the 50% diversion target cannot be met solely by recycling despite recyclables constituting 60% of the generated waste. This is due to the 60% collection efficiency in recyclable collection (implemented in Eq. 5), as well as the 90% separation efficiency of MRF_N (enforced by Eq. 10); so in the third stage a 40,000 Mg/yr WTE facility is built to achieve the 50% diversion target, while the rest of the waste is landfilled. The combination of Eq. 37 and Eq. 49 ensures that the cost of building the WTE facility every 20 years indefinitely is included in the net present cost. The significant system changes found in each stage of the Diversion scenario further illustrate the insights that can only be gained from a multi-stage LCA framework.

In the GHG scenario, the maximum possible mass of recyclables was processed through MRF_N in each stage leading to the least GHG emissions. Interestingly, although the GHG scenario had a budget limit of $73 million; the model found that the absolute minimum GHG solution costs only $64 million. To achieve the maximum amount of recycling, a 22,000 Mg/yr MRF_N was built in the first stage, and expanded to 27,000 Mg/yr in the second stage. For the expansion, Eq. 30 and Eq. 31 combine to ensure that the 22,000 Mg/yr of capacity that existed in the first stage is considered replaced, so that only the additional capacity is paid for (as described by Eq. 51). This allows the entire 27,000 Mg/yr of expanded capacity to be included as repeated capacity (in Eq. 49).

The results from these relatively simple scenarios show that the model functions correctly. It also shows the utility of a multi-stage generalizable framework. One could easily envision more complicated scenarios including multiple policy targets that could be readily implemented in this framework.

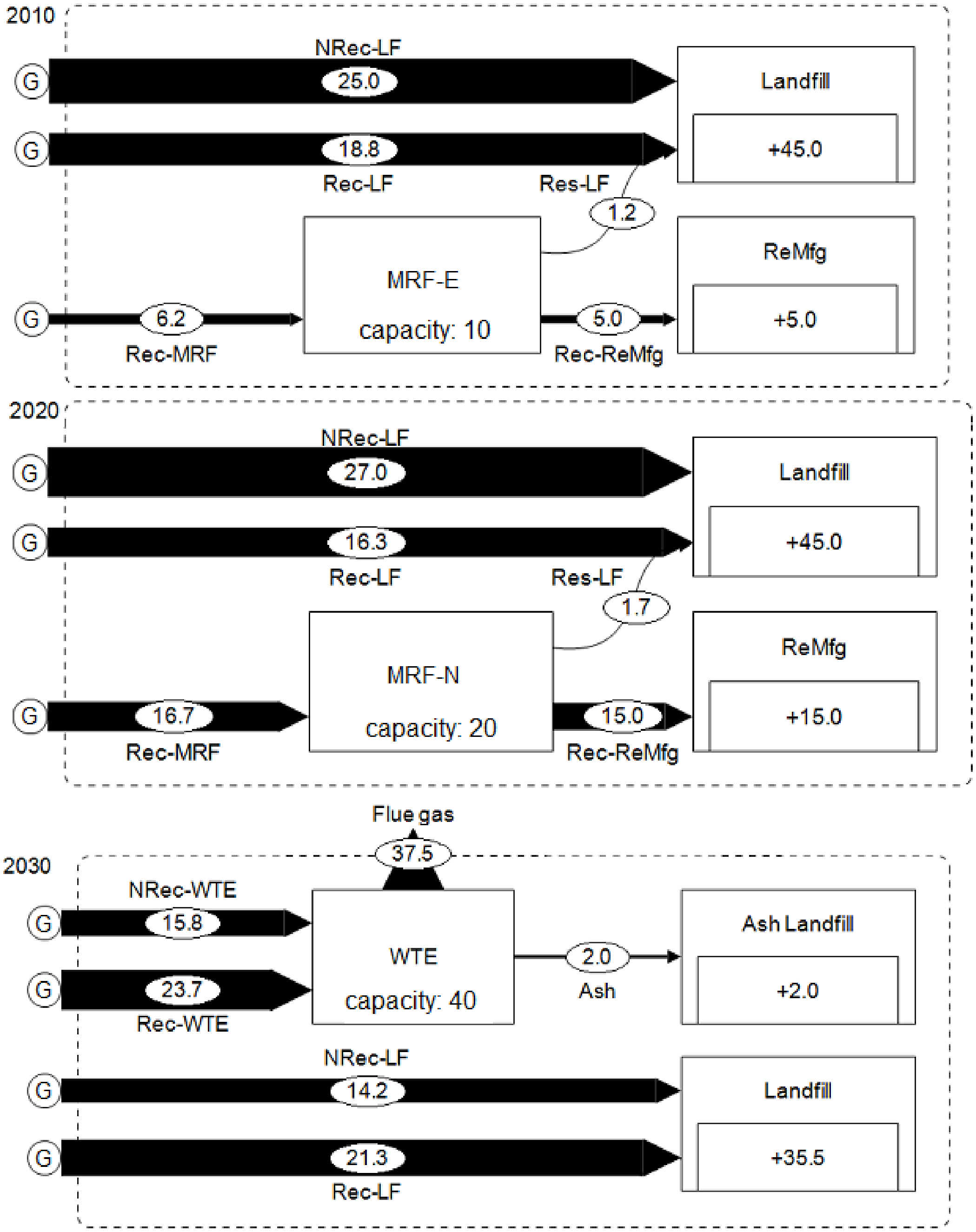

Figure 2-6. Material flow diagrams for each stage of the Diversion scenario. The numbers represent mass in 1000 Mg/yr. Recycling is performed using the 10,000 Mg/yr MRF_E in the first stage and a new 20,000 Mg/yr MRF_N in the second stage before a 40,000 Mg/yr WTE facility is built to meet the final 50% diversion target. G – waste generation, NRec-LF – Flow of NRec to the LF, Rec-LF – Flow of Rec to the LF, Rec-MRF – Flow of Rec to the MRF, Res-LF – Flow of MRF residual to LF, Rec-ReMfg – Flow of Rec to ReMfg, NRec-WTE – Flow of NRec to WTE, and Rec-WTE – Flow of Rec to WTE.

2.5.2 *Computational performance*

The illustrative scenarios were implemented in the GNU Mathematical Programing Language (GMPL) and solved using both the GNU Linear Programming Kit (GLPK) as well as CPLEX's mixed integer linear solver. The illustrative scenarios were solved on a 64-bit Windows 7 machine with an Intel Core i7-620M dual-core processor (2.67 GHz with 4 MB cache) and 8 GB of RAM. The illustrative scenarios each had approximately 600 constraints, 500 continuous variables, and 34 binary variables. The solve time for each illustrative scenario was under one second for both solvers. A larger, more representative system was also implemented and solved to ensure that this framework is scalable. The larger system added a mixed waste MRF, anaerobic digester, and composting treatment processes as well as a mixed organics collection process. The larger system was run for six, 5-year time stages, and included 30 waste materials. The optimization model for the larger system had approximately 55,000 constraints, 60,000 continuous variables, and 145 binary variables. The solve times (using the aforementioned solvers) for the larger system under similar scenario assumptions are shown in Table 2-5. The results show that the diversion and GHG scenarios take significantly more computation time to solve, and that CPLEX offers significant computation benefits over GLPK. The GLPK results should be seen as a worst-case estimate since it includes minimal pre-solve, has not been configured for multi-threading, and the algorithmic parameters have not been tuned to minimize the solve time. The results show that the model is generalizable and scalable, and that it still solves in reasonable time using typical hardware and readily available solvers, even for larger and more representative SWM systems.

Table 2-5. Solve times for a representative system using typical laptop hardware with CPLEX and GLPK solvers.

Scenario	CPLEX	GLPK
Base	0:00:04	0:00:54
Diversion	0:04:18	25:48:42
GHG	0:08:11	4:15:13

2.5.3 Implications, conclusions, and future work

As the illustrative results show, application of this new model framework, SWOLF, can produce useful insights that are relevant to policy formulation and the response of SWM systems to future policies. The framework is generalizable to include numerous SWM treatment facilities and collection options, and solves in a reasonable amount of time using readily available hardware and software. The framework can be used to quantify SWM-related GHG abatement costs that could be compared to abatement costs in other industries and activities to better allocate spending for GHG mitigation. The framework can also incorporate economies of scale through the use of multiple instances of the same process type. For example, instead of a single MRF, users could define a small, medium, and large MRF, each having its own minimum build capacity as well as economic and environmental performance.

LCA of SWM requires the coupling of detailed bottom-up unit process models in an integrated modeling framework aimed at achieving strategic SWM objectives. Work is underway to finalize SWM LCA process models for anaerobic digestion, collection, composting, gasification, landfills, material recovery facilities, refuse derived fuel production, transfer stations, and WTE that include over 40 airborne and waterborne emissions categories and several environmental impact categories as well as capital and operating costs. Coupling these finalized LCA models to the framework presented here will allow researchers and SWM decision-makers to explore the various environmental and economic trade-offs associated with SWM policies and technologies using readily available hardware and software. Additional work that uses these process models to analyze larger, more representative systems that incorporate projections of potential future energy scenarios is also underway. Once completed, the integrated modeling framework could be used to perform case studies for interested SWM decision-makers. This generalizable and scalable stage-wise LCA-based modeling framework represents a significant advancement in integrated SWM decision-making.

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3 USE OF THE SOLID WASTE OPTIMIZATION LIFE-CYCLE FRAMEWORK TO MINIMIZE FUTURE COST AND ENVIRONMENTAL IMPACTS FROM SOLID WASTE MANAGEMENT

3.1 Introduction

Solid waste management (SWM) systems must proactively adapt to changing waste composition, policy requirements, and an evolving energy system to cost-effectively and sustainably manage future solid waste. Policy makers have taken an increasing interest in reducing environmental impacts associated with SWM; to this end, many U.S. states and cities have instituted ambitious landfill diversion goals. For example, both California and Florida have recently set goals of 75% diversion by 2020 (California, 2012 and Florida, 2010), while cities such as San Francisco, Oakland, and Seattle have set “zero waste” goals with the intent of eliminating landfill disposal (SF, 2013; Oakland, 2013; Seattle, 2013). In the future, GHG mitigation policies that affect the U.S. energy mix as well as the cost of energy and emissions could significantly impact the cost and strategic direction of SWM. For example, a carbon tax or cap-and-trade program could increase both the cost of fuel for waste collection and the value of energy generated from SWM processes (e.g., landfill-gas-to-energy, waste-to-energy combustion, or anaerobic digestion). In addition to critically examining the efficacy of waste diversion and GHG policies for decreasing environmental impacts, solid waste managers must consider the implication of future policy requirements when designing SWM infrastructure that is typically in operation for decades.

In addition to the influence of solid waste policy targets and an evolving energy system on SWM decision making, systemic changes to waste generation and composition could have significant impacts. For example, 2010 per capita paper generation decreased to 120 kg per person from 180 kg per person in 2000 and now represents 20% of generated municipal solid waste (MSW) compared to 30% in 2000. In contrast, per capita food and yard waste generation increased, and these wastes require different diversion technologies than paper.

This changing waste generation will affect the cost and effectiveness of diversion programs as well as the life-cycle emissions from SWM treatment processes.

Optimizable decision frameworks have been used to develop waste management strategies that reduce cost and environmental impacts by systematically searching potential technology choices and mass flows to identify optimal SWM strategies (e.g., Kaplan, et al., 2009; Huang, et al., 1997; Chang et al., 1996); however, these static analyses do not have the capability to consider changes to the SWM and energy systems over time; a dynamic, multistage model is necessary to consider these changes.

The <u>S</u>olid <u>W</u>aste <u>O</u>ptimization <u>L</u>ife-cycle <u>F</u>ramework (SWOLF) is an optimizable dynamic life-cycle assessment (LCA) framework for integrated SWM (Levis et al., 2013). SWOLF couples a detailed set of life-cycle process models with a multi-stage optimization model that is used to minimize cost or environmental impacts from a user-defined SWM system over time. This study represents the first application of SWOLF, which is used to draw generalizable insights into future SWM by analyzing the SWM system of a hypothetical, but realistic, suburban U.S. city over the next 30 years. The optimization framework, SWM system, and scenario analysis are described in the Modeling Framework. This is followed by presentation and discussion of the results from the scenarios.

3.2 Problem Description and Modeling Approach

The foundation of this study is a stage-wise optimized LCA of the SWM system for a hypothetical suburban U.S. city. The functional unit is the total mass of mixed MSW set out at the curb in the city over a 30-year decision horizon. The functional unit does not include items reused or treated by the waste generator (e.g., clothing used as rags, food waste treated in a garbage disposal, onsite composting). The decision criteria considered in this analysis are cost, landfill diversion, and GHG emissions. When calculating diversion, waste combusted in the waste-to-energy (WTE) facility is included, but landfilled ash is not. Planning decisions were made in six, 5-year increments beginning in 2010 and ending in 2039.

3.2.1 Representative Solid Waste Management System

The model city has a population of 100,000 in 2010 and is assumed to grow at the national average rate for the 30-year decision horizon. The population in each time period was used to estimate waste generation and composition. The U.S. average per capita waste generation for 30 materials was determined for 2000 and 2010 based on U.S. EPA data (U.S. EPA 2002 and U.S. EPA 2011). The annual percent change between the 2000 and 2010 per capita generation of each material was then calculated, and the per capita generation in each time period was estimated by extrapolating that growth rate. Figure 3-1 shows the mass generated for broad waste categories in each stage, while Table B-1 shows the mass generated and composition for each individual waste material in each stage. The material properties for each waste material are shown in Table B-2.

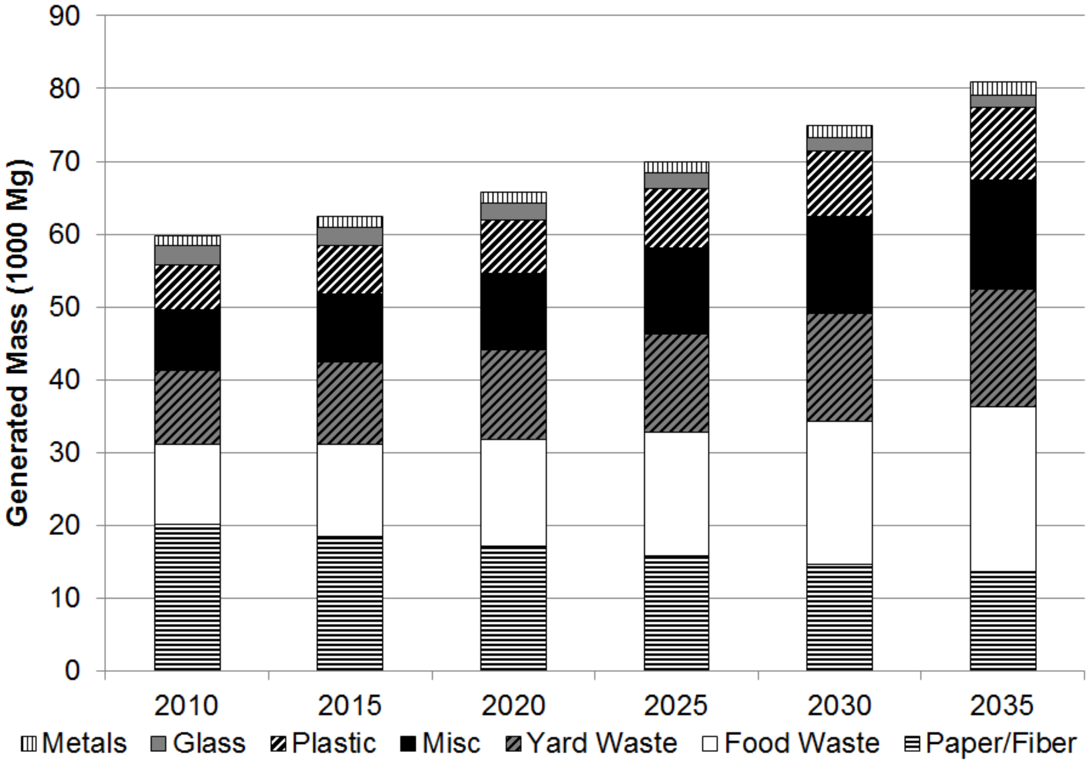

Figure 3-1. Mass of waste generated by waste category in each stage. Waste composition by specific waste materials is provided in Table B-1. Paper/ Fiber generation decreases by 32%, while food waste generation increases by 108%, which indicates that different treatment processes may be better suited to meet future SWM needs.

Waste generated in the city originates in one of three sectors: (1) single family, (2) multifamily, or (3) commercial. The proportion of each waste material generated in each sector was estimated as described in Table B-3 and was held constant throughout the time horizon. The collection separation efficiencies for mixed organics collection and commingled recyclable collection are presented in Tables B-4 and B-5, respectively, and are based on U.S. EPA (2011) data.

Figure 3-2 shows the modeled collection options, treatment processes, and mass flows for the system. All waste materials can be collected by mixed and residual waste collection, but only designated materials (Table B-1) can be collected by single stream recycling or mixed organics collection (i.e., recyclables and food and yard wastes, respectively). Food and yard waste may be treated by composting or anaerobic digestion (AD). Non-vegetable food waste cannot be composted due to the risk of disease vector attraction. The optimization model determines which materials are actually collected via the separate collection processes. Two types of material recovery facilities (MRFs) are considered, a single stream MRF (SSMRF) that receives commingled recyclables, and a mixed waste MRF (MWMRF). In the treatment system, both of the MRFs separate specific materials that can then either be recycled or treated by WTE combustion (e.g., to consider whether the benefits of combusting separated paper to produce low carbon renewable electricity are greater than benefits associated with recycling the paper). The MRF separation efficiencies, build and expansion parameters, GHG emission coefficients, and operating costs are shown in Tables B-6 to B-11.

A life-cycle model for each process shown in Figure 3-2 estimates cost and emissions as a function of the mass and composition of the influent waste. The WTE process model is an updated version of that described by Harrison et al. (2000) and reflects current WTE emissions data. The WTE build and expansion parameters, ash separation efficiencies, operating costs, and GHG emission coefficients are shown in Tables B-12 to B-15. AD and composting process models as well as landfill gas modeling and fuel use have been described previously (Levis and Barlaz, 2011a and 2011b). The AD build and expansion parameters, GHG emission coefficients, and operating costs are shown in Tables B-16 to B-18, and the composting build and expansion parameters, GHG emission coefficients, and operating costs are shown in Tables B-19 to B-21. The landfill is assumed to generate electricity from the collected methane using an internal combustion engine, which is the most environmentally beneficial management alternative as about 35% of generated landfill gas is used beneficially in the U.S. (Levis and Barlaz, 2011a). The landfill GHG emission coefficients and operating costs are shown in Tables B-22 and B-23, respectively. Revenue from recyclables sale is based on discussions with MRF operators, and the life-cycle offsets associated with material recovery were developed from published data (RTI , 2003). The remanufacturing GHG emission coefficients and operating costs (i.e., negative revenue) are shown in Tables B-24 and B-25, respectively. Collection fuel use and cost are based on data from the Cary, NC Public Works Department.

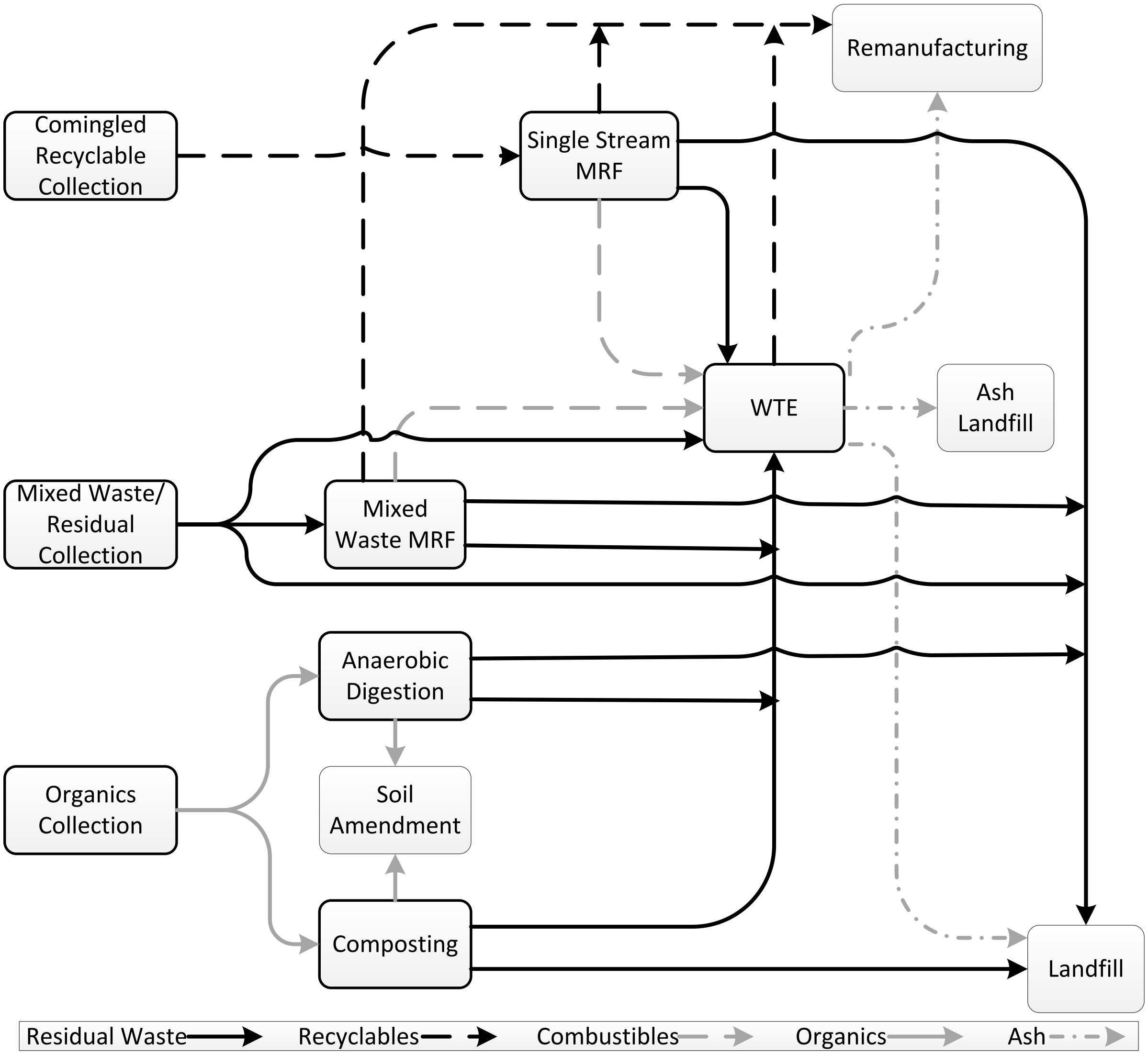

Figure 3-2. Waste management system potential mass flow diagram. Mixed waste collection collects all of the generated waste, while residual collection collects the remaining waste after recyclable and organics collection. Separated material from the MRFs can either be recycled or treated by WTE combustion. Bottom ash can be recycled as aggregate in concrete, and the aluminum and ferrous in the bottom ash can be separated and recycled. The distinction between bottom and fly ash has been removed for simplicity.

3.2.2 *Optimization Modeling*

The stage-wise optimization framework described by Levis et al. (2013) was used for this analysis. In each time stage, the optimization model determines whether to build, expand, or decommission capacity for the modeled SWM processes, and determines the mass of each material collected and treated in each process. The process models include capital costs associated with building and expanding processes, as well as operational costs and emissions associated with collecting and treating material through each process. If capacity is built or expanded, it must be above a user-specified minimum build capacity for that process (Tables B-27, B-12, B-16, and B-19). The SWM processes that exist in the final stage are assumed to be repeated indefinitely to meet the continuing service demand.

Changes to the energy system are modeled by varying fuel prices, electricity prices, electricity generation mix, and transportation fuel efficiency in five year increments. Projections for these values were adapted from the 2012 Annual Energy Outlook reference scenario (U.S. EIA, 2012), and are shown in Figure 3-3.

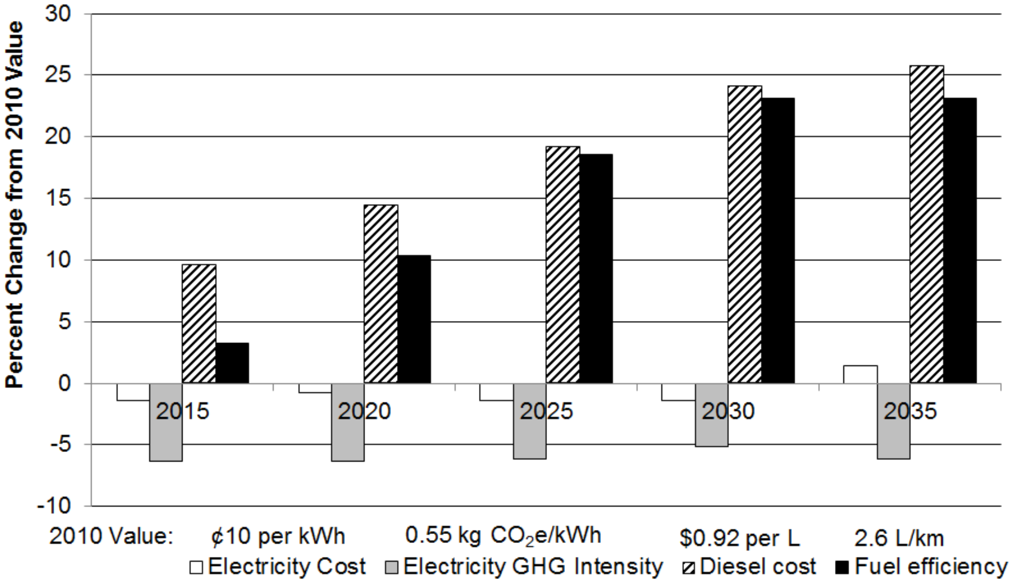

Figure 3-3. Percent change in electricity cost, electricity GHG intensity, diesel cost, and heavy-duty truck fuel efficiency based on U.S. EIA AEO 2012 reference scenario projections. Sale price of electricity is assumed to be half of cost. Prices and costs are in nominal U.S. dollars. Electricity mix and GHG emissions for generation technologies are shown in Table B-25.

3.2.3 Solid Waste Management Scenarios

The existing SWM system in 2010 is assumed to have a 6,000 Mg yr^{-1} (1 Mg = 1000 kg) yard waste composting (YWC) facility (that can also accept food waste) with 20 years of remaining life, and a 12,000 Mg yr^{-1} SSMRF that receives commingled recyclables with 20 years of remaining life. Residual waste is collected and sent to a landfill, as is the residual from the SSMRF and composting facility. The existing landfill is assumed to have enough capacity to accept all of the waste generated during the time horizon. Including this existing infrastructure is important because most cities and counties already have SWM infrastructure or programs in place and the relatively low marginal costs of operating existing facilities relative to building new facilities can affect investment decisions. The use of SSMRF and YWC were assumed because this is typical in many suburban areas; the U.S. EPA estimates that 71% of the U.S. population is served by curbside recyclables collection that requires a MRF, and that there are approximately 3000 YWC facilities in the U.S. that treat nearly 60% of the generated yard waste (U.S. EPA 2011). For future scenarios, the model considers the use of the other treatment processes shown in Figure 3-2 in addition to the existing YWC and SSMRF.

A “business-as-usual” (BAU) baseline scenario was analyzed in which cost is minimized while the system is required to use the existing SSMRF and YWC in every stage and new processes are not considered. Three additional scenarios were investigated and compared to the BAU scenario: (1) minimize cost with no additional targets, called “Min Cost”; (2) Maximize 30-year landfill diversion, called “Max Diversion”; and (3) minimize 30-year GHG emissions, called “Min GHG”.

The optimization model for each scenario consisted of approximately 100,000 continuous variables, 160 binary variables, and 100,000 constraints. The model was implemented in the GNU Mathematical Programing Language (GMPL) and solved using CPLEX’s mixed integer linear solver (GNU, 2012; CPLEX, 2013). The three comparison scenarios solved in 5-50 minutes on a 64-bit Windows 7 machine with an Intel Core i7-620M dual-core processor (2.67 GHz with 4 MB cache) and 8 GB of RAM.

3.3 Results and Discussion

3.3.1 Mass Flows, Costs, and GHG Emissions

Figure 3-4 shows the net present cost (in 2010 U. S. dollars), 30-year cumulative GHG emissions, and 30-year cumulative diversion percent (i.e., the total mass diverted divided by the total mass generated over the 30-year time horizon) for each scenario. Figure 3-5 shows the total incoming mass into each process in each stage, while Figure 3-6 shows the GHG emissions associated with each process in each stage. In the BAU scenario, recyclables are processed in the SSMRF and yard wastes are composted in every stage. The Min Cost scenario saves \$3.2 million (4%) over the BAU scenario, while reducing GHG emissions by an additional 67,000 $MTCO_2e$ (22%). This cost and GHG emission reduction is due to the substitution of a landfill for composting yard wastes, with the subsequent increased carbon storage of leaves and branches in the landfill. This is an example where increasing diversion increases GHG emissions. The Min GHG scenario costs approximately 19% less than the Max Diversion scenario, and reduces GHG emissions by an additional 550,000 $MTCO_2e$ (230%).

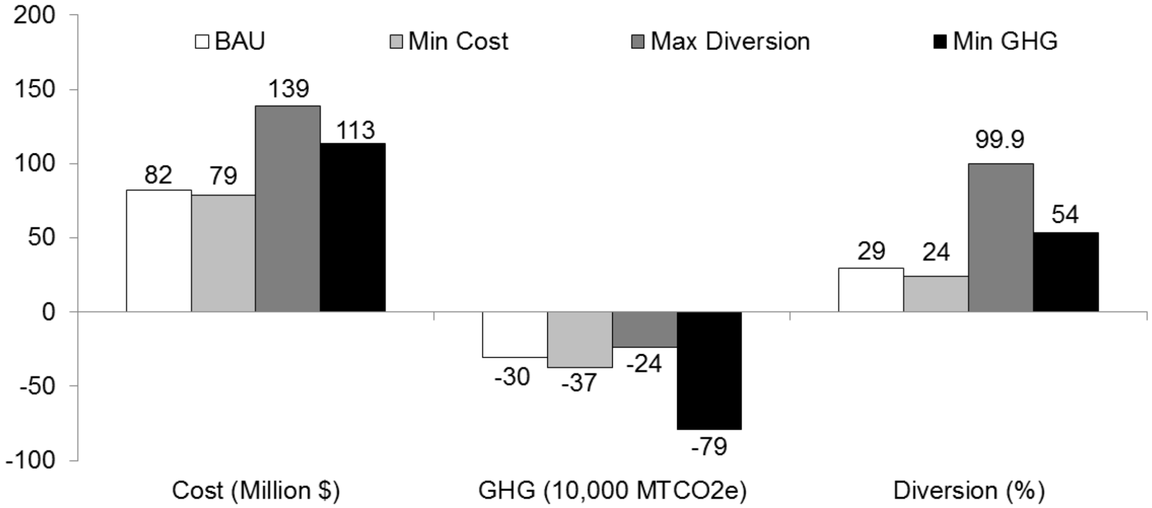

Figure 3-4. Net present cost (2010 U.S. Dollars), 30-year cumulative GHG emissions, and cumulative 30-year diversion for each of the base scenarios. Negative GHG emissions are due to electricity generation offsets (AD, landfill, WTE), material recovery offsets, and carbon storage (AD, composting, landfill).

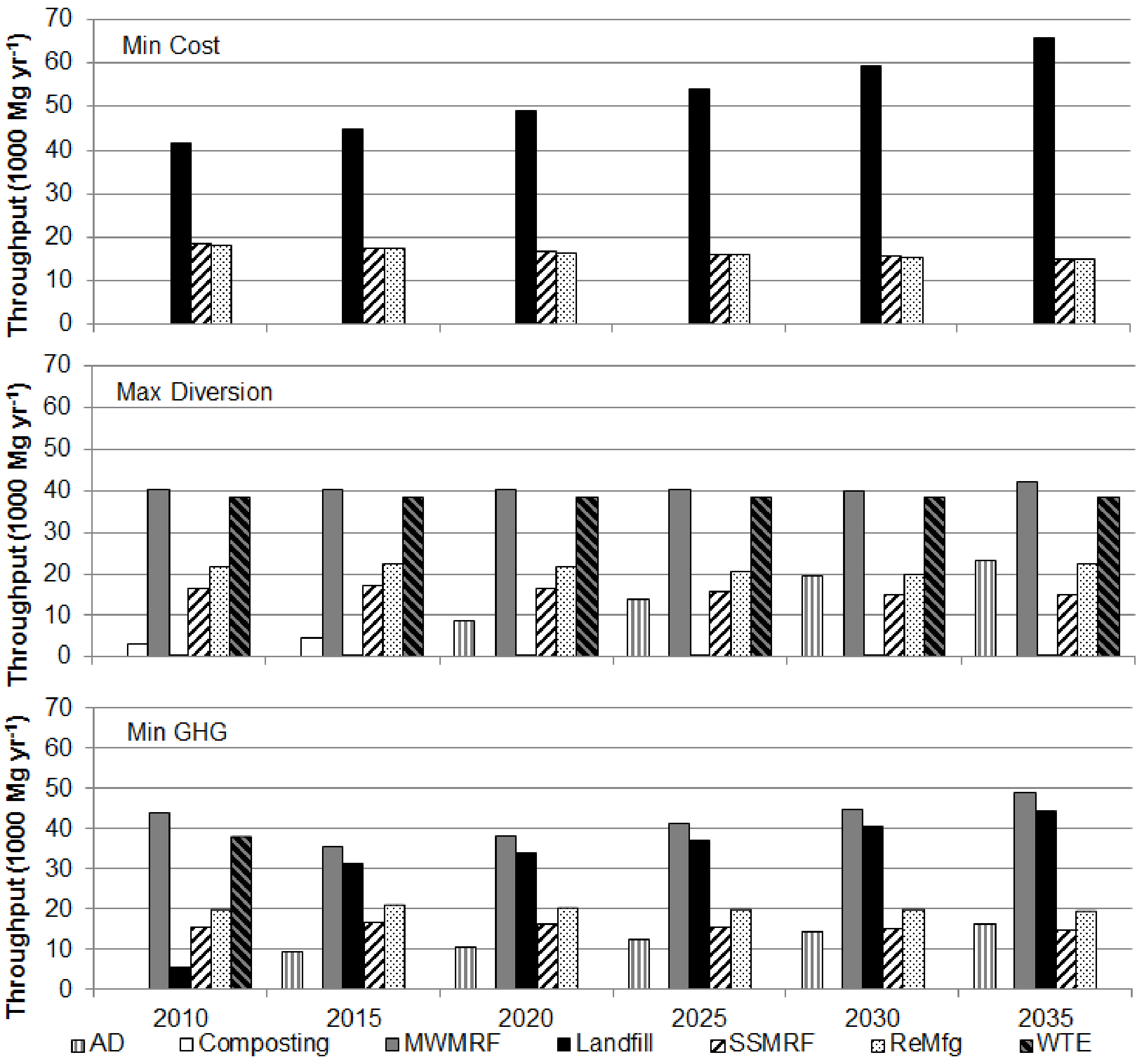

Figure 3-5. The total mass of material entering each process in each stage for the Min Cost, Max Diversion, and Min GHG scenarios. A landfill and SSMRF are used in all scenarios, and the Max Diversion and Min GHG scenarios both additionally use AD, composting, MWMRF, and WTE.

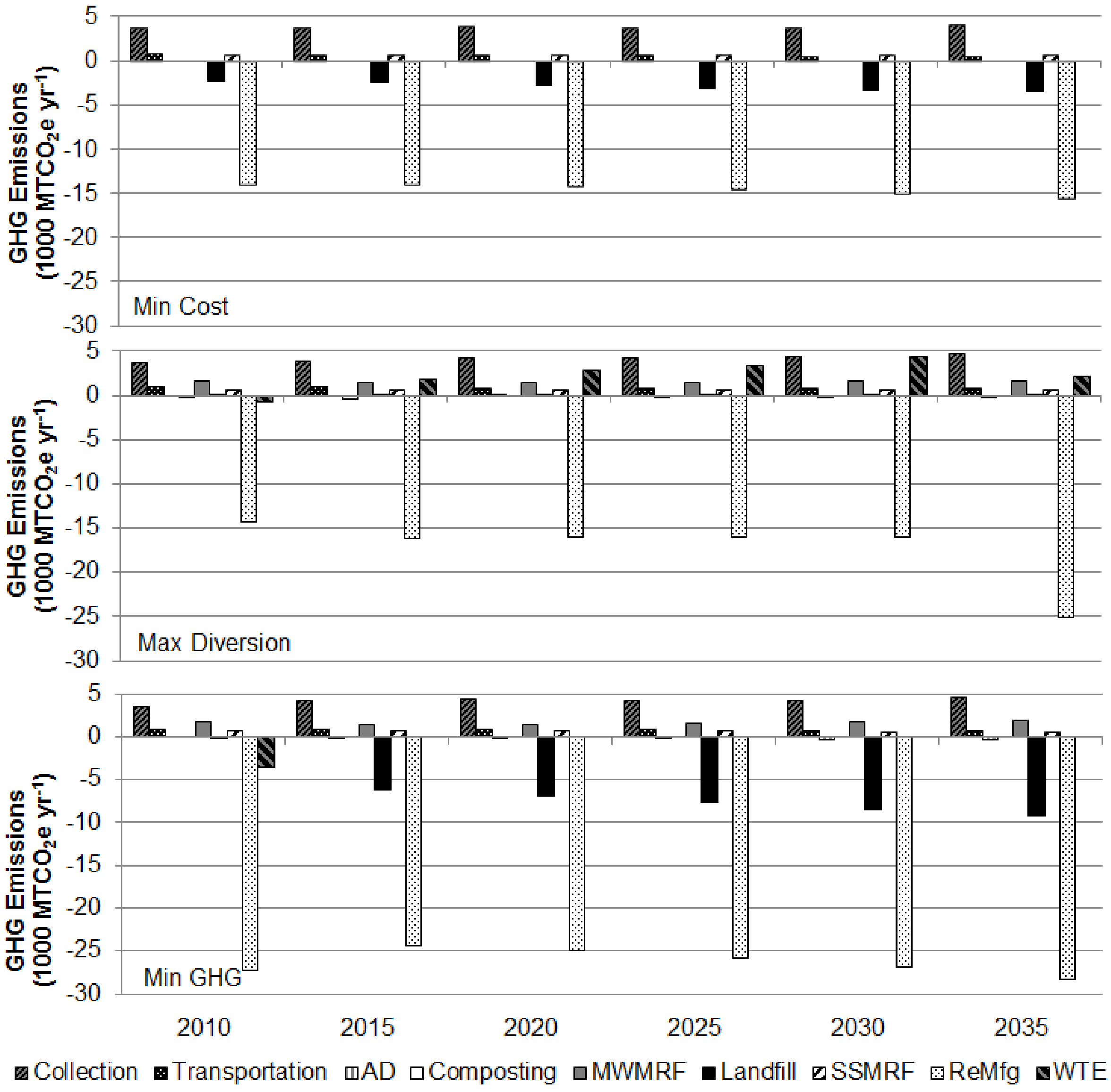

Figure 3-6. The annual GHG emissions from each process in each stage for the Min Cost, Max Diversion, and Min GHG scenarios. Transportation represents any transport of materials after initial curbside collection. Collection is the greatest net generator of GHG emissions in all scenarios, and remanufacturing is the greatest GHG sink in all scenarios. The Min GHG scenario has greater remanufacturing benefits than the Max Diversion scenario because only materials with net GHG benefits are recycled in the former case.

In the Max Diversion scenario, recyclables are collected and separated in a SSMRF in all stages, while the residual waste is sent to a MWMRF where additional recyclables are recovered. Yard wastes are composted in the first two stages, while AD is utilized for food and yard waste treatment from 2020 onwards with increasing throughput to manage the increasing generation of food waste. The residuals from both MRFs and organics treatment (i.e., composting and AD) are combusted in a WTE facility, and the ferrous, aluminum, and bottom ash are recovered, while the fly ash is landfilled. In the Max Diversion scenario every material is beneficially recovered to the extent possible as defined by the separation efficiencies in Tables B-4 to B-6, and the residuals are then combusted for energy, with the post-combustion metals and bottom ash also being recycled (Table B-13). The only material entering a landfill is the fly ash remaining from the combustion of MRF and organic treatment residuals.

In the first stage of the Min GHG scenario, recyclables are collected separately and recovered in an SSMRF, while residual waste from the SSMRF is sent to WTE. After the first stage, organic wastes are separately collected and anaerobically digested. The AD throughput increases throughout the time horizon as increasing amounts of food and yard wastes are generated. In each stage, the residual from AD is sent to a landfill or WTE. Residual waste at the curb is collected and sent to a MWMRF, and the residual from the MWMRF is split between the landfill and WTE (to meet the WTE minimum throughput). The WTE facility is used only in the first stage because there is more paper and less plastic than in the following stages (Figure 3-1). Plastics combustion results in fossil CO_2 emissions and as the GHG intensity decreased from 2010 to 2015 by approximately 6% (Fig. 3-3), the benefits of WTE decrease. Waste is then increasingly landfilled, which achieves carbon storage and electricity offset benefits. The interrelated factors driving the use of WTE illustrate the need for comprehensive analyses to support SWM decision making. The major difference in mass flows between the Min GHG and Max Diversion scenarios is the lack of WTE in the Min GHG scenario after the first stage. The use of WTE in the Max Diversion case leads to a significant GHG penalty as the generated mass of plastic increases. The Min GHG scenario additionally reduces emissions compared to the Max Diversion scenario by landfilling third class mail and magazines instead of recycling these materials. The emissions associated with the assumed 400 km transportation of bottom ash to remanufacturing in the Max Diversion case are greater than the emissions associated with landfilling the bottom ash.

In this model, bottom ash was assumed to be beneficially used in concrete with no net emissions or cost savings.

The process-specific GHG emissions in Figure 3-6 show that waste collection is the primary net source of GHG emissions in every scenario, while remanufacturing and landfilling offer the greatest net GHG reductions. In the Max Diversion and Min GHG scenarios, the results also show that WTE is a net reducer of GHG emissions in the first stage, but is a net generator in all of the subsequent stages. This is partially because as waste composition changes, the cost and GHG emission profiles of technologies also change. The operating costs associated with sending the as-generated mixed waste to WTE decrease by 11% from 2010 to 2035 because of the increase in plastic waste that is the most energetic fuel in WTE (Tables B-1 and B-15). The GHG benefits associated with WTE simultaneously decrease by 68% due to composition changes throughout the time horizon and from the use of cleaner fuels in the broader electricity mix from 2015 onward (Table B-14). There are similar changes to the effectiveness of other processes that can only be evaluated through the use of a dynamic multistage framework in which waste composition and the energy mix changes with time.

3.3.2 GHG Mitigation Costs

Figure 3-7 shows the GHG mitigation costs (i.e., the cost per reduction in mass of CO_2e emitted) and annual GHG emissions reductions for the Min Cost and Min GHG scenarios compared to the BAU scenario (the Max Diversion GHG mitigation cost is not shown because it increases emissions compared to the BAU scenario). These mitigation costs would be less if compared to a landfill-only scenario, since the BAU case already includes recycling and YWC. The Min Cost scenario reduces GHG emissions by 22% and reduces cost by 4% compared to the BAU scenario, so it has negative mitigation costs, but it also leads to a lower reduction in GHG emissions relative to the Min GHG scenario. The use of a SSMRF instead of landfilling, which occurs in all of the scenarios, also has negative mitigation cost because it earns revenue and reduces GHG emissions.

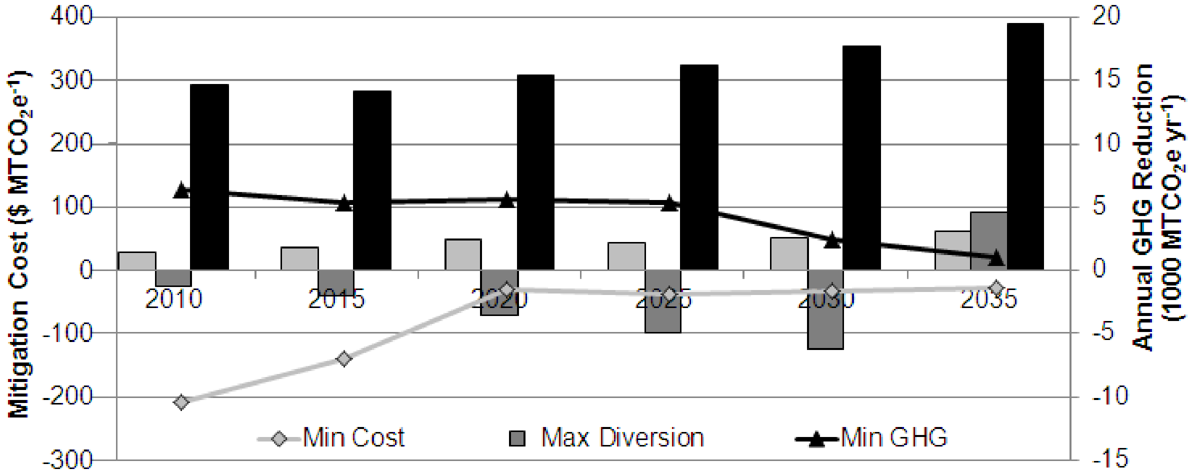

Figure 3-7. Annual GHG mitigation cost and GHG reduction for Min Cost, Max Diversion, and Min GHG scenarios compared to the business-as-usual (BAU) scenario. Negative mitigation costs indicate that there are cost savings associated with the GHG reductions. The bars represent GHG reductions while the lines represent mitigation costs. Only the GHG reductions are shown for the Max Diversion scenario because it increases GHG emissions relative to the BAU scenario. Costs are in nominal 2010 U.S. dollars.

3.3.3 Cost, Diversion, and GHG Emission Trade-offs

Figure 3-8 shows the trade-off between net present cost and diversion as well as between cost and GHG emissions. Line 1 shows the maximum diversion and Line 3 shows the associated GHG emissions that can be achieved at a specified system cost. Line 4 shows the minimum GHG emissions and Line 2 the associated diversion, also at a specified cost. The trade-offs show that for maximally cost-effective systems, minimizing GHG emissions (at a specified cost) increases diversion (Lines 2 and 4), but that maximizing diversion (at a specified cost) often increases GHG emissions (Lines 1 and 3). Most of the additional cost above the Min Cost scenario in both the Max Diversion and Min GHG tradeoff analyses are due to achieving the final increments of diversion and GHG reductions. For example, 85% diversion can be achieved for less than a 25% increase in cost, but maximum diversion of 99.9% increases cost over the Min Cost scenario by 75% (Line 1). Similarly GHG emissions can be reduced by over 700,000 MTCO$_2$e for less than a 10% increase in cost, but the next 80,000 MTCO$_2$e reduction increases costs by 44% (Line 4).

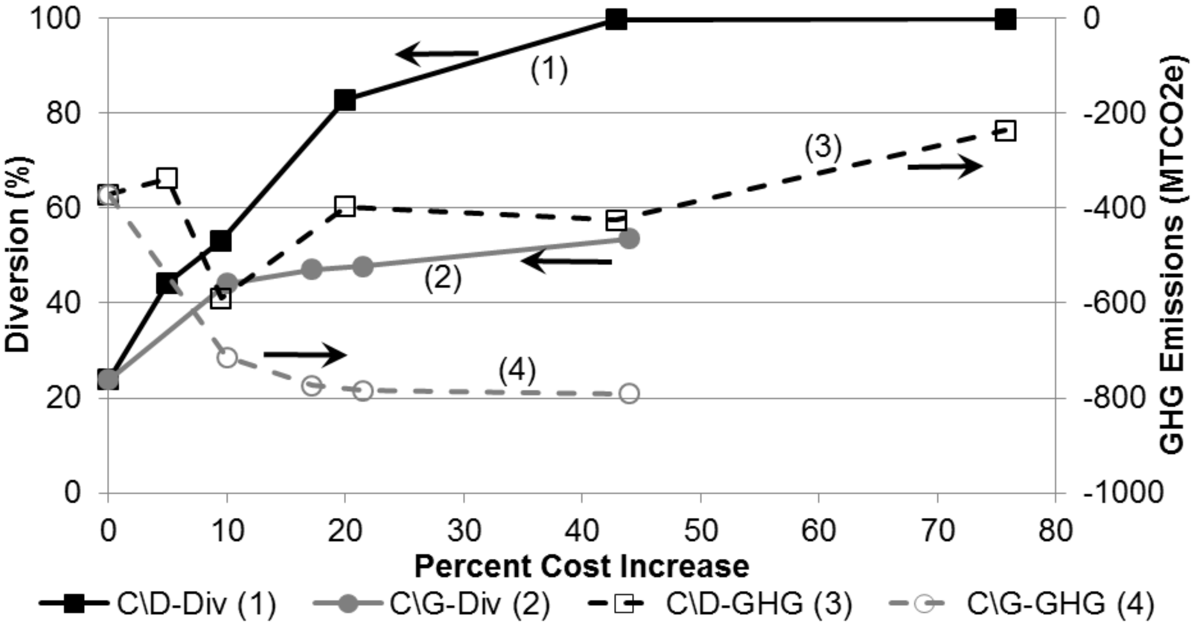

Figure 3-8. Trade-offs for cost vs. 30 yr diversion (C\D) and cost vs. 30 yr GHG emissions (C\G). The C\D points represent the system achieving the maximum diversion for the specified cost, and the C\G points represent the system achieving minimum GHG emissions at the specified cost. Cost is in 2010 U.S. dollars. (Div: Diversion, GHG: Greenhouse gas emissions).

The results show numerous ways to cost-effectively reduce GHG emissions and increase material recovery. Every included process was implemented in at least one of the scenarios, which shows that they all have value in meeting cost, diversion, or GHG targets. The first technology implemented to reduce GHG emissions is recycling in a SSMRF, which is implemented in every scenario because it earns net revenue while reducing GHG emissions and increasing diversion. Figure 3-9 shows the mass throughput and GHG emissions for each process and stage of the trade-off scenario where GHG emissions were minimized with a cost 10% greater than the Min Cost scenario, which cost $79 million. The model found solutions that reduced GHG emissions by an additional 340,000 MTCO$_2$e while only increasing costs by 10% by incrementally phasing in the use of the MWMRF and composting. Staged implementation of technologies as well as technology switching due to changes in waste generation, waste composition, and the energy systems are only possible through the use of dynamic multistage analyses.

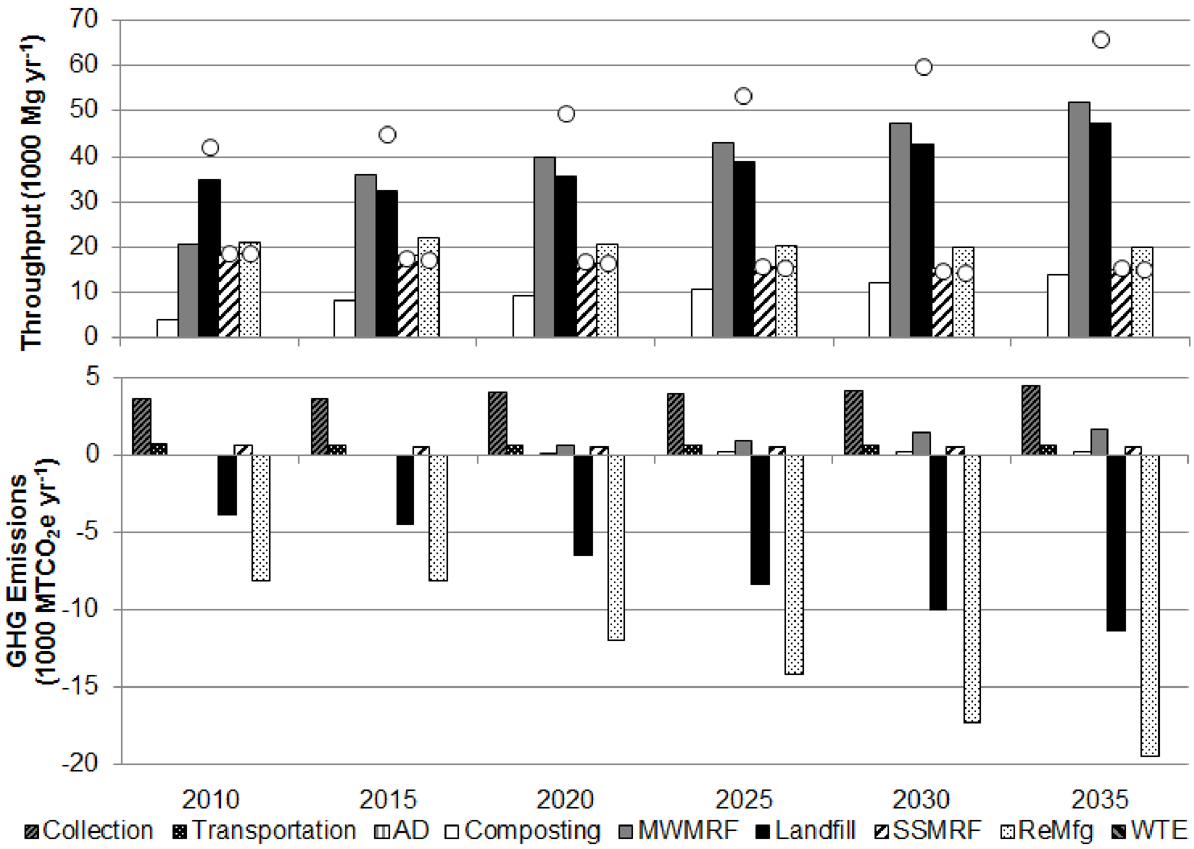

Figure 3-9. Mass throughputs and GHG emissions from each process in each stage of the trade-off scenario that minimized GHG emissions with a cost 10% greater than the Min Cost scenario. White circles show corresponding non-zero throughputs for Min Cost scenario. Net present cost was $87 million, 30 yr GHG emissions were -710,000 $MTCO_2e$, and the 30 yr diversion rate was 44%.

3.3.4 Discussion

Nearly 50% of American households are located in suburbs, so the insights from this analysis are applicable to numerous waste management decision-makers, though specific case studies of individual systems that incorporate location-specific parameters and constraints may result in different or additional recommendations. The results of this analysis show the utility of stage-wise life-cycle optimization for integrated SWM. The Min Cost scenario was able to reduce GHG emissions while saving money over the BAU scenario by eliminating YWC. This result and those in the trade-off analysis show that GHG emissions often increase with increased diversion. The results also showed that the relative GHG benefits of WTE are dependent on waste composition and electricity GHG intensity. While WTE may reduce GHG emissions based on current waste composition, this could change if the waste stream becomes enriched with plastics in place of paper. Analyses that consider changes to waste composition over time require a stage-wise modeling framework. SWM strategies designed to increase diversion led to increases in GHG emissions in this study, so SWM decision makers should be aware of the actual environmental impacts they wish to reduce. Future analyses should consider how SWM could adapt to varying energy system projections (e.g., high natural gas use, high renewable energy implementation, or a price on GHG emissions). Additional examination of other environmental impacts (e.g., resource use, eutrophication, and toxicity) could identify critical tradeoffs that can inform future plans for sustainable integrated SWM systems.

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4 OPTIMAL SOLID WASTE MANAGEMENT STRATEGIES FOR PROACTIVELY ADAPTING TO SOLID WASTE MANAGEMENT, ENERGY, AND CLIMATE POLICIES

4.1 Introduction

The future of sustainable solid waste management (SWM) will be shaped by greenhouse gas (GHG) policy and changes to the broader energy system. Over the last decade, the U.S. energy system has changed rapidly, and will likely continue to do so in the coming decades. For example, between 2001 and 2011 electricity generation from natural gas and renewables increased by 68% and 91%, respectively, while coal use has decreased by 9% and now satisfies 44% of the total U.S. electrical energy demand (U.S. EIA, 2012a). This changing electricity mix affects the cost and emissions associated with electricity use as well as the life-cycle benefits (i.e., avoided emissions) of energy recovery at landfills, waste-to-energy (WTE) combustion facilities, and anaerobic digestion (AD) plants.

Future changes to the energy system will be driven by technology, economics and environmental policy. As of April 2013, 37 states and the District of Columbia had renewable portfolio standards (RPSs) or goals, which require a specified percentage (10-40%) of electricity in those jurisdictions to be generated from renewable sources (U.S. DOE, 2013). GHG mitigation policies such as carbon taxes or cap-and-trade could place additional constraints on the future energy system. The state of California, representing 12% of the U.S. population, began a statewide cap-and-trade program in 2013 as part of their effort to reduce GHG emissions to 1990 levels by 2020. That represents a reduction of 174 million $MTCO_2e$ from business-as-usual projections, and the state plans to reduce GHG emissions from SWM by over 10 million $MTCO_2e$ (5.7% of the total statewide reduction) to meet that target (California ARB, 2008). Additionally, nine Northeastern states, representing 13% of the U.S. population, are members of the Regional Greenhouse Gas Initiative (RGGI), which is a cap-and-trade program for electric utilities with the goal of reducing GHG emissions from the electricity sector by 53% by 2020 compared to the 2009 baseline (RGGI, 2012).

Changes in the transportation sector could have additional impacts on SWM. Fuel efficiency for diesel powered medium and heavy duty trucks is expected to increase by 20% and 27%, respectively, by 2039 (U.S. EIA 2012b). Collection and transport of waste are currently the largest contributors to cost and fossil energy use in most SWM systems (Kaplan et al., 2009a). Many waste management companies have begun to switch to hybrid and natural gas vehicles to reduce fuel costs, which could significantly affect the costs and environmental impacts associated with SWM activities, since the most commonly used diversion technologies typically require additional collection and transport of separated waste fractions.

Several SWM processes include energy recovery, which makes it crucial to consider the broader energy system when analyzing SWM. WTE combustion facilities produce electricity through the direct combustion of solid waste, while biodegradable materials in landfills and AD facilities produce biogas that can be used to generate electricity or steam, or be processed into vehicle fuel. SWM diversion policies could provide additional incentives to recover energy from solid waste, and changing waste composition will impact beneficial energy generation from SWM activities (e.g., food waste and paper behave differently in AD and WTE). Given all these considerations, SWM planning models should consider how changes in the energy system and waste composition will affect future solid waste management. It is critical to analyze the interrelated effects of energy and GHG policy with SWM policies to ensure that they work together to cost-effectively reduce environmental impacts from SWM.

This study represents the first optimizable dynamic life-cycle assessment (LCA) to explore how potential changes to the energy system and GHG policy affect SWM. The Solid Waste Optimization Life-cycle Framework (SWOLF) (Chapter 2; Levis et al., 2013a) was combined with energy system modeling results (Babaee et al., 2013) to draw insights into how the energy system and GHG mitigation policies affect SWM by analyzing the SWM system of a hypothetical suburban U.S. city for 30 years into the future. Section 4.2 describes how the energy system and SWM policies were modeled. Sections 4.3 and 4.4, respectively, describe the SWM system and the scenarios and cases that were studied. Finally, Section 4.5 presents and discusses the results of the case study.

4.2 Policy Modeling

4.2.1 Energy System and GHG Policy

The future of the U.S. energy system and the fate of GHG policy are inherently uncertain due to technological changes, economics, and a changing political environment. For example, natural gas prices have dropped by two-thirds since 2008 due the increased use of hydraulic fracturing and the general economic downturn (U.S. EIA, 2012a); during this time there have been numerous national, regional, and state-wide discussions about implementing policies to reduce fossil fuel consumption and GHG emissions. The effects of low natural gas prices, an RPS, and a cap-and-trade system are specifically considered in this study, but the energy system model is sufficiently flexible to consider additional possibilities, such as a carbon-tax, feed-in tariffs, or biofuel credits. Changes to scenario-specific fuel prices or energy policies can produce systemic effects on energy technology deployment, utilization, and emissions.

The energy system modeling described by Babaee et al. (2013) consists of two primary components: The Integrated MARKAL-EFOM System (TIMES) (Loulou et al., 2005), which serves as a generic energy optimization framework and operates on the National U.S. TIMES Dataset (NUSTD). TIMES is a widely used bottom-up energy system model, which represents an energy system as a network of technologies linked together via flows of energy commodities (Loulou et al, 2005). TIMES performs linear optimization to identify the least-cost way to satisfy end-use demands, subject to user-imposed constraints such as emissions limits and maximum growth rates on technology capacity. Growth rate constraints prohibit technologies from being implemented faster than can be reasonably expected. For example renewable electricity generation cannot increase from 10% of generation in one stage to 100% of generation in the next. Additionally, the total capacity of technologies may be constrained based on physical supply (e.g., there are only so many high quality sites for wind electricity generation). Model outputs, specified by time stage, include the optimal installed capacity and utilization by technology, equilibrium energy prices, and emissions.

NUSTD is a TIMES compatible input dataset containing fuel prices, technology cost and performance estimates, and end-use demands that represent the U.S. as a single region over the next four decades. Only the first 30 years of projection, 2010-2039, were used for this analysis. The NUSTD dataset consists of four parts: fuel supply, electric sector, transport sector, and the remaining end-use sectors (i.e., commercial, residential, industrial). The fuel supply is represented by a set of exogenously specified fuel prices drawn from the output to the Annual Energy Outlook (AEO) 2012 (U.S. EIA, 2012). The electric sector contains 32 generation technologies and the price and electricity mix can change in each stage. The electricity mix in each stage was then used to calculate the GHG intensity from electricity generation based on the GHG intensity associated with each technology shown in Table B-26. GHG intensity is a measure of the GHG emissions from an activity. For electricity generation, GHG intensity is measured in kg CO_2e kWh^{-1}. The transportation sector includes light duty, heavy duty, and off-highway vehicles. The cost and GHG intensity of heavy-duty transportation was used to calculate the cost and GHG emissions associated with waste collection and inter-facility transportation. Heavy-duty transportation costs were calculated in each stage using the fixed and variable costs assumed in the NUSTD (existing technologies were assumed to have the same fixed cost as the equivalent new technology), as well as the marginal fuel prices calculated in each stage by the model. GHG intensity associated with transportation in this analysis is measured in kg CO_2e/vehicle km traveled (vkmt). The output values for electricity and transportation mix, as well as the input fuel prices, transportation cost, and emissions were used to determine life-cycle emissions and costs of the SWM processes for each 5-year stage.

4.2.2 Solid Waste Management Policy

The foundation of this study is a stage-wise optimized LCA of an SWM system under different energy and climate policy scenarios. The functional unit for this LCA is the total mass of generated mixed municipal solid waste (MSW) set out at the curb over the decision horizon. The functional unit does not include waste items reused or treated by the waste generator (e.g., clothing used as rags, food waste treated in a garbage disposal, and onsite composting). The mixed integer linear stage-wise optimization framework described in Chapter 2 (Levis et al., 2013a) was used for this analysis. In each time stage, the optimization model determines whether to build, expand, or decommission capacity for the modeled SWM processes, and determines the mass of each material collected and treated in each process in response to user imposed objectives and constraints. The process models include capital costs associated with building and expanding processes, as well as operational costs and emissions associated with collecting and treating material through each process. If capacity is built or expanded, it must be above a user-specified minimum build capacity for that process. The SWM processes that exist in the final stage are assumed to be repeated indefinitely to meet the continuing service demand.

Policy makers have taken an increasing interest in reducing environmental impacts associated with SWM; to this end, many U.S. states and cities have instituted ambitious landfill diversion goals. For example, both California and Florida have recently set goals of 75% diversion by 2020, (CalReycle, 2012; Florida EPA, 2010) while cities such as San Francisco, Oakland, and Seattle have set "zero waste" goals with the intent of eliminating landfill disposal (San Francisco Environment, 2013; City of Oakland, 2013; City of Seattle, 2013). Diversion targets are readily modeled in SWOLF by limiting landfill disposal in each stage. Many SWM decision makers, like those in California, are also looking to reduce the GHG emissions from SWM. SWOLF can model GHG reduction targets from SWM by capping GHG emissions either in specific stages or cumulatively over the model time horizon. The effects of a combined diversion-GHG reduction policy are analyzed in this study.

4.3 Solid Waste Management System Description

The decision criteria considered in this analysis are cost, landfill diversion, and GHG emissions. Planning decisions were made in six, 5-year increments beginning in 2010 and ending in 2039. All waste that is not disposed in a landfill or ash landfill is considered as diversion.

Waste generation and composition data developed in Chapter 3 (Levis et al., 2013b) were used in this analysis, and additional descriptions of the system characteristics and the process models are provided in Appendix B. The model city has a population of 100,000 in 2010 and is assumed to grow at the projected national average rate for the 30-year decision horizon. The U.S. average per capita waste generation for 30 materials was determined for 2000 and

2010 based on U.S. EPA data (U.S. EPA, 2002 and U.S. EPA, 2011), and waste generation and composition were extrapolated from these values and the population (Table B-1). The material properties for each waste material are shown in Table B-2.

Figure 4-1 shows the modeled collection options, treatment processes, and mass flows for the system. All waste materials can be collected by mixed and residual waste collection, but only designated materials (Table B-1) can be collected by single stream recycling or mixed organics collection (i.e., recyclables and food and yard waste, respectively). Food and yard waste may be treated by composting or AD. Non-vegetable food waste cannot be composted due to the risk of disease vector attraction. The optimization model determines which materials are actually collected via the separate collection processes. Two types of material recovery facilities (MRFs) are considered; a single stream MRF (SSMRF) that receives commingled recyclables, and a mixed waste MRF (MWMRF) that receives mixed waste. In the treatment system, the MRFs separate materials that can then either be recycled or treated by WTE. The landfill is assumed to generate electricity from the collected methane using an internal combustion engine, which is the most environmentally beneficial management alternative since approximately 35% of generated landfill gas is used beneficially in the U.S. (Levis and Barlaz, 2011a).

The existing SWM system in 2010 is assumed to have a 6,000 Mg yr^{-1} (1 Mg = 1000 kg) composting facility, which can accept yard and food waste, with 20 years of remaining life, and a 12,000 Mg yr^{-1} SSMRF that receives commingled recyclables with 20 years of remaining life. The sizes of the existing facilities were chosen to represent realistic facilities for a city with the assumed population. The existing landfill is assumed to have enough capacity to accept all of the waste generated during the time horizon. Including this existing infrastructure is important because most cities and counties already have SWM infrastructure systems or programs in place and the relatively low marginal costs of operating existing facilities relative to building new facilities can affect investment decisions.

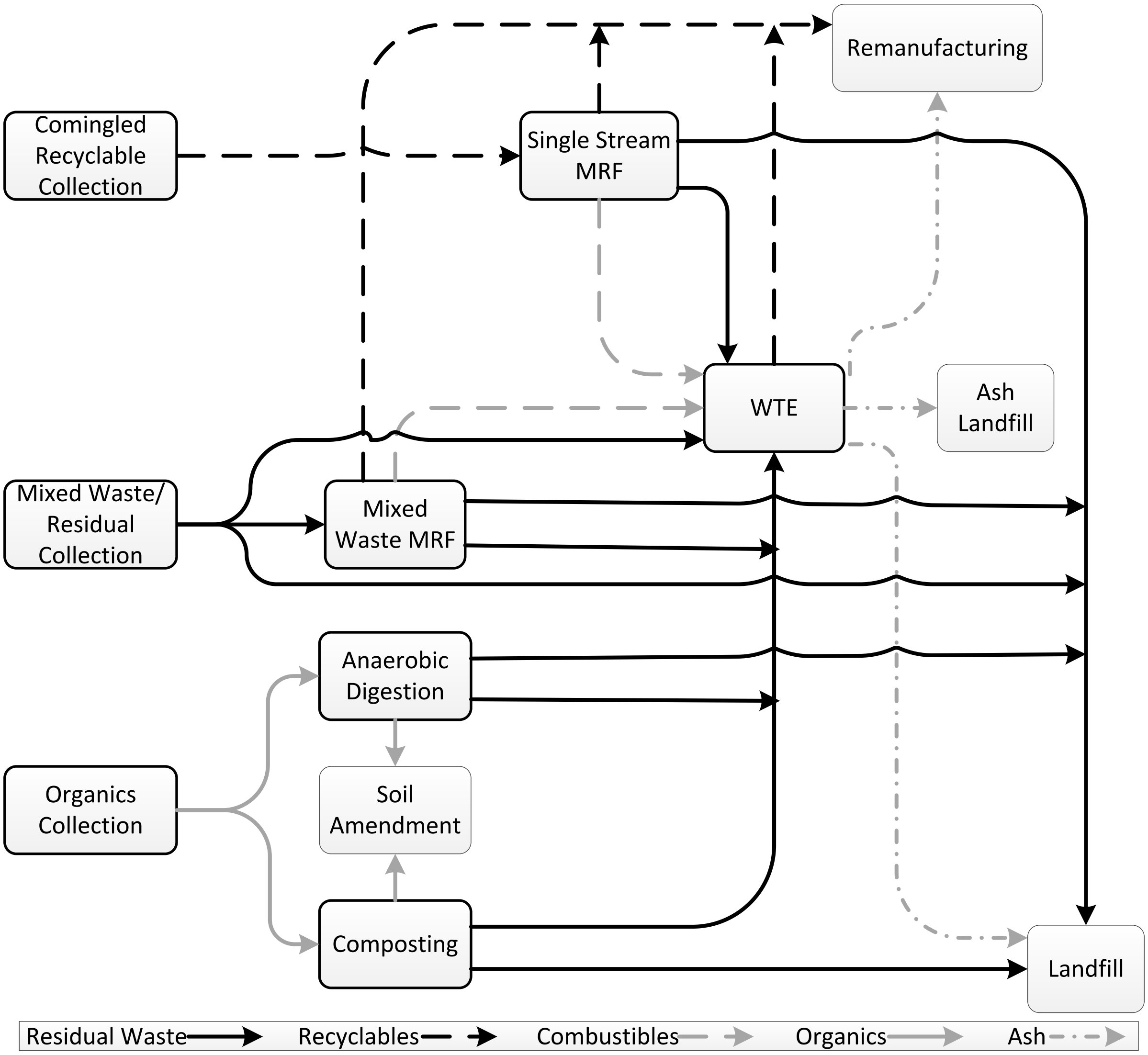

Figure 4-1. Waste management system mass flow diagram representing potential material flows through the wate management system. Mixed waste collection collects all of the generated waste, while residual collection collects the remaining waste after recyclable and/or organics collection. Separated material from the MRFs can either be recycled or treated by WTE combustion. Bottom ash can be recycled as aggregate in concrete, and the aluminum and ferrous in the bottom ash can be separated and recycled. The distinction between bottom and fly ash has been removed for simplicity.

4.4 Scenarios and Cases

Four energy scenarios were considered: (1) a reference scenario that used AEO reference fuel prices (U.S. EIA, 2012) with no RPS or CO_2 policy (Reference); (2) an RPS scenario that used reference fuel prices and implemented an RPS, but no CO_2 policy (RPS); (3) a low natural gas price scenario that used the lower natural gas prices projected by AEO (U.S. EIA, 2012) with no RPS or CO_2 policy (LowNG); and (4) a combined RPS and CO_2 policy scenario that used reference fuel prices and implemented an RPS and a cap-and-trade system (CO2). The energy scenarios are shown in Table 4-1.

Table 4-1. Energy System Scenarios, SWM Policy Scenarios, and subsequent cases analyzed.

Energy Scenarios	Description
Reference	Used AEO reference fuel price projections, with no RPS or CO_2 policy.
RPS	Same as Reference except included RPS with targets shown in Table 4-2.
LowNG	Same as Reference except used AEO low natural gas price projections.
CO2	Same as Reference except included RPS and cap-and-trade system with values shown in Table 4-2.

SWM Scenarios	Description
Min Cost	Minimize net present system cost.
EnvPol	Minimize net present system cost subject to stage-wise GHG and diversion targets.[a]

Case Name	SWM Scenario	Energy Scenario
RefBase	Min Cost	Reference
RPSBase	Min Cost	RPS
LowNGBase	Min Cost	LowNG
CO2Base	Min Cost	CO2
RefEnvPol	EnvPol	Reference
RPSEnvPol	EnvPol	Reference
LowNGEnvPol	EnvPol	LowNG
CO2EnvPol	EnvPol	CO2

a. In the EnvPol scenario, cost is minimized while GHG emissions cannot exceed the RefBase case in 2010 or 2015. GHG reductions are doubled from the RefBase case in 2020 and 2025, and quadrupled in 2030 and 2035. The RefBase case achieves 30% diversion in 2010, and this must be met in 2010 or 2015 in the EnvPol scenario. The diversion target is then increased to 40% in 2020 and 2025, and 50% in 2030 and 2035.

Table 4-2 shows how the RPS requirement and CO_2e cap change in each stage, as well as the associated CO_2e price. The CO_2e price associated with the GHG permits in the cap-and-trade system as calculated by TIMES was assumed to be enacted on the life-cycle GHG emissions associated with processing each material through each process.

Table 4-2. Variation in RPS renewables requirement, and CO_2 price for the RPS and CO2 scenarios[a,b]

	2010	2015	2020	2025	2030	2035
RPS Renewables Requirement (%)	0	9.5	20	20	20	20
Industry-wide CO_2 reduction from 2010 (%)	-	8.7	16.6	18.8	25	31.3
CO_2 Price ($/MT$CO_2$e)	0.0	5.7	14.4	14.3	14.5	14.5

[a.] The CO_2 scenario includes both an RPS and a CO_2 policy.

[b.] Energy policies are adapted from Babaee et al., 2013.

The first stage (2010-2014) was assumed to be constant in all of the scenarios, so changes to the energy system began in 2015. The variation in transportation and electricity cost and GHG intensity are shown for each energy scenario in Figure 4-2. The changes in the heavy-duty transportation and electricity mixes for each energy scenario are shown in Tables C-1 through C-4, and C-6 through C-9 in Appendix C, respectively.

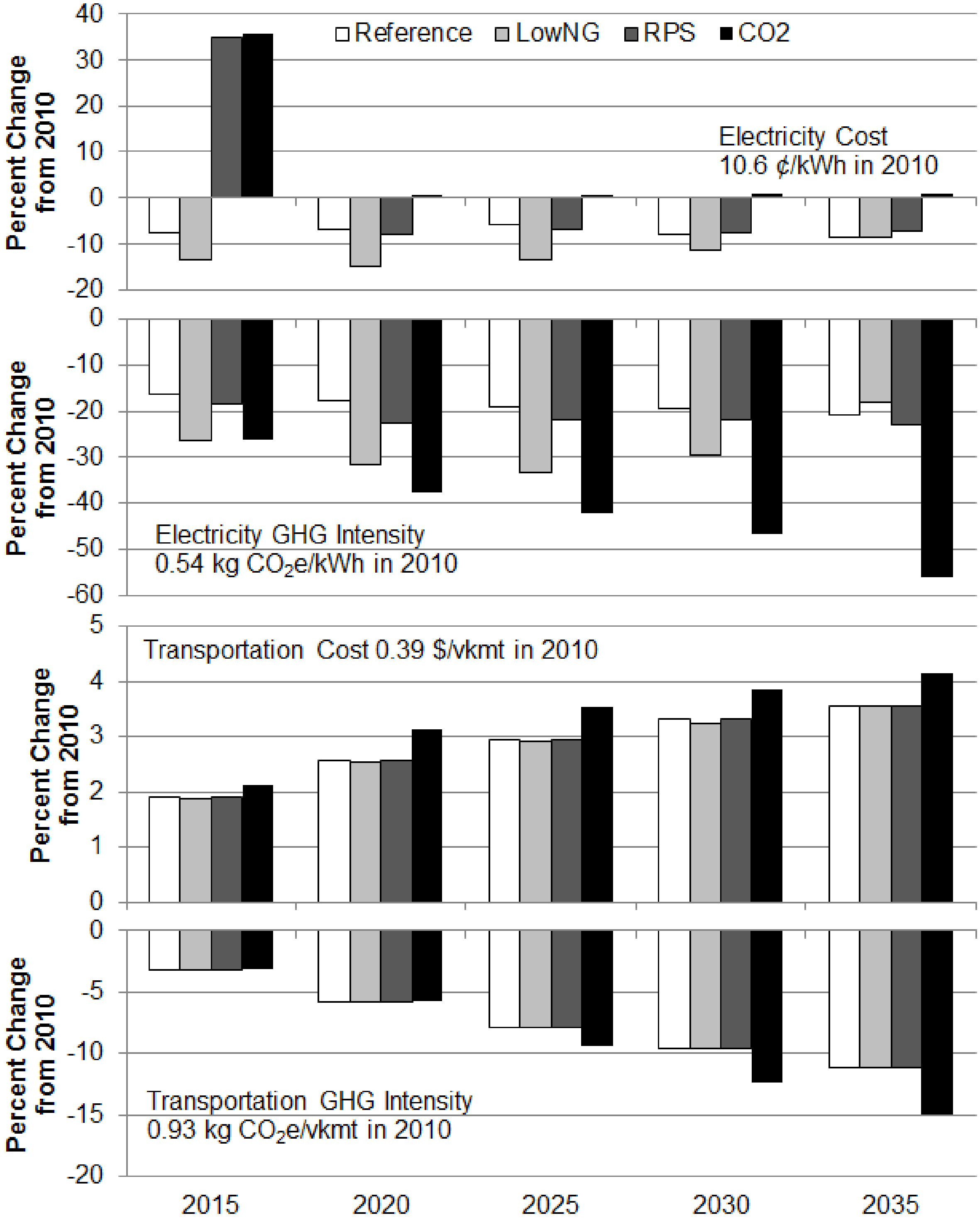

Figure 4-2. Change in energy system parameters from 2010 baseline based on energy modeling described in Section 4.2.1. Most of the variation in electricity GHG intensity is due to fuel switching from coal to natural gas or renewables. Transportation cost changes are small since diesel vehicles comprise the majority of transport in all scenarios. (vkmt = vehicle kilometer traveled)

Two SWM scenarios were considered and were combined with the four energy scenarios to create the eight cases that were analyzed as summarized in Table 4-1. The first SWM scenario minimized net present system cost without additional environmental targets or constraints (Min Cost). This SWM scenario was combined with the Reference energy scenario to create the baseline case, called “RefBase”. The RefBase baseline case was used to develop the SWM Environmental Policy (EnvPol) scenario to represent a situation where SWM decision-makers are trying to cost-effectively reduce GHG emissions and increase landfill diversion. The EnvPol scenario minimized net present system cost while meeting increasing stage-wise GHG and diversion targets. The EnvPol scenario is similar to the policy situation in California where SWM decision-makers need to simultaneously increase diversion and reduce GHG emissions.

The optimization model for each case consisted of approximately 100,000 continuous variables, 160 binary variables, and 100,000 constraints. The model was implemented in the GNU Mathematical Programing Language (GMPL) and solved using CPLEX’s mixed integer linear solver (GNU, 2012; CPLEX, 2013). The Min Cost cases solved in 2-5 minutes, and EnvPol cases solved in 1-2 hours on a 64-bit Windows 7 machine with an Intel Core i7-620M dual-core processor (2.67 GHz with 4 MB cache) and 8 GB of RAM.

4.5 Results and Discussion

4.5.1 Mass Flows, Costs, and GHG Emissions

Figures 4-3 to 4-7 show the mass throughputs for each process by stage for all eight cases (Table 4-1). The mass throughputs for all of the Base cases are essentially the same (Figure 4-3). The changes in the energy system do not change the minimum cost processes for future solid waste management. The energy system and GHG policy do affect the mass throughputs in the EnvPol cases. The RefEnvPol and RPSEnvPol cases are similar (Figures 4-4 and 4-5), as are the LowNGEnvPol and CO2EnvPol cases (Figures 4-6 and 4-7). The CO2EnvPol scenario makes additional use of the MWMRF and landfill in the final two stages compared to the LowNGEnvPol case to meet the GHG reduction targets. This is because the lower electricity GHG intensity in the CO2EnvPol case reduces the relative benefits of WTE. The

CO2EnvPol case also uses AD in the final stage to achieve the GHG targets, while the LowNGEnvPol uses composting. The similarities among the systems in different cases are due to the similar changes to electricity GHG intensity (Figure 4-2).

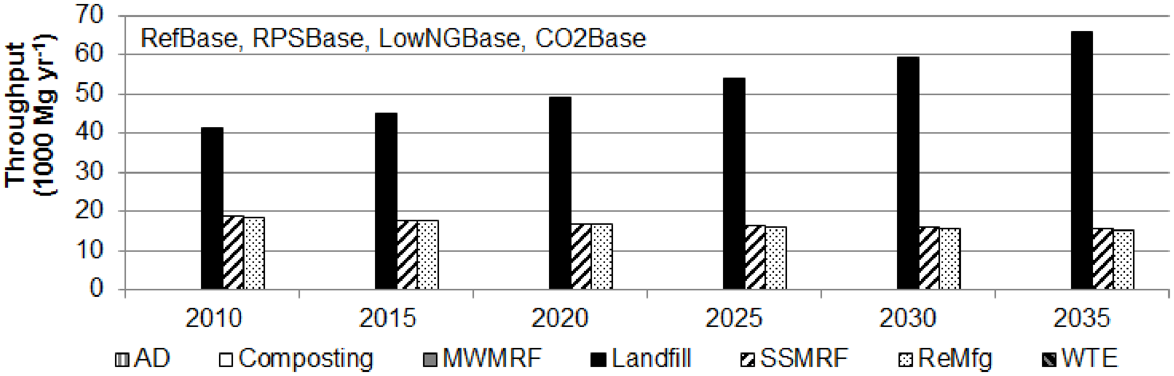

Figure 4-3. The total mass of material entering each process in each stage for the RefBase, RPSBase, LowNGBase, and CO2Base cases. All the energy scenarios for the base case had the same throughputs (except for minor differences [< 1%] in the CO2Base case).

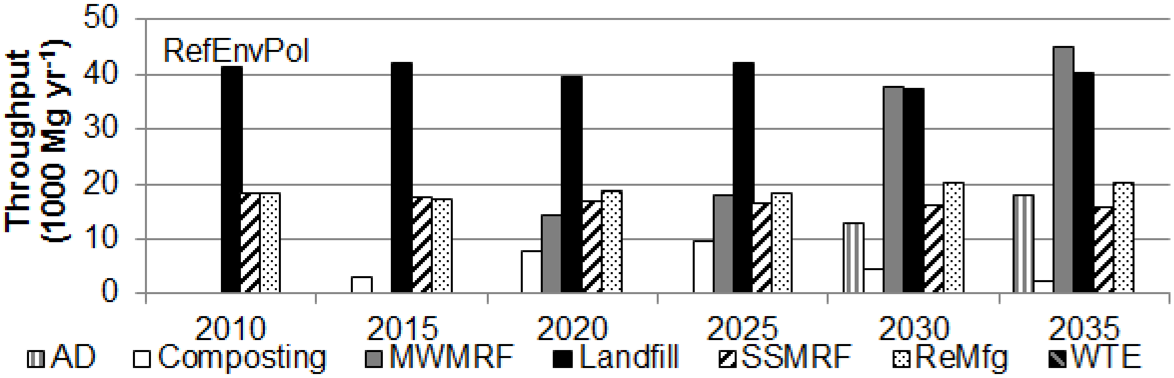

Figure 4-4. The total mass of material entering each process in each stage for the RefEnvPol case.

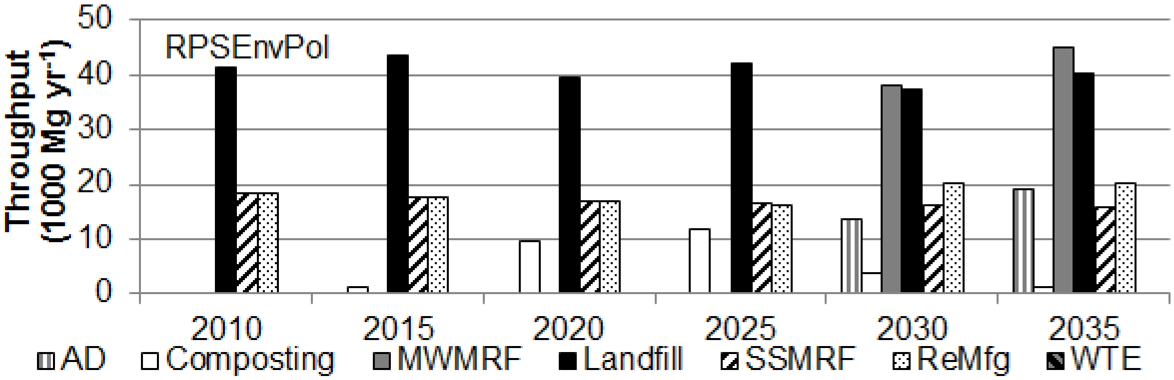

Figure 4-5. The total mass of material entering each process in each stage for the RPSEnvPol case.

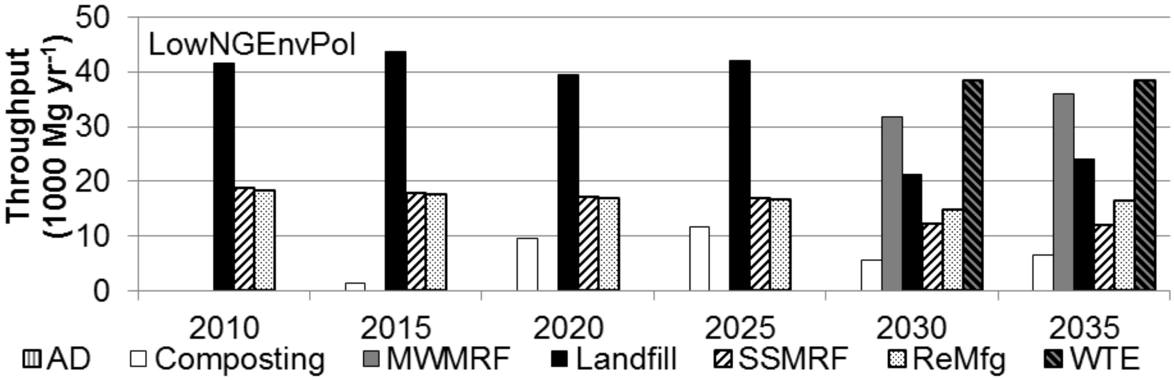

Figure 4-6. The total mass of material entering each process in each stage for the LowNGEnvPol case.

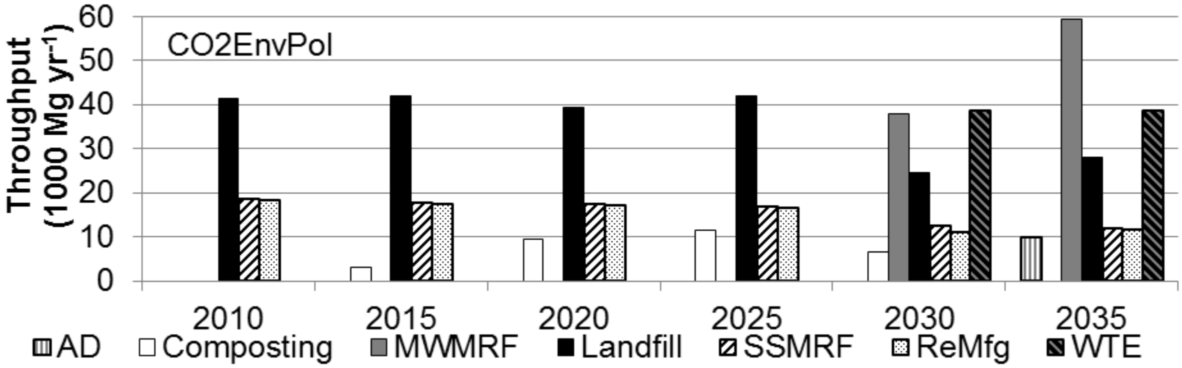

Figure 4-7. The total mass of material entering each process in each stage for the CO2EnvPol case.

Figures 4-8 to 4-15 show the GHG emissions associated with each process in each stage for each case. The greatest difference in the Base cases is that CO2Base case has noticeably reduced benefits associated with landfilling due to the lower electricity GHG intensity. There is a similar reduction in WTE benefits in the CO2EnvPol case compared to the LowNGEnvPol case.

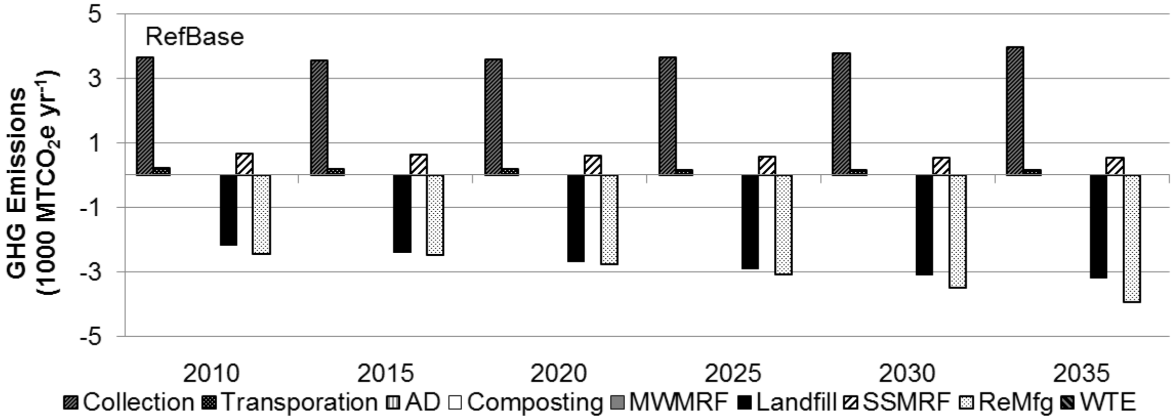

Figure 4-8. The annual GHG emissions from each process in each stage for the RefBase case. The GHG emissions for all base cases are similar. Transportation represents any transport of materials after initial curbside collection.

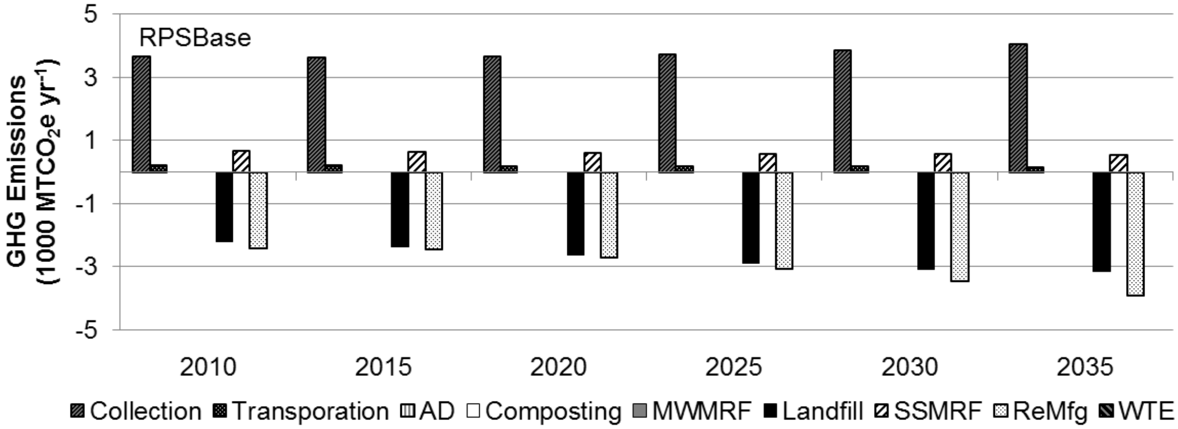

Figure 4-9. The annual GHG emissions from each process in each stage for the RPSBase case. The GHG emissions for all base cases are similar and the GHG emissions. Transportation represents any transport of materials after initial curbside collection.

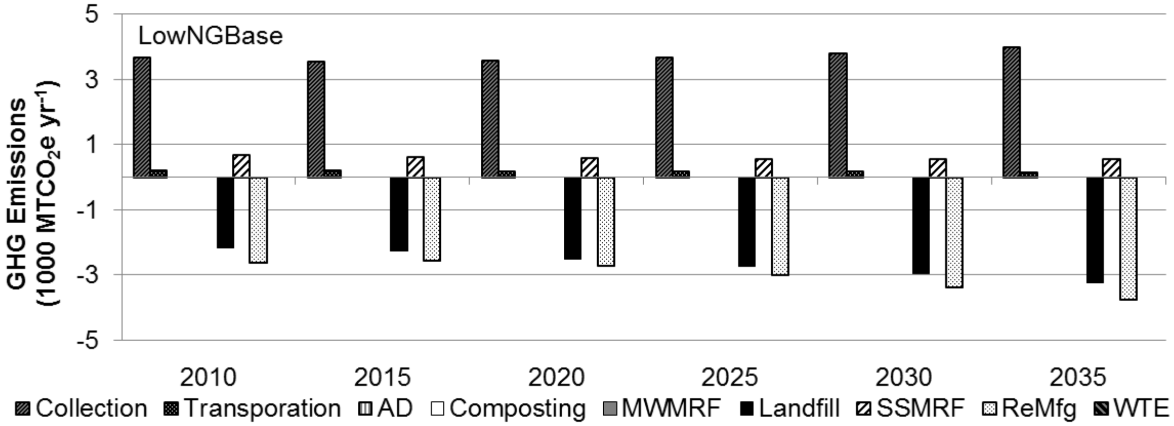

Figure 4-10. The annual GHG emissions from each process in each stage for the LowNGBase case. The GHG emissions for all base cases are similar and the GHG emissions. Transportation represents any transport of materials after initial curbside collection.

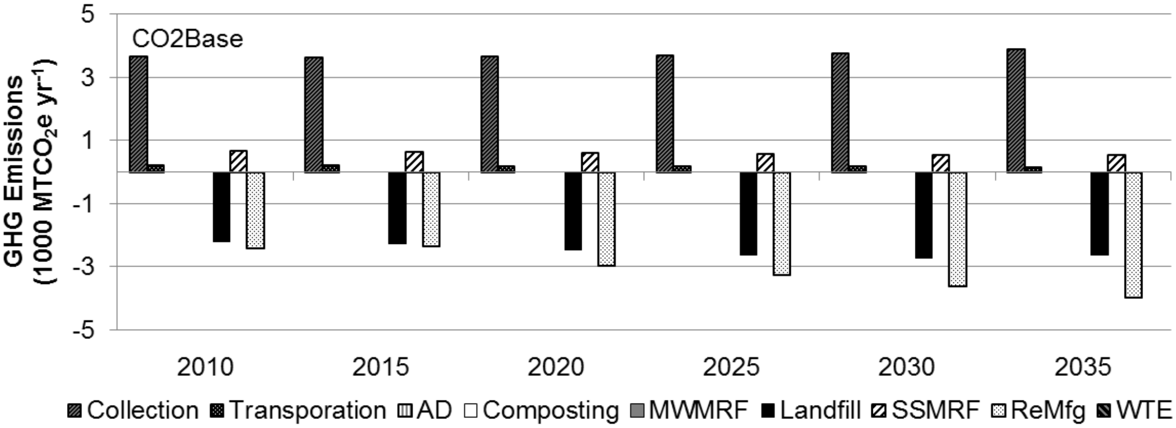

Figure 4-11. The annual GHG emissions from each process in each stage for the CO2Base case. The GHG emissions for all base cases are similar and the GHG emissions. Transportation represents any transport of materials after initial curbside collection.

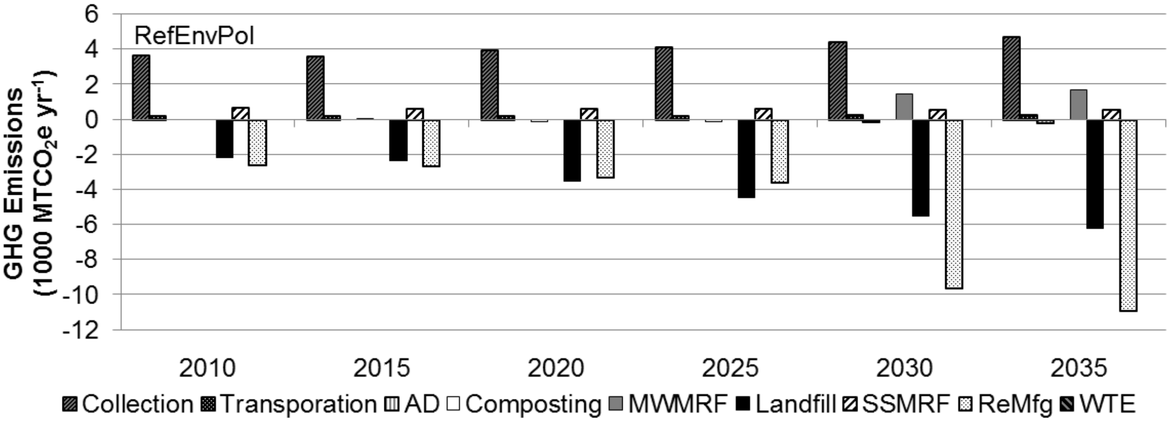

Figure 4-12. The annual GHG emissions from each process in each stage for the RefEnvPol case. Transportation represents any transport of materials after initial curbside collection.

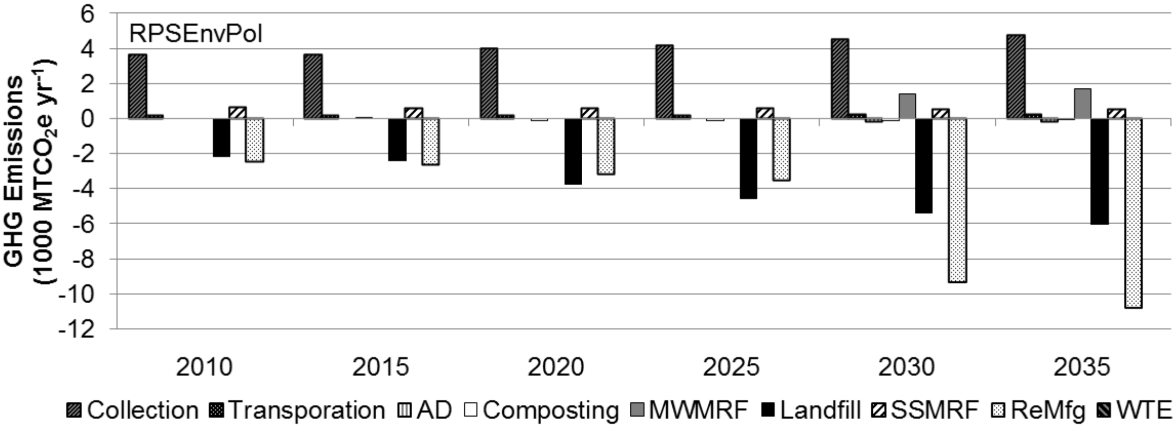

Figure 4-13. The annual GHG emissions from each process in each stage for the RPSEnvPol case. Transportation represents any transport of materials after initial curbside collection.

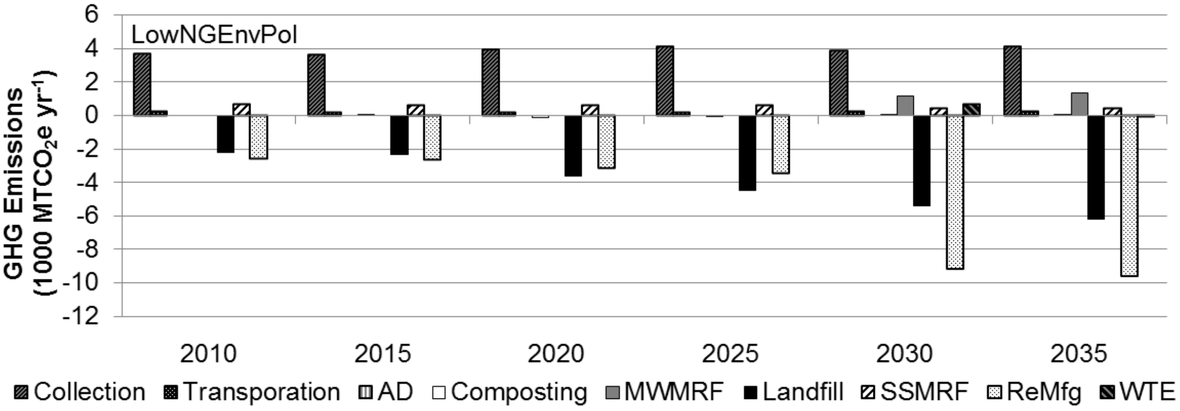

Figure 4-14. The annual GHG emissions from each process in each stage for the LowNGEnvPol case. Transportation represents any transport of materials after initial curbside collection.

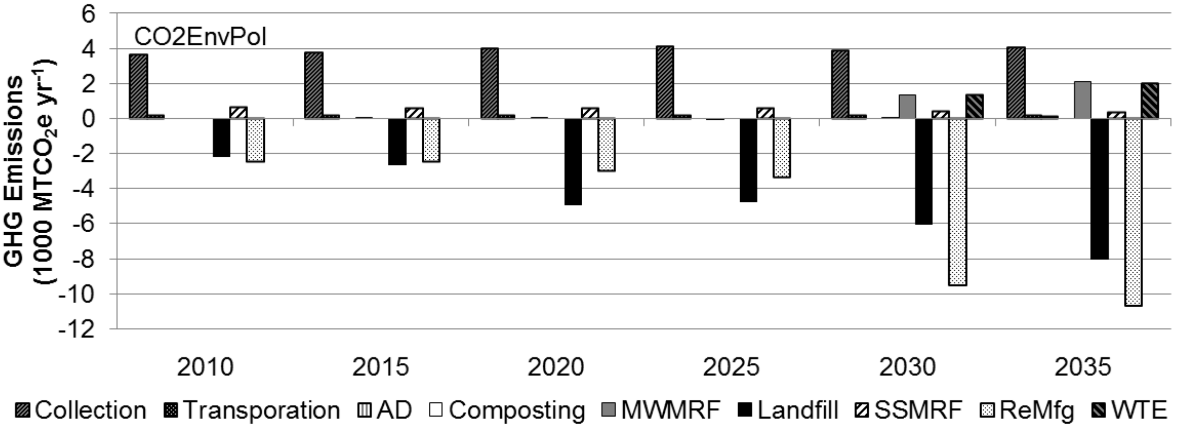

Figure 4-15. The annual GHG emissions from each process in each stage for the CO2EnvPol case. Transportation represents any transport of materials after initial curbside collection.

Table 4-3 shows the annual cost, GHG emissions, and percent diversion in each stage for the RefBase and RefEnvPol cases, and Figure 4-16 shows the percent change in annual cost and GHG emissions for the other cases compared to the corresponding Reference energy case (i.e., the Min Cost cases are compared to the RefBase case, and the EnvPol cases are compared to the RefEnvPol case).

Table 4-3. Annual cost, GHG emissions and percent diversion in each stage for the RefBase and RefEnvPol cases. The percent changes from these values for the other cases are shown in Figure 4-16.

RefBase Results

Stage	Cost ($/Mg)	GHG Emissions (kg CO_2e/Mg)[a]	Diversion (%)
2010	58	-0.8	31
2015	60	-7.6	28
2020	62	-16	25
2025	64	-23	23
2030	65	-27	21
2035	66	-30	19

RefEnvPol Case Results

Stage	Cost ($/Mg)	GHG Emissions (kg CO_2e/Mg)[a]	Diversion (%)
2010	58	-0.8	31
2015	61	-7.6	33
2020	65	-32	40
2025	67	-45	40
2030	75	-110	50
2035	77	-120	50

[a] Negative GHG emissions are due to electricity generation offsets (AD, landfill, WTE), material recovery offsets, and carbon storage (AD, composting, landfill).

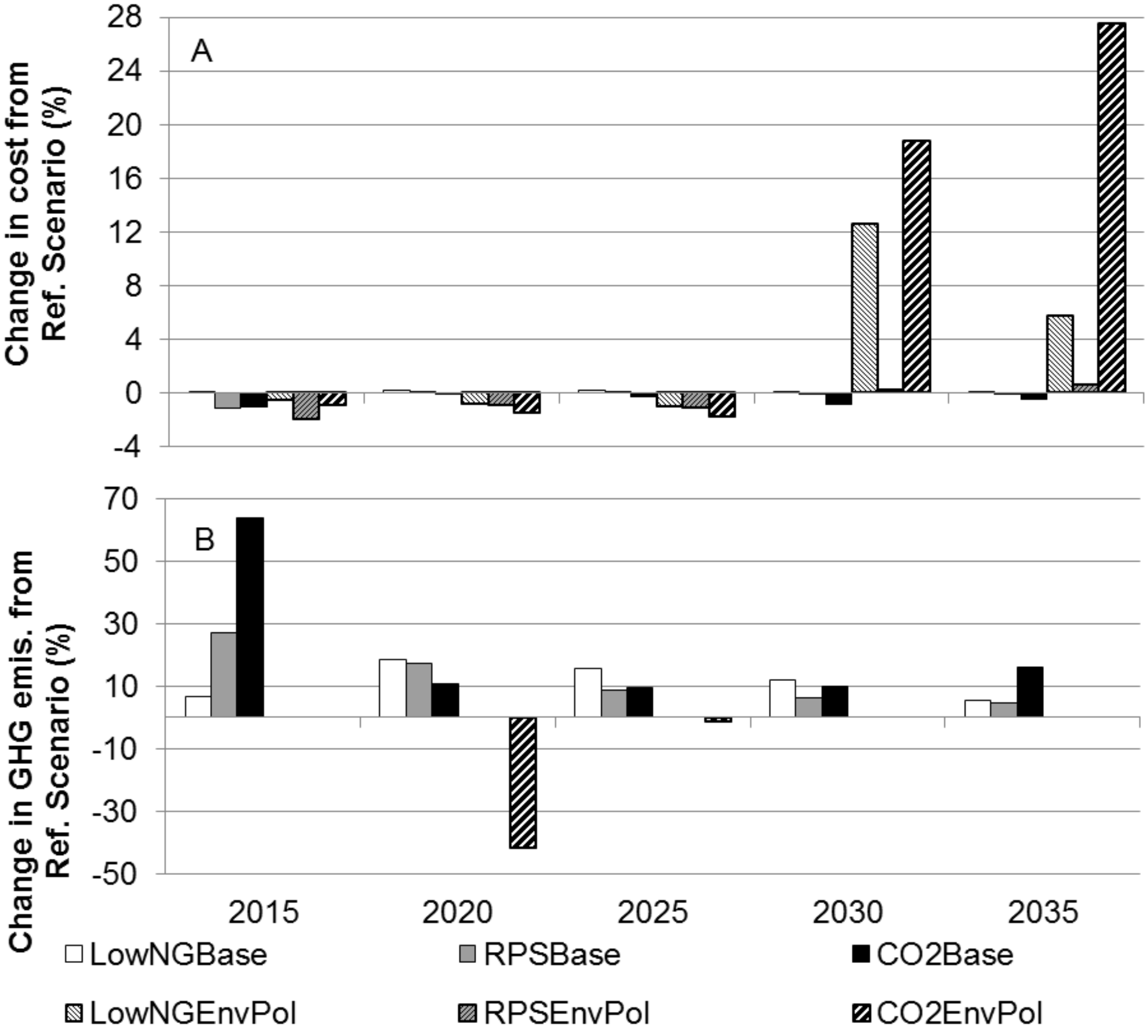

Figure 4-16. The percent change in annual cost (A) and GHG emissions (B) for each stage (after the initial stage, where the systems are the same) and case compared to the corresponding Reference energy scenario case (i.e., the Min Cost cases are compared to the RefBase case, and the EnvPol cases are compared to the RefEnvPol case). Percent change shown in GHG emissions is actually negative percent change because the net GHG emissions in all cases were negative (i.e., negative values in B are better and indicate greater reductions in GHG emissions).

The optimal mass throughputs for the SWM strategy in the Min Cost cases for all of the energy scenarios are the same, but there are variations in cost and GHG emissions due to changes in energy cost and GHG intensity. The other energy scenarios have little effect on the cost of SWM compared to the Reference scenario; the greatest increases in annual cost are in the last two stages of the LowNGEnvPol and CO2EnvPol cases due to the use of WTE combustion.

The variation in GHG emissions is greater than the variation in cost due to the greater changes in GHG intensity (Figure 4-2). The CO2Base case leads to increased emissions associated with SWM in every stage compared to the RefBase case because the offsets associated with both landfilling and ReMfg decrease as the offset electricity use is cleaner. The LowNGBase and RPSBase cases also increase GHG emissions in every stage because offsets are reduced due to the increased use of natural gas and renewables with lower GHG intensity. The EnvPol cases do not vary in GHG emissions in the final two stages because all of the scenarios are closely meeting the GHG constraints. The CO2EnvPol case reduces GHG emissions in 2020 through selective use of the landfill (e.g., leaves are landfilled instead of composted) and increased recycling. The results indicate that while reducing GHG emissions from the energy system will decrease nationwide GHG emissions, they will also decrease the benefits associated with material and energy recovery from SWM activities. The specific changes in cost and GHG emissions are dependent on the relative changes to electricity and transportation cost and GHG intensity.

All the systems in the EnvPol cases use the same general strategy to meet the GHG and diversion targets through 2025: recyclables are separated in a SSMRF and composting is increasingly used. In 2030 and 2035, AD is used for organics instead of composting in the RefEnvPol and RPSEnvPol cases because AD provides additional GHG reduction potential compared to composting, so AD is the most cost-effective way to meet the GHG and diversion targets. In the LowNGEnvPol case, composting is used without AD in 2030 and 2035. The LowNGEnvPol and CO2EnvPol cases both use WTE for collected residual waste as well as for MRF residuals in 2030 and 2035. The CO2EnvPol and LowEnvPol cases cannot meet the GHG targets solely by switching to AD because the lower electricity GHG intensity (Figure 4-2), so the WTE facility must be used. The WTE GHG reductions also fell in the final stages, but enough mass can be sent to WTE to meet the GHG and diversion targets in the final stages. The main energy system driver is electricity GHG intensity and Figure 4-2 shows that the Reference and RPS scenarios are similar, while the LowNG and

CO2 scenarios lead to additional reductions in electricity GHG intensity, which leads to different system choices.

4.5.2 Discussion

Minimum cost SWM strategies with GHG emission and diversion targets were affected by changes to the energy system and GHG policy. This SWM policy arrangement is similar to the case in California where SWM decision-makers have diversion and GHG reduction targets and are operating under a cap-and-trade system. The results indicate that reductions in electricity GHG intensity decrease the environmental benefits of generating electricity from waste (e.g., landfill gas-to-energy, WTE combustion, and AD) as well as the benefits from recycling. Decreases in electricity GHG intensity will reduce economy-wide GHG emissions, and they may also encourage SWM activities that reduce GHG emissions with less reliance on electricity offsets (i.e., recycling, carbon storage in landfills or soils). Such results show the utility of stage-wise life-cycle optimization that integrates energy system projections with comprehensive SWM models.

LCAs of SWM have previously indicated that WTE combustion is a suitable technology for reducing GHG emissions from SWM (e.g., Kaplan et al., 2009a and 2009b; Levis et al., 2013b), but between 2000 and 2010, a net of 16 WTE facilities went offline in the U.S., and total WTE capacity increased by only 0.4%, while solid waste generation increased by 8% (U.S. EPA, 2002 and 2012). The main obstacles to increased WTE combustion are the upfront capital cost as well as the difficulty siting new facilities. Currently 24 states have WTE facilities and 25 states and the District of Columbia consider electricity from WTE to be renewable (ERC, 2010) under their RPS or other renewable incentive programs. Such programs may increase the economic attractiveness of WTE as a means of reducing GHG emissions from SWM. The benefits of these incentive programs could be partially negated if fossil carbon containing plastic waste increases, paper waste decreases, or the relative benefits of WTE combustion is offset through the use of other cleaner electricity generation technologies. An integrated stage-wise analysis is necessary to consider how best to respond to these interrelated factors.

This analysis focused on policies associated with diversion and GHG emissions reduction targets for SWM, but there are additional policies that are used to reduce the environmental impacts from SWM. Such policies can be readily modeled in SWOLF by forcing the use of AD or composting for yard wastes. LCAs have indicated that separate organics treatment in composting or AD facilities can be an effective way to increase diversion and reduce GHG emissions (e.g., Levis and Barlaz, 2011b; Morris et al., 2013); correspondingly from 2000 to 2010 yard waste composting has increased by 22%, as more cities and counties have implemented curbside yard waste collection and composting (U.S. EPA, 2012). AD of solid wastes only operates at the pilot or small commercial scale in the U.S., but there are numerous facilities in Europe and the Dufferin facility in Toronto is the first full-scale AD facility for solid waste in North America (Levis et al., 2010). The main obstacle preventing additional AD is the upfront capital cost, but feed-in tariffs and other energy policies could make AD more economically attractive in the future (Sanscartier et al., 2012). Additional examination of other environmental impacts (e.g., resource use, eutrophication, and toxicity) could identify critical tradeoffs that can inform future plans for sustainable integrated SWM systems.

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5 CONCLUSIONS

This research resulted in a mathematical modeling framework capable of identifying solid waste management (SWM) strategies that minimize cost or environmental impacts subject to policy constraints and demonstrated the framework for analysis of a solid waste system under various SWM policies, energy systems, and greenhouse gas (GHG) policy. The stage-wise integrated life-cycle optimization model for SWM developed in this research is capable of minimizing costs, emissions, or environmental impacts while considering all typical SWM processes and their interdependencies at the municipal scale (Chapter 2). The Solid Waste Optimization Life-cycle Framework (SWOLF) produced useful insights that are relevant to policy formulation and the response of SWM systems to SWM and GHG policies. The framework is generalizable to include numerous SWM treatment facilities and collection options, and solves in less than two hours using readily available hardware and software.

Two case studies were developed that represent the first applications of SWOLF, an optimizable dynamic life-cycle assessment framework for SWM. The applicability of SWOLF to provide insights into a realistic SWM system was shown through a case study of a hypothetical suburban city from 2010-2039 (Chapter 3). The case study analysis demonstrated the utility of stage-wise life-cycle optimization for SWM. The results indicated that GHG emissions can increase with increased diversion, which suggests that diversion targets and material disposal bans may be counterproductive towards reducing GHG emissions in some instances. Specifically, the modeling results found that landfilling instead of composting branches and leaves could decrease GHG emissions, and that recycling materials such as office paper or magazines could also increase GHG emissions compared to landfilling. In addition, the model found that SWM strategies designed to reduce GHG emissions were more cost effective at reducing GHG emissions than SWM strategies designed to increase diversion, which indicates that SWM decision-makers should focus on the actual environmental impacts they wish to reduce, instead of using potentially problematic proxies such as landfill diversion. The case study found multiple situations where technologies were implemented in stages and/or where implementation was postponed to meet cost or environmental objectives or targets. For example, both the Max Diversion and

Min GHG scenarios used stage-wise switching of AD and composting throughputs based on changes to waste composition and generation. Practically, this allows for deferred deployment of capital and the opportunity to re-evaluate a decision close to the time of technology deployment.

The model was then used to investigate the effects of energy, GHG, and SWM policy on optimal SWM strategies for the same SWM system from 2010-2039 (Chapter 4). This case study required integration of SWOLF with energy system modeling results to investigate how changes in GHG policy and the energy system affect SWM process and system performance. All of the SWM environmental policy (EnvPol) cases implemented technologies in stages to meet the increasingly stringent GHG and diversion targets. These staged decisions can only be analyzed through the use of a multi-stage framework like SWOLF. The analysis of the effects of the energy system and GHG policy scenarios showed that minimum cost SWM strategies with GHG emission and diversion targets were affected by a carbon policy. Specifically, the model found that reductions in electricity GHG intensity over time decrease the environmental benefits of generating electricity from waste (e.g., landfill gas-to-energy, waste-to-energy [WTE] combustion, and anaerobic digestion [AD]). Both case study analyses suggested that source separated recycling using a material recovery facility (MRF) could reduce costs and GHG emissions while increasing diversion. Additionally, both analyses found that increased WTE combustion and AD could reduce GHG emissions while increasing landfill diversion, especially in later stages of the energy system analysis with increasingly stringent diversion and GHG policy targets.

Fundamentally, the research illustrated the utility of integrated analysis for cost-effective environmental decision and policy support in SWM. The case studies represent the first application of an optimizable dynamic life-cycle assessment framework for SWM and showed that it is critical for SWM decision makers to systematically consider changes to waste composition and generation, SWM policy, the U.S. energy system, and potential future GHG mitigation policies when developing cost-effective SWM strategies. The case studies focused on a single suburban system, but the generalized framework could readily consider urban or rural systems that have different collection systems and constraints. Similarly, additional SWM processes could be added to the framework (e.g., refuse-derived-fuel, gasification, transfer stations, or mechanical-biological treatment) to further investigate how new or different treatment options affect optimal SWM. Future research to develop specific case studies of individual systems that incorporate location-specific parameters and constraints will likely result in different or additional recommendations. Examination of other environmental impacts (e.g., resource use, eutrophication, and toxicity) could identify critical tradeoffs that inform future plans for sustainable integrated SWM systems. Finally, future analysis of additional energy and GHG policies such as feed-in tariffs, biofuel credits, or carbon taxes could provide insights into cost-effective implementation of energy generation technologies.

APPENDICES

APPENDIX A. Input data for illustrative system in Chapter 2

Table A-1. Capital costs for waste management processes.

Process	Build Cost ($\$/Mg\text{-}yr^{-1}$)	Expansion Cost ($\$/Mg\text{-}yr^{-1}$)	Minimum Build ($Mg\text{-}yr^{-1}$)	Minimum Expansion ($Mg\text{-}yr^{-1}$)	Lifetime (yr)
WTE	700	1400	40,000	40,000	20
MRF_N	200	400	20,000	5000	20
MRF_E	NA	400	10,000[a]	5000	10[b]

[a] Actual existing capacity.

[b] Remaining life.

Table A-2. Utilization costs for waste management processes and waste materials.[a]

Process	Recyclables ($/Mg)	Non-Recyclables ($/Mg)
Mixed waste collection[b]	30	30
Commingled recyclable collection[b]	33	33
Residual waste collection[b]	45	45
Landfill	20	20
Waste-to-energy	50	50
Ash Landfill	10	10
Existing Material recovery facility	20	N/A
New Material recovery facility	15	N/A
Remanufacturing	-100	N/A

[a] Costs are assumed in the example to be constant for all stages.

[b] Collection costs are assumed in the example to be the same for each destination.

Table A-3. Utilization costs for waste management processes and waste materials.[a]

Process	Recyclables ($kg\ CO_2e/Mg$)	Non-Recyclables ($kg\ CO_2e/Mg$)
Mixed waste collection	10	10
Commingled recyclable collection	15	15
Residual waste collection	12	12
Landfill	-60	30
Waste-to-energy	-140	-40
Ash Landfill	7	7
Material recovery facility	10	N/A
Remanufacturing	-500	N/A

[a.] Emissions are assumed in the example to be constant for all stages.

[b.] Collection emissions are assumed in the example to be the same for each destination.

Table A-4. Transportation costs for waste management processes and waste streams (\$/Mg).[a]

Process	Landfill	Waste-to-Energy	Ash Landfill	ReMfg
Material recovery facility	10	10	N/A	100
Waste-to-energy	10	N/A	0[b]	N/A

[a] Costs are assumed in the example to be constant for all stages.

[b] WTE and ash landfill are assumed to be co-located.

Table A-5. Transportation emissions for waste management processes and waste streams (kg CO_2e/Mg).[a]

Process	Landfill	Waste-to-Energy	Ash Landfill	ReMfg
Material recovery facility	3	3	N/A	30
Waste-to-energy	3	N/A	0[b]	N/A

[a] Emissions are assumed in the example to be constant for all stages.

[b] WTE and ash landfill are assumed to be co-located.

APPENDIX B. Solid waste management case study system information

Solid Waste Management System and Material Properties

Table B-1. Waste generation and composition in each time period.

	Waste Composition (%)					
Waste Material	2010	2015	2020	2025	2030	2035
Leaves[o]	6.8	7.2	7.5	7.8	7.9	8.0
Grass[o]	5.2	5.5	5.7	5.9	6.0	6.1
Branches[o]	5.0	5.3	5.6	5.7	5.8	5.9
Food Waste-Veg.[o]	14.5	16.2	17.8	19.4	20.9	22.3
Food Waste- Non-Vegetable[o]	3.6	4.0	4.5	4.8	5.2	5.6
Wood	5.1	5.5	5.9	6.2	6.5	6.7
Textiles	4.7	5.3	5.9	6.6	7.2	7.9
Rubber/Leather	0.5	0.6	0.6	0.6	0.7	0.7
Newsprint[r]	4.5	3.5	2.7	2.0	1.5	1.2
Corr. Cardboard[r]	14.2	13.4	12.5	11.5	10.5	9.5
Office Paper[r]	2.4	1.9	1.5	1.2	0.9	0.7
Magazines[r]	0.7	0.6	0.5	0.4	0.3	0.3
3rd Class Mail[r]	2.0	1.7	1.4	1.2	1.0	0.8
Folding Cartons[r]	2.7	2.6	2.4	2.2	2.1	1.9
Bags and Sacks[r]	0.5	0.4	0.3	0.2	0.2	0.1
Paper-Non-recyclable	6.8	5.7	4.8	3.9	3.2	2.6
HDPE-Trans. Cont.[r]	0.4	0.4	0.4	0.4	0.4	0.4
HDPE-Pig. Cont.[r]	0.7	0.8	0.8	0.9	0.9	0.9
PET-Containers[r]	1.4	1.7	2.1	2.4	2.8	3.2
Plastic Film[r]	1.9	1.8	1.6	1.5	1.3	1.2
Plastic-Non-Recyclable	5.7	6.0	6.3	6.4	6.6	6.6
Ferrous Cans[r]	1.1	1.0	0.9	0.8	0.7	0.6
Ferrous Metal-Other	0.2	0.3	0.4	0.5	0.7	0.8
Aluminum Cans[r]	0.7	0.6	0.6	0.5	0.5	0.4
Aluminum-Foil[r]	0.2	0.2	0.3	0.3	0.3	0.3
Al-Non-recyclable	0.1	0.1	0.1	0.1	0.1	0.1
Glass-Brown[r]	2.6	2.3	2.0	1.7	1.4	1.2
Glass-Green[r]	1.1	1.0	0.8	0.7	0.6	0.5
Glass-Clear[r]	0.7	0.7	0.6	0.5	0.4	0.3
Misc. Inorganic	3.6	3.6	3.6	3.5	3.4	3.3
Total Mass (Mg yr^{-1})[a]	59,833	62,367	65,701	69,866	74,903	80,906

[a] Waste generation data are in Mg yr^{-1} for a city with the population of 100,000 in 2010-2014, 105,021 in 2015-2019, 110,042 in 2020-2024, 115,218 in 2025-2029, 120,395 in 2030-2034 and 125,576 in 2035-2039. Population growth is based on projected U.S. total growth from the U.S. Census Bureau (2012).

[o] Designates waste materials that can be collected by mixed organics collection.

[r] Designates waste materials that can be collected by commingled recyclables collection.

Table B-2. Material properties used in the LCA model.

Waste Material	Moisture Content[a] (%)	Ash Content[a] (%)	Lower Heating Value[a] (MJ/dry kg)	Methane Yield[b] (m^3/dry Mg)	Lab Decay Rate[c] (yr^{-1})	Carbon Storage Factor[d] (kg C/dry Mg)
Leaves	38.2[e]	9.8[e]	13.5[e]	30.6	17.8	470
Grass	82[e]	13.6[e]	13.5[e]	136	31.1	240
Branches	15.9	3.4	19.0	62.6	1.6[f]	380[g]
Food Waste-Veg.	77	3.6	18.3	300.7	15.0[f]	80[g]
Food Waste-Non-Veg.	57	5.8	24.6	300.7	15.0	80
Wood[h]	16	9.4	19.0	11.6	6.5	437
Textiles	6	3.4	19.8	46.4	3.1	10
Rubber/Leather	7[i]	10.7[i]	25.2[i]	0	0	310[j]
Newsprint	13	7.3	17.1	74.3	3.5	420
Corr. Cardboard	17	11.0	15.1	152.3	2.1	260
Office Paper	9	12.2	12.5	217.3	3.1	50
Magazines	6	23.3	11.5	84.4	12.7	270
3rd Class Mail	9	24.9	13.1	84.4	12.7	270
Folding Cartons	22	11.2	15.0	152.3	2.1	260
Bags and Sacks	22	11.2	15.0	152.3	2.1	260
Paper-Non-recyclable	25	8.5	17.2	132.1	12.7	100
HDPE-Trans. Cont.	10[k]	6.2[k]	36.5[k]	0	0	0
HDPE-Pig. Cont.	10[k]	6.2[k]	36.5[k]	0	0	0
PET-Containers	10[k]	6.2[k]	36.5[k]	0	0	0
Plastic Film	14[l]	4.2[l]	40.1[l]	0	0	0
Plastic-Non-Recyclable	7	5.1	32.0	0	0	0
Ferrous Cans	13[m]	100[m]	0	0	0	0
Ferrous Metal-Other	13[m]	100[m]	0	0	0	0
Aluminum Cans	8	100	0	0	0	0
Aluminum-Foil	19	78	6.8	0	0	0
Al-Non-recyclable	19	100	0	0	0	0
Glass-Brown	5	100	0	0	0	0
Glass-Green	3	100	0	0	0	0
Glass-Clear	12	100	0	0	0	0
Misc. Inorganic	37[n]	96.6[n]	0	0	0	0

[a.] Moisture content, ash content, and lower heating values adapted from Riber and Christensen (2009) except as noted in note e.

[b.] Methane yield provided by Staley and Barlaz (2009), except wood.

[c.] Lab Decay Rate adapted from de la Cruz and Barlaz (2010), except wood – see note h.

[d.] Carbon Storage Factor determined from Staley and Barlaz (2009), except wood.

[e.] Moisture content from NRAES (1998), ash content, and lower heating value from yard waste, flowers Riber and Christensen (2009).

[f.] Lab decay rate values do not distinguish between vegetable and non-vegetable food waste.

[g.] Carbon storage factors do not distinguish between vegetable and non-vegetable food waste, Staley and Barlaz (2009).

[h.] Methane yield and decay rate and carbon storage developed from Wang et al (2011).

[i.] Rubber/Leather values based on 10% rubber and 90% leather weighted average for chemical composition.

[j.] Assumed non-degradable and that all of the biogenic carbon is stored.

[k.] Plastic bottle values for HDPE chemical compositions.

[l.] Soft plastic for plastic film chemical compositions.

[m.] Food Cans (tinplate/steel) for ferrous cans.

[n.] Mapped to “Other non-combustibles” in Riber and Christensen (2009).

Table B-3. Percent of each material generated in each sector.

Waste Material	Single Family	Multi-family	Commercial
Leaves	80	0	20
Grass	80	0	20
Branches	80	0	20
Food Waste-Veg.	40	20	40
Food Waste-Non-Veg.	40	20	40
Wood	0	0	100
Textiles	40	20	40
Rubber/Leather	40	20	40
Newsprint	60	30	10
Corr. Cardboard	7	3	90
Office Paper	20	10	70
Magazines	60	30	10
3rd Class Mail	60	30	10
Folding Cartons	60	30	10
Bags and Sacks	60	30	10
Paper-Non-recyclable	40	20	40
HDPE-Trans. Cont.	40	20	40
HDPE-Pig. Cont.	40	20	40
PET-Containers	40	20	40
Plastic Film	20	10	70
Plastic-Non-Recyclable	40	20	40
Ferrous Cans	40	20	40
Ferrous Metal-Other	20	10	70
Aluminum Cans	40	20	40
Aluminum-Foil	40	20	40
Al-Non-recyclable	40	20	40
Glass-Brown	40	20	40
Glass-Green	40	20	40
Glass-Clear	40	20	40
Misc. Inorganic	40	20	40
Total Distribution of Waste by Sector	41.3	13.7	45.0

Table B-4. Maximum percent of generation that is separated by a waste generator for mixed organics collection.

Waste Material	Single Family	Multi-family	Commercial
Leaves	95	-	95
Grass	95	-	95
Branches	95	-	95
Food Waste-Veg.	60	60	60
Food Waste-Non-Veg.	60	60	60

The maximum collection efficiencies shown in Table B-4 and B-5 determine the maximum percent of each generated waste material that can separated by a waste generator. The optimization model can choose to separate out less than this amount to for example meet diversion or GHG emissions constraints. Such a solution could be implemented by collecting different materials in different sub-communities, so if the model recommended only separating 45% of generated newsprint, a solid waste manager could include separate newsprint collection in 50% of sub-communities.

Table B-5. Maximum percent of generation that is separated by a waste generator for commingled recyclables collection.[a]

Waste Material	Single Family	Multi-family	Commercial
Newsprint	90	90	90
Corr. Cardboard	90	90	90
Office Paper	90	90	90
Magazines	80	80	80
3rd Class Mail	80	80	80
Folding Cartons	70	70	70
Bags and Sacks	70	70	70
HDPE-Trans. Cont.	40	40	40
HDPE-Pig. Cont.	40	40	40
PET-Containers	40	40	40
Plastic Film	20	20	20
Ferrous Cans	97	97	97
Ferrous Metal-Other	20	20	20
Aluminum Cans	70	70	70
Aluminum-Foil	20	20	20
Glass-Brown	50	50	50
Glass-Green	50	50	50
Glass-Clear	50	50	50

[a] Developed from U.S. EPA (2011) based on percent recovered and assumption that 71% of households are served by curbside collection.

Material Recovery Facilities

The modeled material recovery facilities (MRFs) are both automated systems. They both use disc screens to separate out OCC and other paper from the containers stream, while a vacuum is used to pull out plastic film. The containers are then processed through a glass breaker screen, and the glass is sorted by color using an optical sorter after being separated from fines using an air knife. The overs from the glass breaker screen contain mostly plastic and metal containers. The HDPE and PET are then separated out using an optical sorter, and aluminum and ferrous materials are recovered with an eddy current separator and a magnet, respectively. All of the separated materials except glass are then baled. The model also includes pickers that negatively sort out dangerous or contaminating materials from the recyclable streams. The materials that are not recovered form the residual. The mixed waste MRF (MWMRF) additionally uses a trommel to sift out fines and organics before the other separation processes. The separation efficiencies for both MRFs are shown in Table B-6. The recovery of all materials is reduced in the MWMRF compared to the single stream MRF (SSMRF) because of contamination and soiling of materials. The capital cost, build, and expansion parameters for both types of MRF are shown in Table B-7. The GHG emissions and operating costs are shown in Table B-8 and Table B-9, respectively. The emissions include electricity use and rolling stock fuel use. The operating costs include electricity and fuel costs as well as labor and equipment costs. The variations in operating costs and GHG emissions are due to how specific sub-processes are allocated to a given material (e.g., the magnet electricity use is only allocated to ferrous materials). The changes in operating cost and GHG emissions in the different stages are due to changes in electricity GHG intensity and electricity cost in each stage as shown in Figure 3-3 of the main body.

Table B-6 Separation efficiency for material recovery facilities (%).

Waste Material	Single Stream	Mixed Waste
Newsprint	99	25
Corr. Cardboard	99	80
Office Paper	98	25
Magazines	99	25
3rd Class Mail	99	25
Folding Cartons	99	25
Bags and Sacks	99	25
HDPE-Trans. Cont.	98	80
HDPE-Pig. Cont.	98	80
PET-Containers	98	80
Plastic Film	90	25
Ferrous Cans	98	90
Ferrous Metal-Other	98	90
Aluminum Cans	97	90
Aluminum-Foil	97	90
Glass-Brown	95	50
Glass-Green	95	50
Glass-Clear	95	50

Table B-7 Build and expansion parameters for material recovery facilities.

Process	Min Build ($Mg\ yr^{-1}$)	Min Exp ($Mg\ yr^{-1}$)[b]	Build Cost ($\$\ Mg^{-1}\ yr^{-1}$)	Expand Cost ($\$\ Mg^{-1}\ yr^{-1}$)[b]	Life (yr)
SSMRF	12,000	6000	7.38	7.38	20
MWMRF	24,000	12,000	7.38	7.38	20

[a.] Minimum expansion capacity was assumed to be half of the minimum build capacity.
[b.] Expansion costs are assumed to be the same as build costs.

Table B-8 GHG emissions coefficients in each stage for single stream MRF (kg CO_2e/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Newsprint	37	36	36	36	36	36
Corr. Cardboard	36	36	36	36	36	36
Office Paper	37	36	36	36	36	36
Magazines	37	36	36	36	36	36
3rd Class Mail	37	36	36	36	36	36
Folding Cartons	37	36	36	36	36	36
Bags and Sacks	37	36	36	36	36	36
HDPE-Trans. Cont.	39	38	38	38	39	38
HDPE-Pig. Cont.	39	38	38	38	39	38
PET-Containers	39	39	39	39	39	39
Plastic Film	37	36	36	36	36	36
Ferrous Cans	39	38	38	38	38	38
Ferrous Metal-Other	39	38	38	38	38	38
Aluminum Cans	38	38	38	38	38	38
Aluminum-Foil	38	38	38	38	38	38
Glass-Brown	44	44	44	44	44	44
Glass-Green	44	44	44	44	44	44
Glass-Clear	44	44	44	44	44	44

Table B-9 GHG emissions coefficients in each stage for mixed waste MRF (kg CO_2e/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	37	36	36	36	37	36
Grass	37	36	36	36	37	36
Branches	37	37	37	37	37	37
Food Waste-Veg.	37	36	36	36	37	36
Food Waste-Non-Veg.	37	36	36	36	37	36
Wood	37	37	37	37	37	37
Textiles	37	37	37	37	37	37
Rubber/Leather	37	37	37	37	37	37
Newsprint	41	40	40	40	40	40
Corr. Cardboard	39	38	38	38	38	38
Office Paper	41	40	40	40	40	40
Magazines	41	40	40	40	40	40
3rd Class Mail	41	40	40	40	40	40
Folding Cartons	41	40	40	40	40	40
Bags and Sacks	41	40	40	40	40	40
Paper-Non-recyclable	37	37	37	37	37	37
HDPE-Trans. Cont.	84	80	80	80	81	80
HDPE-Pig. Cont.	84	80	80	80	81	80
PET-Containers	51	50	50	50	50	50
Plastic Film	37	37	37	37	37	37
Plastic-Non-Recyclable	37	37	37	37	37	37
Ferrous Cans	57	55	55	55	55	55
Ferrous Metal-Other	57	55	55	55	55	55
Aluminum Cans	47	46	46	46	46	46
Aluminum-Foil	47	46	46	46	46	46
Al-Non-recyclable	47	46	46	46	46	46
Glass-Brown	52	50	50	50	51	50
Glass-Green	52	50	50	50	51	50
Glass-Clear	52	50	50	50	51	50
Misc. Inorganic	37	37	37	37	37	37

Table B-10 Operating cost coefficients in each stage for single stream MRF ($/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Newsprint	17	18	19	19	20	20
Corr. Cardboard	15	16	16	16	17	17
Office Paper	17	18	19	19	20	20
Magazines	17	18	19	19	20	20
3rd Class Mail	17	18	19	19	20	20
Folding Cartons	17	18	19	19	20	20
Bags and Sacks	17	18	19	19	20	20
HDPE-Trans. Cont.	25	25	26	26	27	27
HDPE-Pig. Cont.	25	25	26	26	27	27
PET-Containers	25	26	26	27	27	27
Plastic Film	21	22	22	23	23	23
Ferrous Cans	22	22	23	23	24	24
Ferrous Metal-Other	22	22	23	23	24	24
Aluminum Cans	23	24	24	25	25	25
Aluminum-Foil	23	24	24	25	25	25
Glass-Brown	24	25	25	26	26	26
Glass-Green	24	25	25	26	26	26
Glass-Clear	24	25	25	26	26	26

Table B-11 Operating cost coefficients in each stage for mixed waste MRF ($/Mg) [a].

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	12	13	13	14	14	14
Grass	12	13	13	14	14	14
Branches	16	17	17	18	18	18
Food Waste-Veg.	12	13	13	14	14	14
Food Waste-Non-Veg.	12	13	13	14	14	14
Wood	16	17	17	18	18	18
Textiles	16	17	17	18	18	18
Rubber/Leather	16	17	17	18	18	18
Newsprint	52	53	53	54	54	54
Corr. Cardboard	28	29	30	30	31	31
Office Paper	52	53	53	54	54	54
Magazines	52	53	53	54	54	54
3rd Class Mail	52	53	53	54	54	54
Folding Cartons	52	53	53	54	54	54
Bags and Sacks	52	53	53	54	54	54
Paper-Non-recyclable	16	17	18	18	19	19
HDPE-Trans. Cont.	83	84	85	85	86	86
HDPE-Pig. Cont.	83	84	85	85	86	86
PET-Containers	52	52	53	53	54	54
Plastic Film	20	21	21	22	22	23
Plastic-Non-Recyclable	16	17	17	18	18	18
Ferrous Cans	51	52	53	53	53	54
Ferrous Metal-Other	51	52	53	53	53	54
Aluminum Cans	44	44	45	45	46	46
Aluminum-Foil	44	44	45	45	46	46
Al-Non-recyclable	44	44	45	45	46	46
Glass-Brown	44	45	46	46	46	47
Glass-Green	44	45	46	46	46	47
Glass-Clear	44	45	46	46	46	47
Misc. Inorganic	15	16	17	17	18	18

a. These cost coefficients do not include the cost for downstream management (i.e., WTE or landfill) of the residual stream.

Waste-to-Energy Combustion

The waste-to-energy (WTE) process model is an updated version of that described by Harrison et al. (2000) and reflects current WTE emissions data. The modeled facility was assumed to have a heat rate of 15 MJ/kWh, and a combustion efficiency of 95%. It is assumed that 3% of ash produced from each material is fly ash and the rest is bottom ash. The updates to the model include a consideration of heat lost to moisture and ash in each material, and the ability to separate aluminum (in addition to ferrous metal) from bottom ash. The consideration of the heat losses leads the wet (e.g., food waste and grass) and inert materials (e.g., metals and glass) to have greater GHG emissions and cost, while the dryer combustible materials (e.g., paper and plastic) have lower emissions and costs due the offsets and revenue from the generated electricity. Table B-12 shows the capital cost, build, and expansion parameters for the WTE facility, and Table B-13 shows the separation efficiency for ferrous and aluminum materials from the bottom ash. Table B-14 and B-15 show the GHG emission and operating costs coefficients for each material in the WTE facility, respectively. Negative operating costs indicate that the revenue from the generated electricity is greater than the operating cost. Negative emissions indicate that the offsets associated with the avoided electricity generation are greater than the emissions from combusting the material. The changes in operating cost and GHG emissions in the different stages are due to changes in electricity GHG intensity and electricity cost in each stage as shown in Figure 3-3 of the main body.

Table B-12. Build and expansion parameters for waste-to-energy combustion.

Min Build ($Mg\ yr^{-1}$)	Min Exp ($Mg\ yr^{-1}$)[a]	Build Cost ($\$\ Mg^{-1}\ yr^{-1}$)	Expand Cost ($\$\ Mg^{-1}\ yr^{-1}$)[b]	Life (yr)
48,000	24,000	300	300	20

[a] Minimum expansion capacity was assumed to be half of the minimum build capacity.

[b] Expansion costs are assumed to be the same as build costs.

Table B-13 Separation efficiency for materials from WTE ash.[a]

Waste Material	Separation Efficiency (%)
Ferrous Cans	90
Ferrous Metal-Other	90
Aluminum Cans	65
Aluminum-Foil	65
Al-Non-recyclable	65

[a] Values from discussion with operators for typical WTE facilities.

Table B-14 GHG emissions coefficients in each stage for WTE (kg CO_2e/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	-235	-219	-219	-219	-222	-219
Grass	-4	-3	-3	-4	-4	-4
Branches	-516	-482	-482	-483	-488	-483
Food Waste-Veg.	-75	-70	-70	-70	-71	-70
Food Waste-Non-Veg.	-298	-278	-278	-278	-282	-278
Wood	-518	-483	-483	-484	-490	-484
Textiles	-216	-175	-175	-177	-183	-177
Rubber/Leather	189	241	241	240	231	240
Newsprint	-499	-467	-467	-468	-473	-468
Corr. Cardboard	-417	-390	-390	-391	-395	-391
Office Paper	-383	-359	-358	-359	-363	-359
Magazines	-362	-338	-338	-339	-343	-339
3rd Class Mail	-400	-374	-374	-375	-379	-375
Folding Cartons	-379	-355	-354	-355	-359	-355
Bags and Sacks	-379	-355	-354	-355	-359	-355
Paper-Non-recyclable	-391	-364	-364	-365	-369	-365
HDPE-Trans. Cont.	1266	1338	1338	1335	1324	1335
HDPE-Pig. Cont.	1266	1338	1338	1335	1324	1335
PET-Containers	818	890	890	888	876	888
Plastic Film	1255	1331	1331	1328	1316	1328
Plastic-Non-Recyclable	1258	1323	1323	1321	1311	1321
Ferrous Cans	16	15	15	15	15	15
Ferrous Metal-Other	16	15	15	15	15	15
Aluminum Cans	11	11	11	11	11	11
Aluminum-Foil	-168	-157	-157	-158	-159	-158
Al-Non-recyclable	26	25	25	25	25	25
Glass-Brown	8	8	8	8	8	8
Glass-Green	7	7	7	7	7	7
Glass-Clear	14	13	13	14	14	14
Misc. Inorganic	50	48	48	48	48	48

Table B-15 Operating cost coefficients in each stage for WTE ($/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	17	17	17	17	17	17
Grass	39	39	39	39	39	39
Branches	-9	-8	-9	-8	-8	-10
Food Waste-Veg.	33	33	33	33	33	33
Food Waste-Non-Veg.	11	12	12	12	12	11
Wood	-9	-8	-9	-8	-8	-10
Textiles	-18	-17	-18	-17	-17	-19
Rubber/Leather	-34	-33	-33	-33	-33	-35
Newsprint	-6	-5	-5	-5	-5	-6
Corr. Cardboard	2	2	2	2	2	1
Office Paper	5	5	5	5	5	4
Magazines	7	7	7	7	7	6
3rd Class Mail	3	4	4	4	4	3
Folding Cartons	5	6	5	6	6	5
Bags and Sacks	5	6	5	6	6	5
Paper-Non-recyclable	1	2	2	2	2	1
HDPE-Trans. Cont.	-62	-61	-61	-61	-61	-64
HDPE-Pig. Cont.	-62	-61	-61	-61	-61	-64
PET-Containers	-62	-61	-61	-61	-61	-64
Plastic Film	-67	-66	-67	-66	-66	-69
Plastic-Non-Recyclable	-53	-52	-52	-52	-52	-54
Ferrous Cans	41	41	41	41	41	41
Ferrous Metal-Other	41	41	41	41	41	41
Aluminum Cans	41	41	41	41	41	41
Aluminum-Foil	24	25	24	25	25	24
Al-Non-recyclable	42	42	42	42	42	42
Glass-Brown	41	41	41	41	41	41
Glass-Green	41	41	41	41	41	41
Glass-Clear	41	41	41	41	41	41
Misc. Inorganic	43	43	43	43	43	43

Anaerobic Digestion

The anaerobic digestion (AD) process model is based on an updated version of that described by Levis and Barlaz, 2011a. The modeled AD process is a high solids mesophilic process. Materials are pre-screened, shredded, and added to the reactor with additional water. The retention time is assumed to be 22 days, and the methane collected is based on the methane yield and lab decay rates for each material in Table B-2. The collected methane is combusted in a gas turbine to produce electricity. After leaving the reactor, materials are dewatered, and aerobically cured in windrows and screened. The final soil amendment is transported and land applied and is assumed to offset peat use. Table B-16 shows the capital cost, build, and expansion parameters for AD, and Table B-17 and B-18 show the GHG emissions and operating costs for AD, respectively. Negative GHG emissions indicate that the energy and soil amendment offsets are greater than the processing emissions. Food waste leads to the lowest GHG emissions because it has the highest methane yield (Table B-2). Branches also have low GHG emissions because they are mostly pre-screened out and lead to carbon storage once land applied. The changes in operating cost and GHG emissions in the different stages are due to changes in electricity GHG intensity and electricity cost in each stage as shown in Figure 3-3 of the main body.

Table B-16 Build and expansion parameters for AD.

Min Build ($Mg\ yr^{-1}$)	Min Exp ($Mg\ yr^{-1}$)[a]	Build Cost ($\$\ Mg^{-1}\ yr^{-1}$)	Expand Cost ($\$\ Mg^{-1}\ yr^{-1}$)[b]	Life (yr)
12,000	6000	493	493	20

[a.] Minimum expansion capacity was assumed to be half of the minimum build capacity.

[b.] Expansion costs are assumed to be the same as build costs.

Table B-17. GHG emissions coefficients in each stage for anaerobic digestion (kg CO_2e/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	25	25	24	24	24	24
Grass	14	15	15	15	15	15
Branches	0	-2	-2	-2	-2	-2
Food Waste-Veg.	-43	-39	-39	-39	-40	-39
Food Waste-Non-Veg.	-12	-2	-2	-3	-4	-3

Table B-18. Operating cost coefficients in each stage for anaerobic digestion ($/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	16	17	17	18	18	18
Grass	14	15	15	15	15	15
Branches	7	7	8	8	9	9
Food Waste-Veg.	9	10	10	10	10	10
Food Waste-Non-Veg.	2	2	3	3	3	3

Composting

The composting process model is based on an updated version of that described by Levis and Barlaz (2011a). The modeled composting facility uses windrows with 10 weeks of active composting, during which time the pile is turned every third day, followed by a 4 week curing phase where the piles are turned weekly. After curing, the materials are screened, and the final soil amendment is transported and land applied and is assumed to offset peat use. Table B-19 shows the capital cost, build, and expansion parameters for composting, and Table B-20 and B-21 show the GHG emissions and operating costs for composting, respectively. Negative GHG emissions indicate that the soil amendment offsets (including carbon storage) are greater than the processing emissions. Composting leaves and branches leads to the lowest GHG emissions because of their high carbon storage (Table B-2). The changes in operating cost and GHG emissions in the different stages are due to changes in electricity GHG intensity and electricity cost in each stage as shown in Figure 3-3 of the main body.

TableB-19. Build and expansion parameters for composting.

Min Build ($Mg\ yr^{-1}$)	Min Exp ($Mg\ yr^{-1}$)[a]	Build Cost ($\$\ Mg^{-1}\ yr^{-1}$)	Expand Cost ($\$\ Mg^{-1}\ yr^{-1}$)[b]	Life (yr)
6000	3000	27.43	27.43	20

[a] Minimum expansion capacity was assumed to be half of the minimum build capacity.

[b] Expansion costs are assumed to be the same as build costs.

Table B-20. GHG emissions coefficients in each stage for composting (kg CO_2e/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	-154	-154	-154	-154	-154	-154
Grass	12	12	11	11	11	11
Branches	-21	-21	-21	-21	-21	-21
Food Waste-Veg.	8	8	8	8	8	8
Food Waste-Non-Veg.	55	55	55	55	55	55

Table B-21. Operating cost coefficients in each stage for composting ($/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	21	22	22	22	22	22
Grass	23	23	23	23	23	23
Branches	25	25	25	25	25	25
Food Waste-Veg.	23	23	23	23	23	23
Food Waste-Non-Veg.	23	23	23	23	23	23

Landfill

Landfill gas modeling and fuel use have been described previously by Levis and Barlaz (2011b) Capital costs associated with landfill construction are amortized into the operating costs, and the life of the landfill is based on cumulative capacity. Landfill gas generation was modeled annually based on the methane yields and decay rates in Table B-2. The landfill is assumed to have a bulk decay rate of 0.04 yr^{-1}, so the field decay rates for each material are found by dividing the lab decay rates in Table B-2 by 156 (de la Cruz and Barlaz, 2010). Annual collection efficiencies are then applied until the system is shut-off after 30 years. The collected methane is combusted in an internal combustion engine to generate electricity. The biogenic carbon that does not degrade is considered stored. Ten percent of the fugitive methane is assumed to be oxidized into CO_2 as it passes through the cover. The GHG emissions and operating costs are shown in Table B-22 and B23, respectively. Negative emissions indicate that the energy offsets and carbon storage are greater than process and fugitive emissions. The changes in operating cost and GHG emissions in the different stages are due to changes in electricity GHG intensity and electricity cost in each stage as shown in Figure 3-3 of the main body.

Table B-22. GHG emissions coefficients in each stage for landfill (kg CO_2e/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	-951	-951	-951	-951	-951	-951
Grass	17	18	18	18	18	18
Branches	-760	-759	-759	-759	-759	-759
Food Waste-Veg.	326	328	328	328	328	328
Food Waste-Non-Veg.	601	606	606	606	605	605
Wood	-1266	-1266	-1266	-1266	-1266	-1266
Textiles	370	371	371	371	370	371
Rubber/Leather	-28	-28	-28	-28	-28	-28
Newsprint	-745	-743	-743	-743	-743	-743
Corr. Cardboard	294	297	297	296	296	296
Office Paper	1646	1651	1651	1651	1650	1651
Magazines	-468	-465	-465	-465	-466	-465
3rd Class Mail	-455	-452	-452	-452	-453	-452
Folding Cartons	274	277	277	276	276	276
Bags and Sacks	274	277	277	276	276	276
Paper-Non-recyclable	299	303	303	303	302	303
HDPE-Trans. Cont.	7	7	7	6	6	6
HDPE-Pig. Cont.	7	7	7	6	6	6
PET-Containers	7	7	7	6	6	6
Plastic Film	7	7	7	6	6	6
Plastic-Non-Recyclable	7	7	7	6	6	6
Ferrous Cans	7	7	7	6	6	6
Ferrous Metal-Other	7	7	7	6	6	6
Aluminum Cans	7	7	7	6	6	6
Aluminum-Foil	7	7	7	6	6	6
Al-Non-recyclable	7	7	7	6	6	6
Glass-Brown	7	7	7	6	6	6
Glass-Green	7	7	7	6	6	6
Glass-Clear	7	7	7	6	6	6
Misc. Inorganic	7	7	7	6	6	6
Fly Ash	7	7	7	6	6	6
Bottom Ash	7	7	7	6	6	6

Table B-23. Operating cost coefficients in each stage for landfill ($/Mg).

Waste Material	2010	2015	2020	2025	2030	2035
Leaves	22	22	23	23	23	23
Grass	23	23	23	23	23	23
Branches	22	22	22	22	23	23
Food Waste-Veg.	19	20	20	20	20	20
Food Waste-Non-Veg.	16	16	16	16	17	16
Wood	23	23	23	23	23	23
Textiles	22	22	22	22	22	22
Rubber/Leather	23	23	23	24	24	24
Newsprint	21	21	21	21	21	21
Corr. Cardboard	20	20	20	20	20	20
Office Paper	16	16	16	16	16	16
Magazines	19	19	19	19	19	19
3rd Class Mail	19	19	19	19	19	19
Folding Cartons	20	20	20	20	20	20
Bags and Sacks	20	20	20	20	20	20
Paper-Non-recyclable	17	18	18	18	18	18
HDPE-Trans. Cont.	23	23	23	24	24	24
HDPE-Pig. Cont.	23	23	23	24	24	24
PET-Containers	23	23	23	24	24	24
Plastic Film	23	23	23	24	24	24
Plastic-Non-Recyclable	23	23	23	24	24	24
Ferrous Cans	23	23	23	24	24	24
Ferrous Metal-Other	23	23	23	24	24	24
Aluminum Cans	23	23	23	24	24	24
Aluminum-Foil	23	23	23	24	24	24
Al-Non-recyclable	23	23	23	24	24	24
Glass-Brown	23	23	23	24	24	24
Glass-Green	23	23	23	24	24	24
Glass-Clear	23	23	23	24	24	24
Misc. Inorganic	23	23	23	24	24	24
Fly Ash	23	23	23	24	24	24
Bottom Ash	23	23	23	24	24	24

Remanufacturing

Revenue from recyclables sale is based on discussions with MRF operators. The life-cycle offsets associated with material recovery were developed from published data (RTI, 2003). The GHG emissions and remanufacturing costs (i.e., negative revenue) are shown in Table B-24 and B-25, respectively. Negative GHG emissions values indicate that the emissions savings from recycling are greater than emissions associated with recycling. Positive cost values indicate that companies must pay to have these materials hauled away. Bottom ash recycling is assumed to have no net benefits. The changes in operating cost and GHG emissions in the different stages are due to changes in electricity GHG intensity and electricity cost in each stage as shown in Figure 3-3 of the main body.

Table B-24. GHG emissions coefficients in each stage for remanufacturing (kg CO_2e/Mg)[a].

	2010	2015	2020	2025	2030	2035
Newsprint	-1015	-985	-982	-980	-984	-979
Corr. Cardboard	-749	-758	-755	-751	-748	-750
Office Paper	1361	1348	1348	1349	1351	1349
Magazines	1161	1152	1152	1153	1154	1153
3rd Class Mail	1161	1152	1152	1153	1154	1153
Folding Cartons	-749	-758	-755	-751	-748	-750
Bags and Sacks	-749	-758	-755	-751	-748	-750
HDPE-Trans. Cont.	-2685	-2685	-2685	-2685	-2685	-2686
HDPE-Pig. Cont.	-2685	-2685	-2685	-2685	-2685	-2686
PET-Containers	-3017	-3014	-3014	-3015	-3015	-3015
Plastic Film	-3314	-3310	-3310	-3310	-3311	-3311
Ferrous Cans	-950	-950	-950	-950	-950	-950
Ferrous Metal-Other	-950	-950	-950	-950	-950	-950
Aluminum Cans	-13250	-12705	-12695	-12707	-12783	-12688
Aluminum-Foil	-13250	-12705	-12695	-12707	-12783	-12688
Glass-Brown	-349	-347	-347	-346	-346	-346
Glass-Green	-349	-347	-347	-346	-346	-346
Glass-Clear	-349	-347	-347	-346	-346	-346
Bottom Ash	0	0	0	0	0	0

[a.] Values adapted from RTI (2003) with electricity emissions from Figure 3-3 of the main body.

Table B-25. Operating cost coefficients in each stage for remanufacturing ($/Mg).[a]

	2010	2015	2020	2025	2030	2035
Newsprint	-55	-55	-55	-55	-55	-55
Corr. Cardboard	-77	-77	-77	-77	-77	-77
Office Paper	-50	-50	-50	-50	-50	-50
Magazines	-50	-50	-50	-50	-50	-50
3rd Class Mail	-50	-50	-50	-50	-50	-50
Folding Cartons	-50	-50	-50	-50	-50	-50
Bags and Sacks	-50	-50	-50	-50	-50	-50
HDPE-Trans. Cont.	-330	-330	-330	-330	-330	-330
HDPE-Pig. Cont.	-330	-330	-330	-330	-330	-330
PET-Containers	-290	-290	-290	-290	-290	-290
Plastic Film	0	0	0	0	0	0
Ferrous Cans	-110	-110	-110	-110	-110	-110
Ferrous Metal-Other	-110	-110	-110	-110	-110	-110
Aluminum Cans	-1300	-1300	-1300	-1300	-1300	-1300
Aluminum-Foil	-1300	-1300	-1300	-1300	-1300	-1300
Glass-Brown	-20	-20	-20	-20	-20	-20
Glass-Green	1	1	1	1	1	1
Glass-Clear	-28	-28	-28	-28	-28	-28
Bottom Ash	0	0	0	0	0	0

[a.] Negative costs indicate the revenue associated with selling each material.

Energy System

Table B-26. Electricity related parameters in each time stage.[a]

		Electricity Fuel Mix (%)					
Fuel Type	GHG Emissions ($g\ CO_2e/kWh$)[b]	2010	2015	2020	2025	2030	2035
Coal	1001	43.5	39.4	40.5	40.5	40.2	39.4
Petroleum	840	0.7	0.6	0.6	0.6	0.6	0.6
Natural Gas	469	23.6	25.4	23.8	24.1	25.5	26.4
Nuclear Power	16	20.5	21.4	21.6	21.1	20.1	19.2
Pumped Storage/Other	4	0.1	0.0	0.0	0.0	0.0	0.0
Hydropower	4	7.1	7.4	7.2	7.0	6.9	6.8
Geothermal	45	0.4	0.5	0.7	0.8	1.0	1.1
WTE	17	0.4	0.4	0.4	0.3	0.3	0.3
Wood and Biomass	18	0.3	0.8	1.4	1.4	1.1	1.2
Solar Thermal	22	0.0	0.1	0.1	0.1	0.1	0.1
Solar Photovoltaic	46	0.1	0.1	0.1	0.1	0.3	0.6
Wind	12	3.2	3.8	3.7	3.8	3.9	4.3

[a.] Electricity generation mix developed from AEO 2012 Projections (U.S. EIA, 2012).

[b.] GHG emissions developed from IPCC (2011).

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APPENDIX C. Energy scenario data

Table C-1. Percent of heavy-duty transportation demand met by each technology in each stage for the Reference energy scenario.[a]

Technology[a]	2010	2015	2020	2025	2030	2035
THEDSL	89.7	60.9	42.5	28.1	15.8	5.4
THEGSL	9.8	6.6	4.6	3.1	1.7	0.6
THELPG	0.4	0.2	0.2	0.1	0.1	0.0
THECNG	0.2	0.1	0.1	0.1	0.0	0.0
THCNG10	0.0	3.0	3.3	3.5	3.7	4.0
THDSL10P10	0.0	28.3	25.2	23.1	21.1	19.3
THDSL20	0.0	0.0	21.5	38.1	52.3	64.4
THGSL10	0.0	0.6	2.5	3.8	5.0	5.9
THLPG10	0.0	0.1	0.2	0.2	0.3	0.3
THDSL10P20	0.0	0.0	0.0	0.0	0.0	0.0
Total Demand (bnvmt)[b]:	205	248	278	304	333	363

[a.] Values developed from Babaee et al., 2013.
[b.] Definition of technology abbreviations are shown in Table C-5.
[c.] bnvmt = billion vehicle miles traveled.

Table C-2. Percent of heavy-duty transportation demand met by each technology in each stage for the LowNG energy scenario.

Technology[a]	2010	2015	2020	2025	2030	2035
THEDSL	89.7	60.9	42.5	28.1	15.8	5.4
THEGSL	9.8	6.6	4.6	3.1	1.7	0.6
THELPG	0.4	0.2	0.2	0.1	0.1	0.0
THECNG	0.2	0.1	0.1	0.1	0.0	0.0
THCNG10	0.0	3.0	3.3	3.5	3.7	4.0
THDSL10P10	0.0	28.3	25.2	23.1	21.1	19.3
THDSL20	0.0	0.0	21.5	38.1	52.3	64.4
THGSL10	0.0	0.6	2.5	3.8	5.0	5.9
THLPG10	0.0	0.1	0.2	0.2	0.3	0.3
THDSL10P20	0.0	0.0	0.0	0.0	0.0	0.0
Total Demand (bnvmt)[b]:	205	248	278	304	333	363

[a.] Values developed from Babaee et al., 2013.
[b.] Definition of technology abbreviations are shown in Table C-5.
[c.] bnvmt = billion vehicle miles traveled.

Table C-3. Percent of heavy-duty transportation demand met by each technology in each stage for the RPS energy scenario.

Technology[a]	2010	2015	2020	2025	2030	2035
THEDSL	89.7	60.9	42.5	28.1	15.8	5.4
THEGSL	9.8	6.6	4.6	3.1	1.7	0.6
THELPG	0.4	0.2	0.2	0.1	0.1	0.0
THECNG	0.2	0.1	0.1	0.1	0.0	0.0
THCNG10	0.0	3.0	3.3	3.5	3.7	4.0
THDSL10P10	0.0	28.3	25.2	23.1	21.1	19.3
THDSL20	0.0	0.0	21.5	38.1	52.3	64.4
THGSL10	0.0	0.6	2.5	3.8	5.0	5.9
THLPG10	0.0	0.1	0.2	0.2	0.3	0.3
THDSL10P20	0.0	0.0	0.0	0.0	0.0	0.0
Total Demand (bnvmt)[b]:	205	248	278	304	333	363

[a.] Values developed from Babaee et al., 2013.
[b.] Definition of technology abbreviations are shown in Table C-5.
[c.] bnvmt = billion vehicle miles traveled.

Table C-4. Percent of heavy-duty transportation demand met by each technology in each stage for the CO_2 energy scenario.

Technology[a]	2010	2015	2020	2025	2030	2035
THEDSL	89.7	60.9	42.5	28.1	15.8	5.4
THEGSL	9.8	6.6	4.6	3.1	1.7	0.6
THELPG	0.4	0.2	0.2	0.1	0.1	0.0
THECNG	0.2	0.1	0.1	0.1	0.0	0.0
THCNG10	0.0	3.0	3.3	3.5	3.7	4.0
THDSL10P10	0.0	28.3	25.2	23.1	21.1	19.3
THDSL20	0.0	0.0	21.5	19.7	18.0	16.5
THGSL10	0.0	0.6	2.5	3.8	5.0	5.9
THLPG10	0.0	0.1	0.2	0.2	0.3	0.3
THDSL10P20	0.0	0.0	0.0	18.4	34.3	47.9
Total Demand (bnvmt)[b]:	205	248	278	304	333	363

[a.] Values developed from Babaee et al., 2013.
[b.] Definition of technology abbreviations are shown in Table C-5.
[c.] bnvmt = billion vehicle miles traveled.

Table C-5. Definition of heavy-duty transportation technology name abbreviations.

Technology Name	Description
THEDSL	Truck Heavy Existing Diesel Fleet
THEGSL	Truck Heavy Existing Gasoline Fleet
THELPG	Truck Existing Heavy LPG
THECNG	Truck Heavy Exisiting Compressed Natural Gas
THCNG10	Truck Heavy Compressed Natural Gas 2010
THDSL10P10	Truck Heavy Diesel 10 MPG 2010
THDSL20	Truck Heavy Diesel 2020
THGSL10	Truck Heavy Gasoline 2010
THLPG10	Truck Heavy LPG 2010
THDSL10P20	Truck Heavy Diesel 10 MPG 2020

Table C-6. Electricity mix in each stage for the Reference energy scenario.

Technology[a]	2010	2015	2020	2025	2030	2035
EBIOIGCC	0.0	0.0	0.0	0.0	0.0	0.0
EBIOSTMR	0.0	0.0	0.0	0.0	0.0	0.0
ECOALIGCCS	0.0	0.0	0.0	0.0	0.0	0.0
ECOALSTM	0.0	1.7	1.7	1.6	1.5	1.5
ECOASTMR	45.6	36.7	36.8	37.9	37.5	36.8
EGEOBCFS	0.0	0.2	0.5	0.8	1.1	1.4
EGEOR	0.0	0.5	0.4	0.2	0.1	0.0
EHYDCONR	7.3	7.8	7.5	7.2	6.9	6.7
EMSWSTMR	0.0	0.4	0.0	0.2	0.1	0.1
ENGAACC	0.0	17.2	14.8	10.4	9.6	12.6
ENGACCR	24.1	6.9	5.8	3.3	4.1	2.1
ENGASTMR	0.1	0.0	0.0	0.0	0.0	0.0
ESOLPVCEN	0.0	0.0	0.0	0.0	0.0	0.0
ESOLPVR	0.0	0.0	0.0	0.0	0.0	0.0
ESOLSTCEN	0.0	0.0	0.0	0.0	0.0	0.1
ESOLTHR	0.1	0.1	0.1	0.0	0.0	0.0
EURNALWR	20.0	19.7	18.8	18.1	17.4	15.9
EURNALWR15	0.0	2.3	3.6	8.2	9.5	10.9
EWNDCL5	0.0	0.0	0.0	1.7	2.5	3.1
EWNDCL6	0.0	3.9	8.2	8.7	8.4	8.1
EWNDR	2.8	2.4	1.9	1.5	1.1	0.7
Total Demand (kWh)	3.95E+12	4.00E+12	4.17E+12	4.33E+12	4.50E+12	4.66E+12

[a.] Values developed from Babaee et al., 2013.

[b.] Definition of technology abbreviations are shown in Table C-10.

Table C-7. Electricity mix in each stage for the LowNG energy scenario.

LowNG						
Technology[a]	2010	2015	2020	2025	2030	2035
EBIOIGCC	0.0	0.0	0.0	0.0	0.0	0.0
EBIOSTMR	0.0	0.0	0.0	0.0	0.0	0.0
ECOALIGCCS	0.0	0.0	0.0	0.0	0.0	0.0
ECOALSTM	0.0	0.0	0.0	0.0	0.0	0.0
ECOASTMR	45.6	31.1	27.9	27.0	29.2	37.0
EGEOBCFS	0.0	0.2	0.2	0.8	1.1	1.4
EGEOR	0.0	0.5	0.4	0.2	0.1	0.0
EHYDCONR	7.3	7.8	7.5	7.2	6.9	6.7
EMSWSTMR	0.0	0.4	0.0	0.0	0.0	0.0
ENGAACC	0.0	27.6	27.4	26.3	24.7	21.0
ENGACCR	24.1	6.2	7.4	8.1	8.4	6.0
ENGASTMR	0.1	0.0	0.0	0.0	0.0	0.0
ESOLPVCEN	0.0	0.0	0.0	0.0	0.0	0.0
ESOLPVR	0.0	0.0	0.0	0.0	0.0	0.0
ESOLSTCEN	0.0	0.0	0.0	0.0	0.0	0.0
ESOLTHR	0.1	0.1	0.1	0.0	0.0	0.0
EURNALWR	20.0	19.7	18.8	18.1	17.4	15.9
EURNALWR15	0.0	0.0	0.0	0.0	0.0	0.0
EWNDCL5	0.0	0.0	0.0	1.9	2.6	3.2
EWNDCL6	0.0	3.9	8.5	8.7	8.4	8.1
EWNDR	2.8	2.4	1.9	1.5	1.1	0.7
Total Demand (kWh)	3.95E+12	4.00E+12	4.17E+12	4.33E+12	4.50E+12	4.66E+12

[a.] Values developed from Babaee et al., 2013.

[b.] Definition of technology abbreviations are shown in Table C-10.

Table C-8. Electricity mix in each stage for the RPS energy scenario.

Technology[a]	2010	2015	2020	2025	2030	2035
EBIOIGCC	0.0	0.3	0.2	0.1	0.2	0.2
EBIOSTMR	0.0	1.1	0.0	0.0	0.0	0.0
ECOALIGCCS	0.0	0.0	0.0	0.0	0.0	0.0
ECOALSTM	0.0	0.6	0.6	0.6	0.6	0.6
ECOASTMR	45.6	36.7	36.8	37.9	37.5	37.0
EGEOBCFS	0.0	0.2	0.5	0.8	1.1	1.4
EGEOR	0.0	0.5	0.4	0.2	0.1	0.0
EHYDCONR	7.3	7.8	7.5	7.2	6.9	6.7
EMSWSTMR	0.0	0.7	0.0	0.2	0.1	0.1
ENGAACC	0.0	15.6	11.1	8.4	8.3	8.7
ENGACCR	24.1	7.7	3.0	2.9	4.1	3.8
ENGASTMR	0.1	0.0	0.0	0.0	0.0	0.0
ESOLPVCEN	0.0	0.0	0.0	0.0	0.0	0.0
ESOLPVR	0.0	0.0	0.0	0.0	0.0	0.0
ESOLSTCEN	0.0	0.2	0.2	0.2	0.2	0.2
ESOLTHR	0.1	0.1	0.1	0.0	0.0	0.0
EURNALWR	20.0	19.7	18.8	18.1	17.4	15.9
EURNALWR15	0.0	2.3	2.2	4.9	5.2	7.2
EWNDCL5	0.0	0.0	7.7	8.1	8.7	9.4
EWNDCL6	0.0	3.9	9.1	8.7	8.4	8.1
EWNDR	2.8	2.4	1.9	1.5	1.1	0.7
Total Demand (kWh)	3.95E+12	4.00E+12	4.17E+12	4.33E+12	4.50E+12	4.66E+12

[a.] Values developed from Babaee et al., 2013.

[b.] Definition of technology abbreviations are shown in Table C-10.

Table C-9. Electricity mix in each stage for the CO_2 energy scenario.

Technology[a]	2010	2015	2020	2025	2030	2035
EBIOIGCC	0.0	0.3	0.2	0.1	0.2	0.2
EBIOSTMR	0.0	1.1	0.0	0.0	0.0	0.0
ECOALIGCCS	0.0	0.0	1.0	3.1	8.6	12.0
ECOALSTM	0.0	0.0	0.0	0.0	0.0	0.0
ECOASTMR	45.6	32.1	27.8	25.9	24.2	18.5
EGEOBCFS	0.0	0.2	0.5	0.8	1.1	1.4
EGEOR	0.0	0.5	0.4	0.2	0.1	0.0
EHYDCONR	7.3	7.8	7.5	7.2	6.9	6.7
EMSWSTMR	0.0	0.7	0.0	0.0	0.1	0.0
ENGAACC	0.0	21.8	18.1	14.9	10.5	11.2
ENGACCR	24.1	6.7	3.2	2.5	1.8	2.2
ENGASTMR	0.1	0.0	0.0	0.0	0.0	0.0
ESOLPVCEN	0.0	0.0	0.0	0.0	0.0	0.0
ESOLPVR	0.0	0.0	0.0	0.0	0.0	0.0
ESOLSTCEN	0.0	0.2	0.2	0.2	0.2	0.2
ESOLTHR	0.1	0.1	0.1	0.0	0.0	0.0
EURNALWR	20.0	19.7	18.8	18.1	17.3	15.8
EURNALWR15	0.0	2.3	3.6	8.2	10.6	13.6
EWNDCL5	0.0	0.0	7.6	8.3	8.8	9.4
EWNDCL6	0.0	3.9	9.1	8.7	8.4	8.1
EWNDR	2.8	2.4	1.9	1.5	1.1	0.7
Total Demand (kWh)	3.95E+12	4.00E+12	4.17E+12	4.33E+12	4.50E+12	4.66E+12

[a.] Values developed from Babaee et al., 2013.

[b.] Definition of technology abbreviations are shown in Table C-10.

Table C-10. Definition of electricity technology name abbreviations.

Technology Name	Description
EBIOIGCC	Biomass Integrated Gasification Combined-Cycle
EBIOSTMR	Wood/Biomass Steam
ECOALIGCCS	Integrated Coal Gasif. Combined Cycle -- CO2 Capt.
ECOALSTM	Pulverized Coal Steam - 2010
ECOASTMR	Residual Coal Steam
EGEOBCFS	Geothermal - Binary Cycle and Flashed Steam
EGEOR	Geothermal
EHYDCONR	Hydroelectric, Conventional
EMSWSTMR	Municipal Solid Waste Steam
ENGAACC	Natural Gas - Advanced Combined-Cycle (Turbine)
ENGACCR	Natural Gas Combined-Cycle
ENGASTMR	Natural Gas Steam
ESOLPVCEN	Solar PV Centralized Generation
ESOLPVR	Solar Photovoltaic
ESOLSTCEN	Solar Thermal Centralized Generation
ESOLTHR	Solar Thermal
EURNALWR	Pre-Existing Nuclear LWRs
EURNALWR15	Nuclear LWRs in 2015
EWNDCL5	Wind Generation Class 5
EWNDCL6	Wind Generation Class 6
EWNDR	Wind

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