

Solid Waste Management Policy Implications on Waste Process Choices and Systemwide Cost and Greenhouse Gas Performance

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Supporting Information

ABSTRACT: Solid waste management (SWM) is a key function of local government and is critical to protecting human health and the environment. Development of effective SWM strategies should consider comprehensive SWM process choices and policy implications on system-level cost and environmental performance. This analysis evaluated cost and select environmental implications of SWM policies for Wake County, North Carolina using a life-cycle approach. A countyspecific data set and scenarios were developed to evaluate alternatives for residential municipal SWM, which included combinations of a mixed waste material recovery facility (MRF), anaerobic digestion, and waste-to-energy combustion in addition to existing SWM infrastructure (composting, landfilling, single stream recycling). Multiple landfill diversion



and budget levels were considered for each scenario. At maximum diversion, the greenhouse gas (GHG) mitigation costs ranged from 30 to 900 \$/MTCO2e; the lower values were when a mixed waste MRF was used, and the higher values when anaerobic digestion was used. Utilization of the mixed waste MRF was sensitive to the efficiency of material separation and operating cost. Maintaining the current separate collection scheme limited the potential for cost and GHG reductions. Municipalities seeking to cost-effectively increase landfill diversion while reducing GHGs should consider waste-to-energy, mixed waste separation, and changes to collection.

1. INTRODUCTION

Proper solid waste management (SWM) is important to protect human and environmental health and is a critical function of local government. At the local level, waste collection may comprise as much as 40% of municipal solid waste (MSW) management budgets¹ and may be the most fossil fuel-intensive process in SWM systems.² Landfills, which nationally receive over 50% of municipal solid waste, are estimated to be the third largest contributor to anthropogenic methane (CH_4) emissions in the U.S. (17.6%), and landfilling, composting, and waste incineration are reported to be responsible for approximately 2% of U.S. greenhouse gas (GHG) emissions.³ Many local and state policies have been enacted with the goal of improving the cost or environmental performance of SWM systems. For example, yard waste bans have been enacted to increase landfill diversion⁴ and some communities (e.g., Portland, OR; San Francisco, CA; Seattle, WA) have mandated food waste diversion for residential and/ or commercial generators.^{5–8} Because the economic and environmental trade-offs among different SWM system designs are location-dependent^{9,10} and influenced by existing or potential SWM practices and policies,¹¹ strategies enacted with the intent of accomplishing environmental goals may not necessarily achieve them universally (e.g., the benefits of recycling will vary based on the availability of reprocessors and materials markets). Furthermore, piecemeal policies targeted for a specific waste flow or process may have unintended consequences elsewhere in the system that could potentially undermine the intended purpose of the policy. Thus, systematic integrated analysis of SWM alternatives in consideration of local waste characteristics, existing infrastructure, and considerations of multiple stakeholders is necessary to evaluate whether proposed SWM strategies achieve the intended goals and to support development of appropriate policies and plans for future SWM.

Interest in the impact of existing municipal SWM practices on environmental performance, cost, and other metrics is illustrated by regional and national SWM case studies. Supporting Information (SI) Table S1 presents studies that included two or more solid waste processes. In some cases, a life-cycle methodology was used to compare baseline scenarios with alternative SWM approaches,^{9,10,12–29} while other studies employed different methods, such as waste flow analysis³⁰ or

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Figure 1. Potential mass flows through the prevailing and future SWM systems for Wake County, NC. Residual waste includes MSW that remains after source-separated recyclables and organics (only yard waste included in current system) are collected. Mixed waste collection can be used to collect all generated waste. Aluminum and ferrous metal in WTE bottom ash can be separated and recycled, but remaining bottom ash and fly ash are assumed to not be beneficially used in this study. The SI includes waste generation and composition (Section 2), and facility details (Section 3)). Adapted from Levis, J.W.; Barlaz, M. A.; DeCarolis, J.F.; Ranjithan, S. R. Systematic exploration of efficient strategies to manage solid waste in US municipalities: Perspectives from the solid waste optimization life-cycle framework (SWOLF). *Environ Sci Technol.* 2014, *48* (7) 3625–3631.³⁴ Copyright 2014 American Chemical Society.

multiperiod mixed integer linear programming (MILP) along with life-cycle data to analyze geographically different regions (e.g., optimizing for cost by maximizing profit,³¹ maximizing profit while assigning a financial cost to environmental impacts³²). Notably, the number of systematic case studies in the context of U.S. SWM systems is small, even though comprehensive integrated analyses (e.g., life-cycle-based case studies³³) in the U.S. context could contribute to decision support as municipalities increasingly seek SWM strategies to achieve cost and environmental goals while addressing landfill diversion challenges.³⁴

The objective of this study is to assess the cost, environmental performance (i.e., net GHG emissions), and landfill diversion potential for Wake County, North Carolina (NC), considering current and prospective alternative SWM strategies from a life-cycle perspective, while accounting for potential policies and factors that could influence future management choices. Wake County is a large, suburban county in the center of NC, which operates its own landfill (South Wake) with approximately 25 years of remaining capacity.³⁵ County management has a goal to maximize the life of the South Wake Landfill while simultaneously considering cost and environmental impacts. Additional objectives of this paper are to (1) provide methodological insights on modeling a complex SWM system using real data and a life-cycle optimization decision-support tool (the Solid Waste Life-cycle Optimization Framework, SWOLF);³⁶ and (2) perform policy-relevant optimization analyses to support SWM decision-making. The prospective SWM options included combinations of the following: addition of anaerobic digestion (AD), thermal treatment by mass-burn waste-to-energy (WTE), and a mixed waste material recovery facility (MRF), as well as changes to the current collection practice.

2. MODELING APPROACH

This section describes how the Wake County SWM system was represented in SWOLF. More generally, the methodological steps described here provide a roadmap for other researchers to develop thorough, data-driven representations of their own case studies.

2.1. Functional Unit and System Boundaries. A lifecycle approach was used to quantify GHG emissions, costs, and landfill diversion associated with current and potential SWM strategies for Wake County. The functional unit is the annual mass of residential mixed MSW ready for end-of-life treatment (e.g., set out at the curb), and reference flows are the masses of individual waste items (e.g., brown glass, aluminum cans), as detailed in SI Section 2. Landfill diversion is defined as the fraction of generated waste that does not go to a landfill (e.g., landfilled bottom ash from waste-to-energy does not count as diversion). For some scenarios, source-separated recyclables and/or organics can be collected independently, with the remaining waste referred to as residuals. Collected waste is managed at existing or prospective future SWM facilities (Figure 1). The system boundary includes final disposal of residual waste in a landfill and the reprocessing of recovered recyclable materials including beneficial offsets from avoided primary energy and material production. SWM options considered were based on existing practice in Wake County and other available technologies in a U.S. context. The analysis used a 100-year time horizon for environmental emissions. One-hundred-year global warming potential (GWP) was calculated using values from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report which reported that one kg CH₄ is equivalent to 34 kg CO₂ over 100 years.³⁷ The Wake County SWM system was modeled and implemented using SWOLF, which uses a multistage optimization approach based on a mixed-binary linear

scenario name	description	model objective(s) (key constraints)
Base_Case	current practice involves separate collection of residential recyclables to a single-stream MRF and yard waste to composting facilities (single-family residences only)	cost
+FW+AD	Base Case plus food waste cocollected with yard waste and AD enabled (but not required to be selected). Diversion is fixed based on assumed source separation rates.	cost, GHG
+MW	Base_Case with mixed waste MRF enabled	cost (diversion)
+WTE	Base_Case with WTE enabled	cost (diversion)
+MW+WTE	Base_Case with mixed waste MRF and WTE both enabled	cost (diversion) GHG (cost)
+MW+WTE +AnyCollection	as in +MW+WTE, but separate collection of recyclables and yard waste is not required	cost (diversion) GHG (cost)

program, to identify efficient SWM alternatives in consideration of cost and select environmental emissions.³⁶

2.2. Wake County Waste Characteristics and Waste Generation Sectors. Wake County had a population of approximately 1.02 million in 2015 and was the fastest growing metropolitan area in the U.S. between 2000 and 2010.³⁸ Wake County residential waste was assumed to originate from one of three sectors: (1) single-family residential, (2) multifamily residential, or (3) drop-off convenience centers. The county consists of 12 incorporated cities and towns that collect or have contracts for the separate collection of yard waste, recyclables, and residual waste from single-family residences. Waste collection from multifamily units is modeled as two sectors: one representing Raleigh since most multifamily residents live in Raleigh, and the other representing the rest of the county. Each city or town operates convenience (i.e., drop off) centers to collect recyclables and residual waste from residents, and the county operates centers for residents of unincorporated areas. All convenience centers are modeled as a single sector. SI Table S4 presents the mass generated by each residential sector and the amount initially diverted from landfill disposal (i.e., collected for yard waste composting or recycling). SI Tables S5-S7 present the composition of each separately collected waste stream for each sector and the source-separated fraction (i.e., the collection separation efficiency) for each waste item for each sector.

The management of commercial waste was not included in this study since commercial waste is not collected or managed by the municipalities and counties in North Carolina. As some commercial waste is nonetheless managed by the county's landfill, potential implications of commercial waste management are discussed with the results.

2.3. Scenario Descriptions. Scenarios were created to represent current practice and plausible SWM alternative strategies (i.e., technology choices and mass flows) that align with the county's management goals. These scenarios include the addition of food waste collection, AD, WTE, and a mixed waste MRF (Table 1). For each scenario, SWOLF was used to identify SWM strategies that meet specified objectives (e.g., minimize cost, maximize landfill diversion, minimize GHG emissions) subject to waste management targets and constraints.

In the scenario representing current practice in Wake County (Base_Case), recyclables and yard waste are collected separately. For the least-cost strategies, different combinations of processes are enabled, and the minimum cost solutions were found at incrementally increasing diversion requirements. For the least-GHG strategies, minimum GHG solutions were found at incrementally increasing budget levels.

The county is considering food waste diversion, and some small-scale food waste diversion efforts are already in place (primarily drop-off). In addition to the current practice in Wake County, +FW+AD enables food waste collection and AD. Similarly, additional MSW treatment technologies (i.e., mixed waste MRF and WTE) are also enabled, independently and simultaneously, to identify alternative SWM strategies that could increase landfill diversion (scenarios +MW, +WTE, and +MW+WTE) while still potentially utilizing the existing separate (yard waste, single-stream recyclables and residual) waste collection system. As SWM goals could be achieved through alternative strategies that need not necessarily include separate collection of recyclables or yard waste, +MW+WTE +AnyCollection is included to represent the least constrained situation in which any facility type and any collection scheme could be used in appropriate combinations.

2.4. Facility and Process Modeling. SWOLF embeds life-cycle process models that compute waste-item-specific unit cost and emissions coefficients for individual processes in the SWM system, including waste collection,³⁹ transfer stations (simplified version of 40), landfills,⁴¹ composting,⁴¹ AD,⁴¹ MRFs,⁴⁰ mass burn WTE (updated version of 42), and material reprocessing.43 A collection model was created for each sector using collection activity data from multiple sources.^{35,44-46} The landfill model reflects South Wake Landfill operations. Composting facilities in Wake County use windrows and the resulting compost is assumed to be land applied with appropriate mineral fertilizer production offsets.⁴¹ Digestate from a potential new AD facility is assumed to be aerobically cured after AD and prior to land application. The single-stream MRF model represents a facility similar to those used in Wake County. The model representing a potential future mixed waste MRF facility uses lower recovery rates than the single-stream MRF facility to account for lower separation efficiency and losses due to higher contamination expected at mixed waste facilities as described in 40 (SI Table S19). The potential future WTE facility is assumed to be state-of-the art with landfilling of residual ash after iron and aluminum recovery. Each process has associated capital and operating costs (SI Tables S13 and S14), as well as GHG emissions coefficients (SI Table S15) and user-specified minimum build and expansion capacities (SI Table S12). The life-cycle models used for each waste process are the same across all scenarios unless otherwise specified.

Utilization of existing Wake County facilities (South Wake landfill, composting sites, single-stream MRFs) incurs no initial build cost, while building new facilities (WTE, AD, mixed waste MRF) does. Other than sector- and site-specific facility details, waste characteristics, and waste collection parameters, the default SWOLF data and process models were used.³⁶ The default electricity grid mix was assumed to be that of the Southeast Electric Reliability Corporation (SERC), which includes North Carolina (SI Table S22).

3. RESULTS

3.1. Cost-Effective SWM Strategies. Food waste collection was enabled (+FW+AD) to increase diversion compared to Base Case (Figure 2) by increasing food waste



Figure 2. Cost, GHG emissions, facility utilization, and mitigation cost for Base_Case and Food Waste (+FW+AD) scenarios. The sum of "% of Total Waste" may exceed 100% since MSW may be managed at more than one facility. AD was selected by the model only when the objective is minimizing GHG emissions.

source-separation to 50% from 0% in Base_Case and enabling its collection with the current yard waste stream. When cost is optimized for +FW+AD, food waste is treated with singlefamily yard waste at a composting facility, which reduces GHG by 5.9 kg CO_2e/Mg waste, increases cost by 0.47 \$/Mg, and increases diversion from 28% to 31%. When GHG emissions are optimized, food and yard waste are sent to AD to achieve the same 31% diversion; however, this reduces GHG emissions by 6.6 kg CO_2e/Mg waste. Since food waste is 70–80% moisture, ^{47,48} its rapid decomposition and volume reduction would result in less than 1% effective savings in landfill volume.⁴⁹

The mitigation cost is used to estimate the cost-effectiveness of an alternate scenario for reducing GHG emissions compared to Base_Case; it is calculated by dividing the increase in cost by the decrease in emissions. The U.S. Environmental Protection Agency's (EPA) social cost of carbon provides context for the calculated mitigation costs. The social cost of carbon is the dollar value, based on an assumed discount rate (r), of long-term damage caused by a metric ton of CO₂ emitted in a given year. The EPA's 2020 estimate for the social cost of carbon is 46 $MTCO_2e$ (r = 3%) with the baseline assumption of severity and 136 $MTCO_2e$ at high severity.⁵⁰

The +FW+AD cost increases primarily due to additional processing costs for composting or using AD; GHG emission savings are due to reductions in net GHG at the landfill, and GHG offsets from electricity production at AD (Figure 2). The mitigation cost for the cost-optimized +FW+AD solution is 98 $/MTCO_2e$ and 839 $/MTCO_2e$ when GHG is optimized (Table 2). Thus, food waste diversion with composting yields a small increase in landfill diversion and GHG benefits, while the same diversion by using AD would cost more and provide greater GHG reductions.

Solutions at several diversion levels for Base Case, +MW, +WTE, and +MW+WTE (Figure 3) help illustrate the effect of adding different SWM technologies on diversion, energy recovery, or recovery of materials that are not separated by the waste generator (at rates representative of current recyclables separation efficiencies, Table S8). Compared to \$42 M for Base Case, the annualized cost increases to \$45 M for +MW with a mitigation cost of 30 \$/MTCO₂e. The maximum diversion achievable by processing all residual waste at the mixed waste MRF prior to landfilling is nearly 39% compared to 28% for Base Case. WTE use can achieve 80% diversion since waste is reduced to ash and metal is recovered from the bottom ash; however, net GHG emissions offsets are higher for +MW at maximum diversion (39%) than that for +WTE at all diversion levels except at the maximum diversion (i.e., all residual waste is incinerated). Up to 70% diversion, emissions offsets from WTE electricity generation do not outweigh the increase in net emissions resulting from reduced material recovery, reduction in carbon storage at the landfill, and additional emissions from the combustion of plastics (Table S23).

At every diversion level, mitigation cost for +WTE is lower than that for GHG-optimized +FW+AD, but it is higher than that for +MW (Table 2); this is primarily because the capital cost of WTE is between that of AD and of a mixed waste MRF. Thus, while WTE can be used to achieve higher diversion and lower net GHG emissions, a mixed waste MRF can achieve moderate GHG reductions at a lower cost.

The Wake County system achieves the best diversion and GHG emissions when both a mixed waste MRF and WTE are included (+MW+WTE). At 32% diversion, only a mixed waste MRF and landfill are used for residual waste (identical to +MW). The assumed minimum build capacity of WTE (48 000 Mg/yr) is sufficient to achieve 36% diversion cost-effectively without a mixed waste MRF. Use of only a mixed waste MRF achieves no more than 40% diversion; addition of WTE is needed to attain 40% or higher diversion, and the combined use of WTE and mixed waste MRF is more cost-

Table 2. Mitigation Cost for Cost-Minimized Cases in Relation to Base_Case Cost $(\$/MTCO_2e)^a$

	diversion constraint											
scenario	30%	31%	32%	34%	36%	38%	39%	40%	50%	60%	70%	>80% ^c
+FW+AD (least cost)	N/A	98 ^b	-	-	-	-	-	-	-	-	-	-
+FW+AD (least GHG)	N/A	839 ^b	-	_	-	-	-	-	-	-	-	-
+MW	14	17	18	23	27	34	34 ^b	-	-	-	-	-
+WTE	96	96	96	96	96	96	99	101	110	108	112	131 ^b
+MW+WTE	14	17	18	23	96	96	64	54	62	72	85	96 ^b

 a^{-} - indicates an infeasible solution (i.e., the level of diversion is not possible with the given composition and available facility characteristics). ^bMax diversion level. ^cFor +WTE, maximum diversion is 80%. For +MW+WTE, maximum diversion is 83%.



Figure 3. Cost, GHG emissions, facility utilization, and mitigation cost at different diversion levels for scenarios (a) Base_Case, (b) +MW, (c) +WTE, and (d) +MW+WTE. Total waste percentage may exceed 100% since MSW may be managed at more than one facility. Separate collection of single-stream recyclables and yard waste is required. Alternate facility utilization increases to meet the minimum cost objective as the diversion target increases.

effective than using WTE alone. At the maximum diversion, all collected MSW is initially treated at a mixed waste MRF prior to incineration at WTE. Mitigation costs at different diversion targets for +MW+WTE lie between those for +MW and +WTE (Table 2).

3.2. Minimum GHG SWM Strategies. To investigate cost-effective SWM strategies to reduce GHG emissions, GHG emissions-minimizing strategies were identified at increasing budget levels, starting with Base Case cost and then increasing incrementally to the cost of the least GHG strategy (SI Figure S3). Mixed waste MRF and WTE were enabled as in +MW +WTE; also, separate collection of yard waste and recyclables was imposed. Thus, the recyclables separated by households for single stream recyclables collection are directed to the single stream MRF and yard waste to composting. The GHG emissions minimizing strategies use the mixed waste MRF to increase recovery of recyclable materials not separated by residents and consequently increase the associated GHG offsets from material reprocessing. As the budget increases incrementally, the use of WTE (with ash going to landfill) instead of the landfill increases to treat the mixed waste MRF residual. Thus, the GHG optimizing strategies vary in terms of diversion and mitigation cost (SI Figure S3).

3.3. Impact of Separate Collection Requirement. The optimal cost and optimal GHG strategies indicate that the collection process is a major contributor to cost and GHG emissions, and that the contribution is higher when separate collection is required. Taking the sum of the absolute value of all SWM processing costs and GHG emissions (i.e., the total magnitude of processing costs and GHG emissions including net revenue and offsets), waste collection contributes 84% to costs and 30% to GHG emissions in Base Case. Using the 50% diversion case as an example, collection contributed 80% to the sum of the absolute value of process costs and 17% to GHG emissions when separate collection is required (+MW +WTE). Because the contribution of collection to cost and GHG emissions is large, and since compliance with material landfill bans and other policies could be achieved through alternative SWM strategies without necessarily requiring separate collection of yard waste and/or recyclables, an

additional scenario (+MW+WTE+AnyCollection) was considered (Table 1) where all collection and treatment processes in +MW+WTE were enabled (but not required).

Compared to Base_Case, the cost-effective +MW+WTE +AnyCollection strategies have lower cost and GHG emissions for all diversion levels analyzed up to 70% (Figure S4). With no separate recycling collection requirement, fewer materials go to a single-stream MRF. Instead, to increase diversion more cost-effectively, a mixed waste MRF is utilized at lower diversion levels and WTE is utilized between 40% and 70% diversion (Figure 4). To achieve the maximum diversion



Figure 4. Cost, GHG emissions, facility utilization, and mitigation cost for +MW+WTE+AnyCollection scenarios at increasing budget constraints. Mixed waste MRF and WTE use increased as the diversion constraint was increased while minimizing cost. At the minimum GHG, mixed waste MRF is used for material recovery prior to sending residual to WTE for energy recovery.

(82.5%), all residual waste is sent to a mixed waste MRF, with MRF residual going to WTE, and landfill is used for WTE ash only; also, costlier options of separate yard waste collection and composting are used to divert yard waste. Collection costs for +MW+WTE+AnyCollection strategies at all diversion levels are approximately half those of

Base_Case, except at maximum diversion when the same collection scheme as Base_Case is used, resulting in 3.5 times more GHG emissions offsets and over 82% diversion (compared to 28% in Base_Case) at 27% greater cost (mitigation cost is 96 $MTCO_2e$).

The GHG emissions minimizing strategy for +MW+WTE +AnyCollection cost approximately 11% more than the Base_Case (mitigation cost is 31 $/MTCO_2e$) and has 4.5 times more GHG emissions offsets with over 78% diversion. Each strategy for +MW+WTE+AnyCollection costs 28% to 36% less and has 1% to 66% higher GHG emissions offsets than +MW+WTE strategies at the same diversion targets. Thus, alternate treatment options (+MW+WTE) increase opportunities for GHG emissions reductions but at added cost; however, when coupled with no separate collection requirement (+MW+WTE+AnyCollection), both cost savings and GHG emissions reductions improve.

3.4. Results Summary. Net system GHG emissions tend to decrease with increasing diversion, but not monotonically. If landfill diversion is the primary goal, both diversion and environmental goals (i.e., net GHG emissions reductions) could be met at a lower cost by not requiring separate collection of yard waste, recyclables, and residual waste. For example, if GHG reduction is the primary goal while not exceeding 125% of the current cost, a combination of WTE and mixed waste MRF could be used to achieve 60% diversion and more than four times the GHG offsets of Base_Case (Figure 5). But, at the same cost, 80% diversion could be achieved with more than six times the GHG offsets of Base Case if separate collection is not required.

4. SENSITIVITY

Several +MW+WTE strategies were analyzed to evaluate the sensitivity of the results to select process model parameters. We explored the impact on results due to changing the default



Figure 5. Net annualized cost, landfill diversion, and waste treatment choices for Base_Case, +MW+WTE (required separate collection), and +MW+WTE+AnyCollection (any collection scheme). Cost and GHG offsets tend to increase with increased diversion for scenarios with the same collection scheme. Within a given diversion range (e.g., 40-45%), there is a large difference in cost and net GHG offsets. The primary driver of the cost difference is the collection scheme used. In general, a combination of mixed waste MRF with material recovery for remanufacturing and WTE with energy recovery provides GHG emissions reductions at a moderate cost increase. The fraction of each slice of a particular pie chart is representative of the fraction of generated waste entering each indicated treatment process in the respective solution.

settings for the energy grid, mixed waste MRF efficiency parameters (material recovery efficiency and processing costs), and the assumed waste composition.

The default electricity grid was changed to two alternative grids: "Coal" consisted entirely of coal-generated electricity, while "Natural Gas" consisted of the national average split of natural gas generating technologies (i.e., 33% combined cycle, 50% combustion turbine, 17% steam) (SI Table S22). The set of treatment processes selected and the mass flows to meet the increasing diversion targets are not sensitive to the electricity grid assumption; however, the grid assumption has a large impact on the calculated net GHG emissions and associated mitigation costs. For all model runs where GHG savings are realized with increased net cost (i.e., positive mitigation costs), the mitigation cost ranges from 6 to 53 \$/MTCO₂e when using the "Coal" grid, and 31 to 399 \$/MTCO2e for the "Natural Gas" grid. Thus, if the grid were to shift toward more natural gas than coal (i.e., less GHG-intensive), the price of GHG mitigation would increase and could exceed the 2017 U.S. EPA estimate (136 MTCO_2e , assuming high severity impacts) for the social cost of carbon, since a cleaner grid reduces the emission offsets from waste-based energy or recovered resources.

Mixed waste MRF appears in all GHG- and cost-optimized strategies for +MW+WTE. To explore the sensitivity to mixed waste MRF performance, the material separation efficiency at the MRF was decreased by 10% and the processing cost was increased by 10% (SI Table S19); consequently, none of the cost-optimized solutions utilizes a mixed waste MRF, suggesting that the cost-effectiveness of using a mixed waste MRF instead of WTE to achieve higher diversion is sensitive to the MRF's efficiency. This also indicates that the effectiveness of the mixed waste MRF in improving the sustainability of the solid waste system is sensitive to incoming and outgoing rates of contamination and how they affect separation efficiencies, revenues, and beneficial offsets. When the separation efficiencies and processing costs were changed by 5%, use of mixed waste MRF is reduced at each diversion level (e.g., at 70% diversion, when efficiency is reduced by 5%, mixed waste MRF utilization is approximately 10% of that for the default efficiency). However, for GHG-optimized solutions, a mixed waste MRF is used to the same extent as in the default runs even with a 40% decrease in separation efficiency. The mitigation costs at each budget level are within 20% of the default runs, ranging from 54 to 123 \$/MTCO2e. However, this could change if the actual available markets and associated offsets for the recovered materials were reduced due to contamination in the outgoing streams. Applying the reduced mixed waste MRF efficiency parameters to +MW+WTE +AnyCollection produced similar results; mixed waste MRF is not used in cost-optimized scenarios but is used to the same level in the GHG-optimized solutions as in +MW+WTE +AnyCollection.

Sensitivity to waste characteristics was examined by considering an alternative waste composition that was developed based on the annual change in the per capita generation of each waste material estimated by extrapolating the annual percentage change in U.S. per capita MSW generation from 2000 to 2010^{S1} to 2045 (SI Table S10). Recyclable glass generation decreases by over 2% per year during that period, PET container generation increases by 3%, and all types of recyclable paper decrease by 1 to 5% per year. The total change in per capita generation for each material

through 2045 was limited to $\pm 25\%$. The 2045 composition, as a plausible future waste composition, was then applied to the default waste generation amount. Use of SWM treatment processes is largely insensitive to the change in composition, and variations in net cost at each intermediate diversion constraint are within approximately 7% of default. The total amount of separately collected waste is lower in the alternate composition scenario since there is less yard waste and recyclables, which also reduces the collection costs. In the maximum diversion case, the mass of material recycled or composted is reduced by 33%, but total diversion is reduced only by 0.1% since residual waste is still combusted. The minimum GHG emissions are 3% higher than that for the default setting, primarily due to fewer offsets from WTE, composting, landfill, and remanufacturing due to reduction in the generation of recyclable materials and yard waste which reduced the potential GHG offsets.

5. POLICY IMPLICATIONS

Wake County partners with its municipalities to manage the county's MSW and landfill utilization but does not control collection. Thus, identifying optimal SWM strategies for costeffectively improving diversion requires coordination with every level of government and waste collectors since the County cannot by itself impose what might be an efficient overall waste management system for each municipality. Municipalities have responded to the ban of yard waste from North Carolina landfills by implementing dedicated yard waste collection. Similarly, metal and plastic container bans from landfills resulted in recyclable collection at curbside and dropoff centers. Our results show that requiring separate yard waste and recyclables collection negatively affects cost and GHG emissions because collection constitutes the majority of system costs and the residual MSW composition affects the performance of downstream treatment processes. The use of a lifecycle optimization framework instead of a scenario-based lifecycle assessment enabled us to systematically identify the capacity of the SWM system to improve its overall performance by reconsidering current waste collection practices. While recent case studies have cited the benefits of increased source separation and material recovery in integrated SWM,^{9,14,16,17,52} there are trade-offs between the increased costs and the increase in material recovery benefits that should be explored. Some studies in SI Table S1 assumed collection and transportation were the same across scenarios^{12,14} or did not consider it, while others represented collection systems that are widely different from those in Wake County.9,12-14,30 Although integrated case studies where curbside collection was not used (i.e., drop-off or waste collection stations were used) found collection and transportation to have a relatively small impact,²⁶ others highlighted the relatively high contribution of collection or transportation to environmental impacts like GWP.^{15,25} In a U.S. context, curbside collection from single-family and smaller multifamily dwellings is common, as is separate collection of yard waste and recyclables. Our results suggest that changes to the current collection system could benefit municipalities financially and reduce certain environmental impacts (e.g., GWP, landfill diversion), but a finer-level analysis is needed to properly represent considerations of multiple stakeholders in distinct political jurisdictions and site-specific constraints and to identify policy options for increasing diversion.

In addition to any waste minimization initiatives to reduce SWM costs and emissions, alternative SWM facilities are necessary to significantly change diversion or GHG emissions (Figure 5). For example, our results demonstrate that a mixed waste MRF and WTE both improve diversion and GHG reductions at a wide range of mitigation costs. Increasing diversion using only a mixed waste MRF is limited by the composition of the incoming waste, the separation efficiency of the mixed waste MRF and the quality of the recovered materials. Using WTE alone achieves higher diversion and lower GHG levels than using mixed waste MRF alone, but at a higher mitigation cost. The lowest mitigation costs occur when a combination of mixed waste MRF and WTE is used to increase diversion or reduce GHG emissions. For example, net GHG offsets increase by 400% and diversion doubles with an increase of approximately 20% in cost (at a mitigation cost of 96 \$/MTCO₂e) by incorporating a mixed waste MRF for material recovery prior to WTE incineration.

Although using a mixed waste MRF in the optimal strategies for +MW+WTE and +MW+WTE+AnyCollection increases material recovery, its performance is highly sensitive to material recovery estimation as well as the assumed recycled material commodity markets and avoided material offsets. Therefore, contamination is an important consideration, since it reduces the quantity and/or quality of useable recovered materials, consequently affecting cost and environmental offsets. The sensitivity analyses show that a relatively small increase in processing cost (10%) and decrease in material recovery (10%) resulted in the MRF no longer being selected in the cost-optimal solutions. This result mirrors real-world difficulties encountered by recent mixed waste MRF initiatives. A mixed waste MRF in Montgomery, Alabama, for example, closed within 18 months of opening partly due to decline in material commodity prices,⁵³ but is planned to reopen as a mixed waste MRF in late 2018 under a new revenue-sharing agreement between the city and MRF operator.⁵⁴ Speculated low commodity prices, along with contract disputes related to financial penalties to the city if it expanded a recycling program, contributed to the suspension of a proposed mixed waste MRF in Indianapolis.⁵⁵ A "one bin for all" approach was proposed to improve the low landfill diversion rate (<10%) in Houston, Texas by pairing a mixed waste MRF with WTE. But, despite a pledge of private investment and several grants, the program was halted.⁵⁶ Thus, while mixed waste MRF technology could provide material recovery, cost, and environmental benefits, its use must be carefully evaluated in the context of expected waste generation and composition, commodity prices, social pressure, and regulations.

Residential food waste diversion through separate collection is shown to be a relatively expensive way to achieve a small amount of additional landfill diversion (less than 3%) and GHG reductions based on typical participation rates. Addition of a mixed waste MRF or AD as a standalone expansion to the existing SWM system can provide marginal GHG and diversion improvements, but diversion potential is limited, and mitigation costs are high. Therefore, using a WTE alone or in conjunction with a mixed waste MRF is more effective for increasing landfill life in Wake County. Additionally, not requiring separate collection offers significant potential for cost and GHG reductions (Figure 5); however, changes to the current separate collection practice in Wake County should consider the availability of existing infrastructure and the potential effectiveness of material separation at a mixed waste MRF.

Extending the case-specific results yields the following general observations that could influence SWM policies and are potentially applicable in a U.S. or international context. Residential food waste collection is limited in increasing diversion, and, without considering source reduction, additional SWM facilities are necessary to achieve significant diversion. A mixed waste MRF coupled with WTE can provide material and energy recovery benefits and diversion; two important considerations should be (1) a mixed waste MRF design that ensures economic feasibility and adequate material quality, and (2) collection schemes should be redesigned in conjunction with development of new SWM facilities. As a regional entity (e.g., county) often does not necessarily control local waste collection, more collaboration among the cities and the regional entity would be required to develop collection policies and plans in response to SWM infrastructure changes. Furthermore, any strategies requiring new SWM facilities or expanded capacity must consider commercial waste to appropriately size these facilities.

Future work applying life-cycle-based optimization of solid waste management systems can benefit by partnering with SWM units and practitioners to obtain data, elicit feedback, and receive guidance on relevant goals and objectives. Iterative development and analysis of applicable scenarios is a critical process. This study only considered GHGs, cost, and landfill diversion, and the inclusion of other impacts and indicators could lead to different system-specific recommendations. Scenarios that incorporate the technologically possible solutions, including those that may be deemed socially or politically unfavorable, in the applicable time frame of the decision are crucial to ensure that the investigation properly supports and informs SWM decision making.

ASSOCIATED CONTENT

S Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b04589.

Additional background information about Wake County's SWM system including waste generation and composition, SWM facility details, and supplemental results and discussion (PDF)

Workbook of spreadsheets is provided that contains results summary data tables for each scenario (XLSX)

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Notes

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REFERENCES

(1) Chalkias, C.; Lasaridi, K. Optimizing municipal solid waste collection using GIS. *World Sci. Eng. Acad. And Soc.* 2009. AG Loannou Theologou 17–23, 15773 Zographou, Athens, Greece.

(2) National Renewable Energy Laboratory (NREL). Integrated Municipal Solid Waste Management: Six Case Studies of System Cost and Energy Use. A Summary Report. Nov. **1995** NREL/TP-430– 20471. DOI: 10.2172/164934

(3) U.S. Environmental Protection Agency (EPA). U.S. EPA. Greenhouse Gas Reporting Program (GHGRP): 2016 GHGRP Overview Report. 2017. (accessed November 20, 2018). https://www.epa.gov/sites/production/files/2017-09/documents/ry16_ghgrp_overview_report.pdf.

(4) Northeast Recycling Council (NERC). Disposal Bans & Mandatory Recycling in the United States. 2017. https://nerc.org/ documents/disposal_bans_mandatory_recycling_united_states.pdf (accessed November 20, 2018).

(5) Portland City Code. Businesses and multifamily complexes required to recycle. **2012**:17.102.270.

(6) Portland City Code. Separation of recyclables, compost and solid waste. **2012**:17.102.295.

(7) San Francisco City Ordinance. Mandatory recycling and composting ordinance. 2009:100–09.

(8) Seattle Municipal Code. Commercial recycling required. 2015:21.36.082.

(9) Ripa, M.; Fiorentino, G.; Vacca, V.; Ulgiati, S. The relevance of site-specific data in Life Cycle Assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). *J. Cleaner Prod.* **2017**, *142*, 445–60.

(10) De Feo, G.; Ferrara, C.; Iuliano, C.; Grosso, A. LCA of the Collection, Transportation, Treatment and Disposal of Source Separated Municipal Waste: A Southern Italy Case Study. *Sustainability* **2016**, *8* (11), 1084.

(11) Laurent, A.; Bakas, I.; Clavreul, J.; Bernstad, A.; Niero, M.; Gentil, E.; Hauschild, M. Z.; Christensen, T. Review of LCA studies of solid waste management systems - Part I: Lessons learned and perspectives. *Waste Manage.* **2014**, *34* (3), 573–588.

(12) Jia, X.; Wang, S.; Li, Z.; Wang, F.; Tan, R. R.; Qian, Y. Pinch analysis of GHG mitigation strategies for municipal solid waste management: A case study on Qingdao City. J. Cleaner Prod. 2018, 174, 933-44.

(13) Yadav, P.; Samadder, S. R. Environmental impact assessment of municipal solid waste management options using life cycle assessment: a case study. *Environ. Sci. Pollut. Res.* **2018**, *25* (1), 838–54.

(14) Noya, I.; Inglezakis, V.; Gonzalez-Garcia, S.; Katsou, E.; Feijoo, G.; Moreira, M. T. Comparative environmental assessment of alternative waste management strategies in developing regions: A case study in Kazakhstan. *Waste Manage. Res.* **2018**, *36* (8), 689–97. (15) Stanisavljevic, N.; Levis, J. W.; Barlaz, M. A. Application of a Life Cycle Model for European Union Policy-Driven Waste Management Decision Making in Emerging Economies. *J. Ind. Ecol.* **2018**, *22* (2), 341–55.

(16) Aleisa, E.; Al-Jarallah, R. A triple bottom line evaluation of solid waste management strategies: a case study for an arid Gulf State. *Int. J. Life Cycle Assess.* **2018**, 23 (7), 1460–75.

(17) Starostina, V.; Damgaard, A.; Eriksen, M. K.; Christensen, T. H. Waste management in the Irkutsk region, Siberia, Russia: An environmental assessment of alternative development scenarios. *Waste Manage. Res.* **2018**, *36* (4), 373–85.

(18) Hadzic, A.; Voca, N.; Golubic, S. Life-cycle assessment of solidwaste management in city of Zagreb, Croatia. J. Mater. Cycles Waste Manage. 2018, 20 (2), 1286–98.

н

(19) Liu, Y.; Sun, W.; Liu, J. Greenhouse gas emissions from different municipal solid waste management scenarios in China: Based on carbon and energy flow analysis. *Waste Manage*. **2017**, *68*, 653–61. (20) Marino, C.; Nucara, A.; Nucera, G.; Pietrafesa, M. Economic, energetic and environmental analysis of the waste management system of Reggio Calabria. *Heat Technol.* **2017**, *35*, S108–16.

(21) Syeda, A. B.; Jadoon, A.; Chaudhry, M. N. Life Cycle Assessment Modelling of Greenhouse Gas Emissions from Existing and Proposed Municipal Solid Waste Management System of Lahore, Pakistan. *Sustainability* **2017**, *12*, 2242.

(22) Bjelic, D.; Markic, D. N.; Pesic, Z. S.; Sorak, M.; Kikanovic, O.; Vukic, L.; Ilic, M.; Mihajlov, A. Environmental Assessment of Municipal Solid Waste Management in Banjaluka, Bosnia and Herzegovina. *Environ. Eng. Manage. J.* **2017**, *16* (5), 1161–70.

(23) Grzesik, K. Comparative Environmental Impact Assessment of the Landfilling and Incineration of Residual Waste in Krakow. *Environ. Prot. Eng.* **2017**, *43* (4), 135–48.

(24) Yay, A. S. E. Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya. *J. Cleaner Prod.* **2015**, *1* (94), 284–93.

(25) Fernandez-Nava, Y.; del Rio, J.; Rodriguez-Iglesias, J.; Castrillon, L.; Maranon, E. Life cycle assessment of different municipal solid waste management options: a case study of Asturias (Spain). J. Cleaner Prod. 2014, 81, 178–89.

(26) Song, Q.; Wang, Z.; Li, J. Environmental performance of municipal solid waste strategies based on LCA method: a case study of Macau. J. Cleaner Prod. 2013, 57, 92–100.

(27) Belboom, S.; Digneffe, J.; Renzoni, R.; Germain, A.; Leonard, A. Comparing technologies for municipal solid waste management using life cycle assessment methodology: a Belgian case study. *Int. J. Life Cycle Assess.* **2013**, *18* (8), 1513–23.

(28) Nguyen, P. T.; Matsui, Y. Assessment of potential impacts of municipal solid waste treatment alternatives by using life cycle approach: a case study in Vietnam. *Environ. Monit. Assess.* **2013**, *185* (10), 7993–8004.

(29) Nouri, J.; Omrani, G. A.; Arjmandi, R.; Kermani, M. Comparison of solid waste management scenarios based on life cycle analysis and multi-criteria decision making (Case study: Isfahan city). *Iran J. Sci. Technol. Trans A-Sci.* **2014**, 8(A3):257–64. Nouri, J. ORICD: http://orcid.org/0000-0002-9982-3546.

(30) Tunesi, S.; Baroni, S.; Boarini, S. Waste flow analysis and life cycle assessment of integrated waste management systems as planning tools: Application to optimize the system of the City of Bologna. *Waste Manage. Res.* **2016**, *34* (9), 933–46.

(31) Tan, S. T.; Lee, C. T.; Hashim, H.; Ho, W. S.; Lim, J. S. Optimal process network for municipal solid waste management in Iskandar Malaysia. J. Cleaner Prod. 2014, 15, 48–58.

(32) Harijani, A. M.; Mansour, S.; Karimi, B.; Lee, C. Multi-period sustainable and integrated recycling network for municipal solid waste - A case study in Tehran. *J. Cleaner Prod.* **2017**, *151*, 96–108.

(33) Kaplan, P. O.; Ranjithan, S. R.; Barlaz, M. A. Use of life-cycle analysis to support solid waste management planning for Delaware. *Environ. Sci. Technol.* **2009**, *43* (5), 1264–1270.

(34) Levis, J. W.; Barlaz, M. A.; DeCarolis, J. F.; Ranjithan, S. R. Systematic exploration of efficient strategies to manage solid waste in US municipalities: Perspectives from the solid waste optimization life-cycle framework (SWOLF). *Environ. Sci. Technol.* **2014**, *48* (7), 3625–3631.

(35) Wake County North Carolina. *Waste and recycling: Frequently* Asked Questions - South Wake Landfill. http://www.wakegov.com/ recycling/division/swl/Pages/faqs.aspx (accessed November 20, 2018).

(36) Levis, J. W.; Barlaz, M. A.; DeCarolis, J. F.; Ranjithan, S. R. A generalized multistage optimization modeling framework for life cycle assessment-based integrated solid waste management. *Environ. Modell & Softw.* **2013**, *50*, 51–65.

(37) Intergovernmental Panel on Climate Change (IPCC). Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, U.K., 2013. http://www. ipcc.ch/report/ar5/wg1/ (accessed November 20, 2018).

(38) Quick Facts, Wake County North Carolina; United States. Population, Census, April 1, 2010. https://www.census.gov/ quickfacts/fact/table/wakecountynorthcarolina,US/ POP010210#viewtop (accessed November 20, 2018).

(39) Jaunich, M. K.; Levis, J. W.; Barlaz, M. A.; DeCarolis, J. F. Lifecycle process model for municipal solid waste collection. *J. Environ. Eng.* **2016**, *142* (8), 04016037.

(40) Pressley, P. N.; Levis, J. W.; Damgaard, A.; Barlaz, M. A.; DeCarolis, J. F. Analysis of material recovery facilities for use in life-cycle assessment. *Waste Manage.* **2015**, *35*, 307–17.

(41) Levis, J. W.; Barlaz, M. A. Is biodegradability a desirable attribute for discarded solid waste? Perspectives from a national landfill greenhouse gas inventory model. *Environ. Sci. Technol.* **2011**, 45 (13), 5470–5476.

(42) Harrison, K. W.; Dumas, R. D.; Barlaz, M. A.; Nishtala, S. R. A life-cycle inventory model of municipal solid waste combustion. *J. Air Waste Manage. Assoc.* **2000**, *50* (6), 993–1003.

(43) U.S. Environmental Protection Agency (EPA). Multifamily Recycling: A National Study. 2001. Report No.: EPA530-R-01-018. Accessed 11/20/18. https://nepis.epa.gov/Exe/ZyPURL. cgi?Dockey=10000OV5.TXT.

(44) Wake County North Carolina Solid Waste Management Plan: 2012–2022 Planning Period. 2012. http://www.wakegov.com/recycling/division/reports/Documents/2012WCSWMP.pdf (accessed November 20, 2018).

(45) SCS Engineers. Wake County, North Carolina Waste Characterization Study: Summary of Results. 2011. http://www.wakegov.com/recycling/division/reports/Documents/2011%20Waste%20Characterization%20Study%20Final.pdf (accessed November 20, 2018).

(46) Solid Waste Management Annual Reports: Municipal Solid Waste and Construction and Demolition Waste - Exports and Imports, FY 2013-2014. 2018. https://files.nc.gov/ncdeq/Waste%20Management/DWM/SW/

Reports % 20 and % 20 Presentations/

Solid%20Waste%20Management%20Annual%20Reports/ FY%202013-2014/FY13_14_ImportExport.pdf (accessed November 20, 2018).

(47) Lopez, V. M.; De la Cruz, F. B.; Barlaz, M. A. Chemical composition and methane potential of commercial food wastes. *Waste Manage*. **2016**, *56*, 477–490.

(48) Hodge, K. L.; Levis, J. W.; DeCarolis, J. F.; Barlaz, M. A. Systematic Evaluation of Industrial, Commercial, and Institutional Food Waste Management Strategies in the United States. *Environ. Sci. Technol.* **2016**, 50 (16), 8444–52.

(49) De la Cruz, F. B.; Barlaz, M. A. Estimation of waste componentspecific landfill decay rates using laboratory-scale decomposition data. *Environ. Sci. Technol.* **2010**, *44* (12), 4722–4728.

(50) U.S. Environmental Protection Agency (EPA). The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Emissions. https://19january2017snapshot.epa.gov/climatechange/ social-cost-carbon .html (accessed November 20, 2018).

(51) U.S. Environmental Protection Agency (EPA). Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2011. U.S. 2012. Report No.: EPA530-R-13-001. https://archive.epa.gov/epawaste/nonhaz/municipal/web/pdf/mswcharacterization_fnl_060713_2_rpt.pdf (accessed November 20, 2018).

(52) Majeed, A.; Batool, S. A.; Chaudhry, M. N. Environmental Quantification of the Existing Waste Management System in a Developing World Municipality Using EaseTech: The Case of Bahawalpur, Pakistan. *Sustainability* **2018**, *10* (7), 2424.

(53) Recycling Today. Montgomery, Alabama, mixed-waste processing facility announces temporary closure. Recycling Today. 2015, October 5; http://www.recyclingtoday.com/article/ montgomery-alabama-infinitus-waste-processing-temporary-closure/ (accessed November 20, 2018). (54) Rosengren, C. RePower chosen to reopen Montgomery's mixed waste MRF. WasteDive. 2018, March 28; https://www.wastedive. com/news/repower-chosen-to-reopen-montgomerys-mixed-waste-mrf/520113/ (accessed November 20, 2018).

(55) Messenger, B. Indianapolis Suspends Covanta Advanced Recycling Center Plan. Waste Management World. 2016, November 2; Accessed 11/20/2018. https://waste-management-world.com/a/ indianapolis-suspends-covanta-advanced-recycling-center-plan (accessed November 20, 2018).

(56) Flynn, M. Long Rise and Fast Fall of the Ambitious One-Bin Recycling Program; Houston Press, 2017, July 13; https://www. houstonpress.com/news/what-happened-to-ecohub-and-houstonsone-bin-for-all-recycling-plan-9601564 (accessed November 20, 2018).