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Environmental, Economic, and Energy Assessment of the Ultimate Analysis and Moisture Content of Municipal Solid Waste in a Parallel Co-combustion Process

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S *Supporting Information*

ABSTRACT: Use of municipal solid waste (MSW) as fuel for electricity generation reduces landfill disposal and can mitigate air quality degradation associated with combustion of conventional fossil fuels. Co-combustion is a waste-to-energy technology that can use MSW and coal as co-fuels, offering potential energy recovery and reduced air emissions. This research discerns how MSW composition influences the heating value and air pollution for the co-combustion of coal with MSW using five MSW composition scenarios, four of which were derived by a reduction of plastics, organics, paper, or a combination thereof, as compared to the national average MSW composition. Numerous combustion products could be evaluated; this study focused on five high impact air combustion products: SO_2, CO, CO_2, NO, and NO_2. The moisture content was varied from ∼10% (considered dry) to 40% (average MSW moisture). AspenPlus software was used for the deterministic simulation modeling of incineration (MSW only) and parallel co-firing (co-combustion of coal and MSW) to determine theoretical heating values and pollutant effluent concentrations. The United States Environmental Protection Agency (U.S. EPA) models WAR and WARM were used to determine the potential environmental impacts (PEIs) and greenhouse gas emission equivalencies, respectively, for each MSW scenario. For the WAR model, values for each impact category parameter can vary, but each parameter is weighed equally. Of the MSW scenarios studied, the national average held the highest heating value with 8519 MBtu/lb and the lowest occurred for the MSW scenario with recycled paper and composted organics, with 8251 MBtu/lb. Results show that SO_2, CO, CO_2, NO, and NO_2 flue gas concentrations (and therefore PEIs) depend upon the composition and moisture of the MSW, in addition to the MSW/coal ratio. Approximate ranges for the WAR results (PEI/h) are 7410−7663 for NO, 4−8 for NO_2, 18−105 for CO, 30−46 for CO_2, and 89−2152 for SO_2. WARM results show lower net CO_2 emission equivalents to landfill MSW with reduced paper and organics, while combustion is preferred for MSW with paper reduction, organics reduction, and plastics reduction. The results for the national average MSW were independent of the disposal processing method. Reduction in pollutant concentrations did not yield overall cost savings for the electricity producer, as profit was reduced by ∼20−30%. There are savings associated with emission costs using MSW in lieu of coal: up to ∼3.3% for NO, ∼20−47% for NO_2, and ∼95% for SO_2. A hypothetical carbon dioxide tax was also imposed to realize the potential cost savings by reducing CO_2 emissions. In summary, the measurable impact MSW composition and moisture had on pollutant concentration, heating value, and economic parameters was important.

1. INTRODUCTION

In 2010, municipal solid waste (MSW) generation in the United States of America reached 250 million tons, with 54.2% discarded to landfills.[1] Concerns associated with increased landfill disposal include higher maintenance costs and possible leaching of pollutants into the soil and groundwater. The 2011 national gate rate average for the disposal of MSW in the U.S.A. was $44.91 per ton of waste, agglomerated over disposal via landfills, transfer to another facility, and use in waste-to-energy (WtE) units.[2]

Incineration (referring to feed consisting only of MSW) is the primary WtE technology used in the U.S.A., but it is stigmatized by the "not in my backyard" mantra because of potential emissions of species, such as carbon monoxide (CO), carbon dioxide (CO_2), nitric oxides (NO_x: NO and NO_2), sulfur oxides (SO_x: SO_2 and SO_3), and particulate matter (PM), among other pollutants. Air pollution control (APC) devices reduce pollutant emissions from combustion processes, but the cleanliness of the process also can be improved by fuel choice. Co-combustion (feed consisting of MSW and another fuel) is a WtE technology that emphasizes reliable electricity generation and can be performed in parallel (co-fuels fed separately) or via direct (co-fuels fed together) co-firing while controlling pollutants of concern. Although landfill gas is an energy recovery option, it has been determined that the amount of energy obtainable from landfill gas is a magnitude smaller than that of a combustion process on a per MSW mass basis.[3] Therefore, this study focused on combustion process alternative solutions instead of landfill gas recovery.

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A popular co-fuel is coal, but environmental concerns associated with its use include coal mining and tailing disposal, transportation to coal-fired power plant (CFPP), and greenhouse gas (GHG) and air pollutant emissions from its combustion. Coal has been well-studied, and its heat of combustion can be modeled by several correlations (Boie, Dulong, modified Dulong, Grummel and Davis, IGT, or Mott and Spooner), heat of formation correlations, and Kirov correlations for heat capacity.[4] These correlations account for specific elements, primarily C, H, O, N, and S, typically found in various coal types, including anthracite, bituminous, subbituminious, and lignitic. MSW can be composed of significantly more elements than coal,[5] yet a detailed ultimate analysis (elemental composition) of all MSW is impractical for most purposes. Correlations using either the ultimate analysis or proximate analysis (moisture, ash, volatile matter, and fixed carbon fractions) are available to predict the heating value of solid wastes.[6]

Previous research evaluated how a fixed fraction[7,8] or varying fractions[9−11] of the MSW to coal co-fuel distribution could optimize energy conversion efficiency, without altering the MSW composition. It is not known if or how a change in the composition of the MSW influences electricity generation or pollutant emissions. Alternative and beneficial disposal options should be evaluated to determine if it is economically feasible to lower municipal disposal costs. This research addresses these issues using the ultimate analysis of assumed MSW. Key variables, such as the gross energy or higher heating value (HHV), emissions (of CO, CO_2, NO_x, and SO_2), fractional distribution of MSW to coal, and the significance of economic impacts, are considered for parallel co-firing combustion. These simulations will allow for municipalities to better assess the feasibility and optimization of combustion disposal alternatives for their distinct region.

2. EXPERIMENTAL SECTION

This study uses several models (AspenPlus, WAR, and WARM) and evaluation processes to determine the energy and environmental impacts of incineration and co-combustion. Illinois No. 6 (coal I6) was used, because it is representative of coal used in the U.S.A.[12] The configuration of the process plant assumes a hypothetical established CFPP that has the option of being retrofitted for a total capacity of 3000 tons/day of fuel (any combination of MSW, including moisture, and coal I6 feed).

2.1. AspenPlus Configuration. AspenPlus is a process simulation program that predicts plant behavior using mass and energy balances in addition to equilibrium information. The AspenPlus design for the parallel co-fired plant is shown in Figure 1 and is a simplified representation of an existing CFPP. The design specifications for the process plant include two sets of operating conditions: heating value determination and pollution determination. To determine the heating value (the negative of the fuel-specific enthalpy), the reactant and product temperature is 298.15 K at a pressure of 1 atm. For pollution determination, the outlet temperature is determined assuming adiabatic conditions. While it is possible to model each scenario with the same temperature for the combustion chamber, this study did not do so, allowing instead for adiabatic conditions. The primary advantage to this approach is that the combustion chamber in the simulation more realistically represents an actual combustion process. However, results must be interpreted in a manner that takes these temperature variations between simulation runs into account. This study calculated the heating values and pollutant concentrations based on combustion prior to a steam generation unit that can have variable thermal efficiencies.

The equations used by the AspenPlus simulation to determine the heat of combustion are described by the heat of formation method, shown in eqs 1−4. The generalized form of the equations include specific enthalpy (eq 1), heat of formation with sensible heat change (eq 2), heat capacity (eq 3), and heat of formation for combustion products (eq 4)

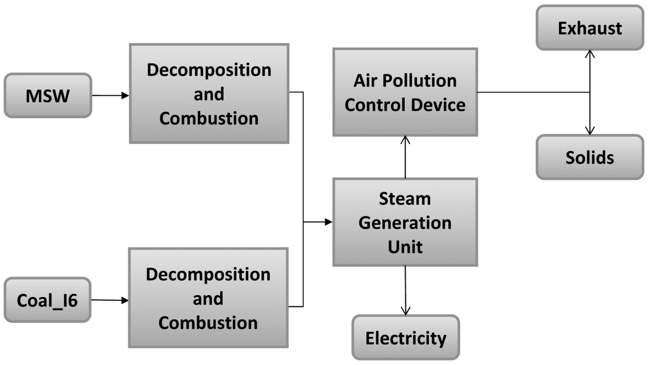

Figure 1. Block diagram of the parallel co-fired combustion plant used in the AspenPlus simulations.

$$\Delta H_{\mathrm{fuel}} = \sum_{k} m_k \Delta H_k \tag{1}$$

$$\Delta H_k = \Delta H_{\mathrm{f},k} + \int_{298.15}^{T} C_{\mathrm{p},k}\, \mathrm{d}T \tag{2}$$

$$C_{\mathrm{p},k} = \alpha_{1,k} + \alpha_{2,k}T + \alpha_{3,k}T^2 + \alpha_{4,k}T^3 \tag{3}$$

$$\Delta H_{\mathrm{f},k} = \Delta H_{\mathrm{c},k} + \Delta H_{\mathrm{f,cp},k} \tag{4}$$

where m_k is the mass fraction, ΔH represents the specific enthalpy, $\Delta H_{\mathrm{f},k}$ is the enthalpy of formation, $\Delta H_{\mathrm{c},k}$ is the enthalpy of combustion, $\Delta H_{\mathrm{f,cp},k}$ is the sum of the enthalpy of formation for each combustion product (cp) multiplied by the mass fraction of the relevant constituent in the fuel, $C_{\mathrm{p},k}$ is the heat capacity, with subscript k in all formulas representing the constituent within the fuel, and T is the temperature. $\Delta H_{\mathrm{f,cp},k}$ recognizes the heat of combustion for each combustion product associated with a constituent, as obtained from the National Institute of Standards and Technology (NIST) Chemistry WebBook[13] and Perry's Chemical Engineering Handbook.[14] The α coefficients were calculated from the NIST Web Thermo Tables.[15]

The property parameters for coal I6 were determined from the modified Dulong correlation for the heat of combustion, a direct correlation evaluated by the Institute of Gas Technology, for the standard heat of formation, and the cubic temperature equation (eq 3).[3] The $\Delta H_{\mathrm{f,cp},k}$ property parameters for the MSW and α coefficients for eq 3 can be found in Tables S1 and S2 of the Supporting Information, respectively.

The assumed density for MSW of 92.76 lb/ft^3 accounts for the average dry weight and moisture content for untreated MSW.[16,17] Air was added to MSW and coal in stoichiometric excess with respect to the fuel composition of 25% in this study and was comprised of 79% N_2 and 21% O_2 on a molar basis. Influent preheated air had a temperature of 100 °C and a pressure of 1 atm.[6,12]

2.2. MSW Compositions and Scenarios. The composition of MSW for combustion can be found in Table 1. The categories listed in Table 1 are typical of solid wastes and are useful for those organizations interested in recycling or composting of these materials. The national average represents what is typically found in landfills.

Municipalities have the option of recycling or composting portions of the MSW that they receive; therefore, the MSW scenarios listed in Table 1 are hypothetical reductions in the most common areas of recycling (paper and plastics) and composting (organics). It is assumed that plastics with high chlorine content, such as polyvinyl chloride, have been removed from the MSW stream prior to being treated in an incineration or co-combustion facility. Each category from Table 1 was converted to an elemental basis, using the weighted

Table 1. MSW Mass Fraction Composition by United States Environmental Protection Agency (U.S. EPA) Component Categories[1] [a]

	MSW 1	MSW 2	MSW 3	MSW 4	MSW 5
	MSW national average	50% paper reduction[b]	50% organics reduction[b]	50% plastics reduction[b]	50% paper and organics reduction[b]
paper	31.00	18.34	35.61	32.98	21.66
metals	8.40	9.94	9.65	8.94	11.74
plastics	12.00	14.20	13.79	6.38	16.77
glass	4.90	5.80	5.63	5.21	6.85
organics	25.90	30.65	14.88	27.55	18.10
textiles	7.90	9.35	9.08	8.40	11.04
wood	6.60	7.81	7.58	7.02	9.22
miscellaneous	3.30	3.91	3.79	3.51	4.61

[a] MSW 2–MSW 5 were calculated by decreasing the mass of the listed component(s) by 50%. [b] As compared to MSW 1.

Table 2. Literature Correlations for Predicting High Heating Values Using Percentages of *C* (Carbon), *O* (Oxygen), *H* (Hydrogen), *S* (Sulfur), *A* (Ash, Inert), and *N* (Nitrogen)

unit	equation	fuel basis	source
HHV (MJ/kg)	$0.2949C + 0.825OH$	dry basis	18
HHV (Btu/lb)	$14096C + 60214(H - O/8) + 3982S$	unknown	19
HHV (kJ/kg)	$337C + 1428(H - O/8) + 95S$	dry basis	modified Dulong[14]
HHV (Btu/lb)	$146.58C + 568.78H + 29.4S - 6.5A - 51.53(O + N)$	dry basis	IGT formula[14]

average composition of each waste category.[14] The elements were summed, resulting in the dry mass fractions shown in the Table S3 of the Supporting Information, and are used in the ultimate and proximate analyses in the AspenPlus software for the parallel co-firing combustion process. For coal, the sulfuric analysis is used in addition to the ultimate and proximate analyses.

Three moisture contents (M) were considered for each MSW scenario: 10.1, 25.0, and 40.0% of the total mass. The moisture content is representative of the combined internal and external moisture that can theoretically be vaporized. Drying MSW or biomass is common but not always performed. The 10.1% value is considered dry for practical applications, whereas the range of 15–40% is typical of untreated MSW.[6,14]

2.3. AspenPlus Model Comparison to Established Correlations. It is impractical to test experimentally the heating value for every ultimate analysis and proximate analysis combination. Thus, correlations are used to predict the heating values. Representative correlations from the literature[14,18,19] can be found in Table 2.

AspenPlus simulation results for heating values (calculated using eqs 1–4, as described above) are compared to results from these correlations in Figure 2. For a given ultimate analysis, there are different associated theoretical heating values (Figure 2). Some equations in Table 2 were developed for dry basis solid wastes, yet the degree of dryness (if all external and internal moisture is vaporized) is not specified and is assumed to vary. Dried MSW (in this study, $M = 10.1\%$) is expected to have a higher heating value because less energy would need to be expended to vaporize water. The variation in Figure 2 could be caused both by external and internal moisture contents of the fuels used to develop the correlations and how well the ultimate analysis alone predicts the heating value for a solid. The variation in heating value within any given correlation as MSW scenarios vary from MSW 1 to MSW 5 is small (Table 1), suggesting that the 50% mass fraction reductions in the paper, organic, or plastic categories do not have a large impact on the heating value. The AspenPlus input parameter DHFGEN (Table S1 of the Supporting Information), which is equivalent to $\Delta H_{f,k}$ in eq 4, impacts the results shown in Figure 2, because this parameter depends upon the combustion products present. Figure 2 does show the overall trend agreement of the AspenPlus calculated heating values to those of established correlations, especially as the amount of moisture increases.

2.4. U.S. EPA WARM and WAR Models. Recycling[20] and MSW management[21,22] studies consider global warming and its impacts by quantifying greenhouse gas (GHG) emissions. The U.S. EPA WARM (waste reduction) model was developed to help waste management strategists determine the amount of GHG emissions for material reallocation decisions.[23] WARM accomplishes this using updated emission factors for a variety of materials, including those commonly found in MSW, in a life-cycle style. Each material is evaluated using life-cycle data while considering the process under which the material is handled to calculate the net GHG emissions.[23] For each process, several life-cycle stages and, thus, parameters were considered. Recycling includes process and non-process energy, transportation energy, and carbon storage. Paper used in this study is assumed to be of mixed sourcing, which in WARM correlates to the combination of corrugated containers, magazines/third-class mail, newspaper, and office paper.[23] Combustion emissions include avoided utility GHG emissions from mass burn facilities and refuse-derived fuel facilities and avoided CO_2 emissions because of metal recovery. Landfilling considered raw material acquisition and manufacturing, transportation to landfill and its methane production, carbon storage, and avoided

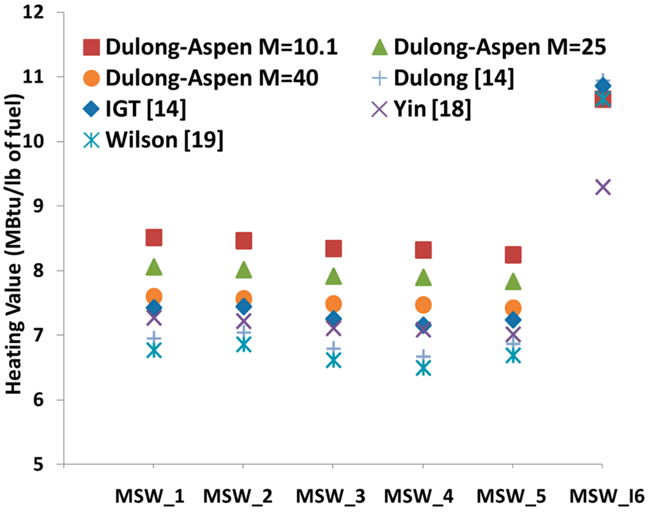

Figure 2. Comparison of heating values for each MSW scenario and for coal I6 (internal moisture only; $M = 10.1\%$). Equations for correlations from the literature can be found in Table 2. MBtu = 1000 Btu.

GHG emissions from energy recovery. Default values for recycling, combustion, and landfilling were used from WARM, for categories that correlated to the MSW materials of paper, metals, plastics, glass, organics, textiles, wood, and miscellaneous. For categories that had several subcategories in WARM, primarily paper, subcategory values were aggregated to obtain a category value. Each parameter in the aforementioned categories has different values depending upon their impact to the material being studied. While the value of each parameter is unique, the weighting of each parameter is unity (although the user of the WARM model may select to more heavily weigh one parameter versus another). This study used the WARM model to determine the net CO_2 emission equivalency for each MSW scenario based on its material composition and the disposal method (combustion or landfill).

The U.S. EPA WAR (waste reduction) algorithm designates a potential environmental impact (PEI) for specific chemical process simulations and was used in this study to determine the total PEI for specific combustion byproducts for each MSW scenario when incinerated, while moisture content was varied. The PEI is a relative measure of a chemical to have adverse human health impacts and is indexed to provide a quantitative measure of the impact of the waste on human health and the environment, with PEI equal to zero representing no adverse impacts.[24] There is no upper bound to PEI. The PEI is based on eight parameters: human toxicity potential ingestion, human toxicity potential dermal, terrestrial toxicity, aquatic toxicity, global warming potential, ozone-depleting potential, photochemical oxidation, and acidification.[25] The WAR model allows the user to assign categorical weights to each parameter; however, the weight of each of the eight parameters is assumed equivalent in this study.

2.5. Economic Evaluation for MSW Scenarios. Previous studies have evaluated the economic and social benefits of WtE plants[26] and recycling with government incentives,[25,27] and the results of these studies suggest that several approaches and parameters are needed to determine the monetary significance of using co-fuels with coal. This study accounts for several operating parameters for the hypothetical CFPP while assuming that the capital costs to modify the plant are negligible for the purpose of comparing one MSW scenario to another in the same plant. Equations 5−7 were developed to determine the profit of each MSW scenario with varying distributions of coal as the co-fuel

$$\begin{aligned}\text{expenditures} = {} & \Phi\{\omega_{\%}[\alpha + \zeta + \gamma_{\#}(\delta + \xi)] \\ & + ghf[\eta_{\text{NO}}V_{\text{NO}}(\lambda_{\text{NO}} + \theta) + \eta_{\text{NO}_2}V_{\text{NO}_2}(\lambda_{\text{NO}_2} + \theta) \\ & + \eta_{\text{SO}_2}V_{\text{SO}_2}(\lambda_{\text{SO}_2} + \theta)] + \iota\nu\}\end{aligned} \tag{5}$$

$$\text{revenue} = \left(\frac{\text{HV}}{B}\right)\mu + \gamma_{\#}\omega_{\%}\Phi(\varsigma_{\#} + \psi) \tag{6}$$

$$\text{profit} = \text{revenue} - \text{expenditures} \tag{7}$$

where Φ is the operating days/year, ω is the mass flow rate of MSW (tons of MSW/day), % represents the five different mass fractions of MSW, α is the disposal cost of MSW (\$/ton of MSW), ξ is the cost of sorting the MSW and recyclables (\$/ton of MSW), γ is the mass fraction of recyclable material (plastic, paper, or organic), # represents the numerical identifier of each MSW scenario, δ is the transit cost to collect recyclables (\$/ton of recyclables), ξ is the administrative cost to the municipality to collect MSW and/or recyclables (\$/ton of combined recyclables), g is the conversion of tons to grams (1.10231×10^{-6} tons/gram), h converts seconds into hours (3600 s/h), f converts hours into days, η is the conversion for the ideal gas law (g/L) equal to (pressure × molar mass of pollutant)/(R × temperature) with $P = 1$ atm, $R = 0.082$ L atm K^{-1} mol^{-1}, and $T = 1250$ K, V is the volumetric flow rate of pollutant (L/s), λ is the cost for operating the APC devices (\$/ton of pollutant emissions), θ is the emission and air permitting fees (\$/$\sum$(tons of NO_x, SO_2, PM, and volatile organic matter)), ι is the mass flow rate of coal (tons of coal/day), ν is the coal spot price in the Illinois Basin (\$/ton of coal), HV is the heating value (Btu/year), B is the heat rate (Btu/MWh), μ is the wholesale market price valuation for electricity sales (\$/MWh sold), ς is the selling price of the recyclable material (\$/ton of recyclable material), and ψ represents the municipal revenue collected from residential recycling pick-up (\$/ton of combined recyclables).

Economic evaluation of each MSW scenario was performed using information from several government, private sector, and nonprofit groups pertaining to the State of Illinois. A summary of the parameters and source information found in eqs 5−7 appears in Table S4 of the Supporting Information. While there is no current tax in the United States for CO_2 emissions, recent legislative decisions within the U.S. EPA to regulate CO_2 cause speculation regarding a future tax. Therefore, this study used a proposed tax to calculate the cost savings of reducing CO_2 emissions. The consumer price index was used to adjust all monetary values to 2013 U.S. dollars.[28]

3. RESULTS AND DISCUSSION

3.1. Power Generation. The heating value of the MSW is shown in Figure 2 for combustion without coal co-fuel. In general, for pure MSW at 10.1% moisture, the Aspen calculations indicate at least a 20% decrease in the heating value compared to the coal selected for this analysis. The three moisture scenarios shown in Figure 2 indicate that the scenario with the highest moisture content is closest to the values in the literature. This signifies that the determination of a "dry" basis for MSW is inconsistent and affects the heating value determination. Therefore, moisture should not be assumed constant for all equations presented in the literature. Among the MSW scenarios, MSW 5 has the lowest heating value, while the national average has the highest. However, the magnitude of the changes is deemed insignificant because there was little variation in heating values obtained for MSW 1−MSW 5 (less than 4% for scenarios 2−5, as compared to scenario 1). Thus, municipalities seeking to maintain a specific heating value may do so even when recycling or composting reductions in one or several categories are performed.

In addition to the heating value varying by MSW composition, the presence of moisture also influences the heating value obtained for each MSW scenario. The variation in heating value as a result of moisture is linear because the latent heat of vaporization for water is constant. Drying should be considered for MSW, as is a common practice, to determine if the additional heating value realized is substantiated by the additional energy spent to dry the MSW prior to combustion.

3.2. Air Pollution Impacts. While coal is one of the most cost-effective fuel sources for electricity generation,[29] it produces, among other pollutants, NO_x (precursor for ozone), SO_2 (precursor for acid rain and PM), CO (toxicity in high concentrations and precursor for ozone), and CO_2 (GHG). Co-fuels, such as MSW, may contain on a percent basis decreased amounts of pollutant precursors, thus lowering overall emissions.[9,30] The focus of this study, however, was not to corroborate that co-combusting MSW with coal would provide pollution benefits but instead to determine the dependency of those benefits upon MSW composition and moisture content.

Generally, it was assumed that a linear relationship exists between the mass fractional amount of the element in the fuel and the corresponding amount of species in the flue gas (eq 8)

$$\begin{aligned}\text{predicted} &= m_{\text{cp,MSW 1}}\frac{m_{\text{element,MSW \#}}}{m_{\text{element,MSW 1}}} \\ \text{model} &= m_{\text{cp,MSW \#}}\end{aligned} \tag{8}$$

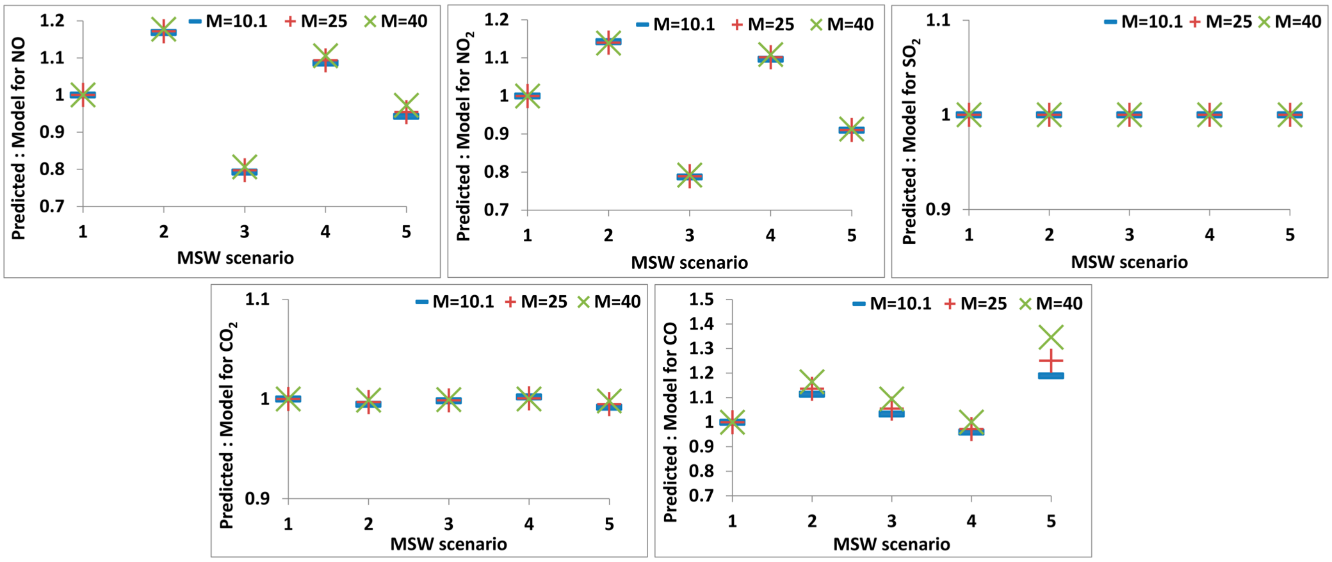

Figure 3. Ratio of the linearly scaled predicted mass fraction of each pollutant (predicted) to the Aspen-derived (model) volume fraction, on the basis of input element of nitrogen for NO and NO_2, sulfur for SO_2, and carbon for CO_2 and CO.

where $m_{\text{cp,MSW}\,\#}$ is the AspenPlus-modeled mass flow rate for the combustion product for MSW scenario # (# ranges from 1 to 5) and $m_{\text{element,MSW}\,\#}$ is the mass of the element (N, S, or C) found in the combustion product in the original fuel for MSW scenario #, for any of the three moisture scenarios. However, this does not account for nonlinear combustion chemistry. This study determines how well a linear relationship ("predicted") compares to the AspenPlus model concentrations ("modeled"), using MSW 1 as the base case on a volume basis (Figure 3).

If the linear scaling using the amount of an element in the fuel appropriately predicted the corresponding pollutant concentration, the modeled pollutant concentrations, which are based on reaction kinetics, would be equivalent. Figure 3 shows that the ratio between these two values is not consistently unity, particularly for CO and NO_x, indicating the importance of using more accurate representations of combustion chemistry. The relationship between the model output and the linear predictions does not depend upon the moisture content, suggesting that the influence of the moisture content can be predicted by the linear relationships.

Pollutant flue gas concentrations are scaled ($^{\text{sc}}$ notation) to account for elemental mass differences in fuel composition (eq 9) and normalized by the corresponding flue gas mass flow rate for pure coal ($^{\text{nm}}$ notation) for ease of comparison, according to eq 10.

$$m_{\text{cp,MSW}\,\#}^{\text{sc}} = \frac{m_{\text{element,MSW 1},M=10.1}}{m_{\text{element,MSW}\,\#}} m_{\text{cp,MSW}\,\#} \tag{9}$$

$$m_{\text{cp,MSW}\,\#}^{\text{nm}} = \frac{m_{\text{cp,MSW}\,\#}^{\text{sc}}}{m_{\text{cp,coal}}^{\text{sc}}} \tag{10}$$

Scaling allows changes in pollutant flow rates to be attributed solely to changes in combustion conditions. Scaled flue gas mass flow rates for NO_x, SO_2, CO, and CO_2 from each scenario (MSW fraction and moisture) are given in Table S5 of the Supporting Information. Post-Air Pollution Control (APC) device values for NO_x and SO_2 were based on assumed efficiencies of APC devices of 44[31] and 80%,[32] respectively. Scaled and normalized results for national average MSW are shown in Figure 4. Note that, by presenting results in a normalized fashion, the selection of APC efficiencies has no influence, assuming that such efficiencies are constant. Results for individual species are discussed below.

3.2.1. SO_2. The emission of SO_2 is of concern for any fossil fuel or industrial combustion process as this pollutant causes adverse effects on the respiratory system and allows proliferation of PM.[33] Many existing or new CFPPs have scrubbers installed to control the amount of SO_x released, yet it is desirable to reduce the amount of SO_2 in the flue gas because running the APC equipment is expensive. The normalized mass (derived from eq 10) of SO_2 in the flue gas is shown in Figure 4a and shows that increasing the MSW fraction always decreases SO_2, consistent with other studies.[30,34] The five MSW scenarios do not show significant differences in SO_2, showing that the MSW composition did not influence the fraction of sulfur speciated to SO_2. Increasing the moisture content of the MSW did not show any noticeable reductions in SO_2. For example, within the 100% MSW scenarios, the SO_2 concentration decreased by less than 1% when moisture increased from 10.1 to 40%.

3.2.2. NO_x. The total NO_x concentration is the summation of NO and NO_2. In the scenarios presented here though, the amount of NO_2 is exceedingly small. Therefore, the focus of the discussion is on NO. The NO_x level is influenced by the amount of fuel NO_x (fuel-derived N combustion product) and thermal NO_x (high-temperature air-derived N combustion product), the contributions of which depend upon operating conditions. Results for NO (derived from eq 10) are shown in Figure 4b. An increase in the moisture content within any one MSW scenario shows a negligible effect on NO (Figure 4b). However, Figure 5 shows that an increase in moisture is also associated with a decrease in the combustion chamber temperature, consistent with the reported trends by Chen et al.[35] According to Chen et al.,[35] moisture and temperature have a significant influence on how biomass (fuel) N is speciated upon combustion and nitrogenous species (NH_3, particulate N, etc.) beyond NO and NO_2 become significant as operating conditions change. There exists a smoldering effect with an increased moisture content in the fuel, resulting in lower combustion temperatures and an increase in emission (mass of

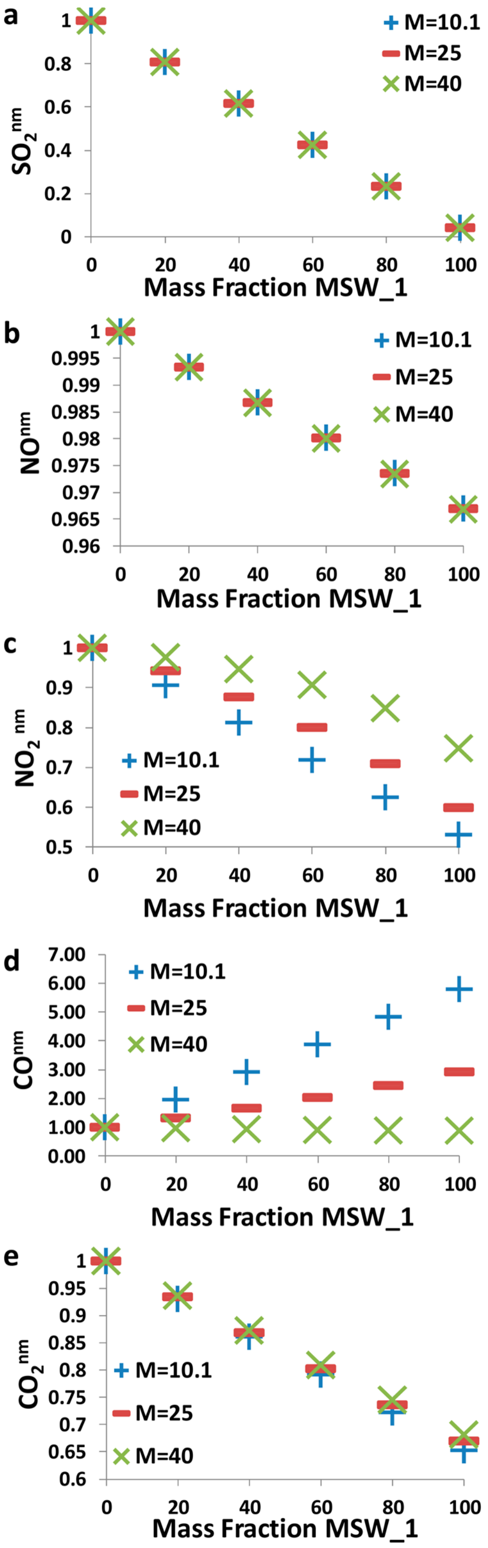

Figure 4. Normalized (in comparison to pure coal) and scaled (to account for fuel composition) flue gas ratios based on the mass fraction of MSW and moisture content (eq 10) for pollutants: (a) SO_2, (b) NO, (c) NO_2, (d) CO, and (e) CO_2. The baseline is unity. The *y*-axis labels vary depending upon the pollutant. MSW 2−MSW 5 can be found in Figure S1 of the Supporting Information.

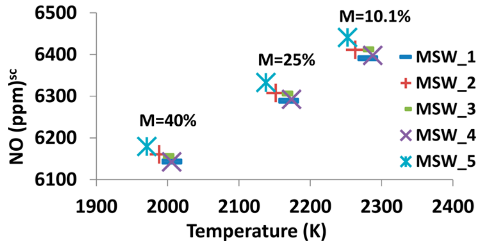

Figure 5. Comparison of the temperature, scaled NO mixing ratios, and moisture content for each of the five 100% MSW scenarios.

pollutant per mass of carbon burned) for certain N species.[35] In addition, Kurose et al.[36] concluded that thermal NO_x drastically decreases with increased moisture and became nearly negligible as the moisture content in their fuel approached 40%; however, as moisture increased, fuel NO_x increased. Figure 4b shows that moisture has little effect on normalized NO, and thus, the effects of the decrease of thermal N and increase of fuel N are offset. NO_2 has a net effect of decreasing as the MSW fraction increases in the fuel feed, although with increased moisture, NO_2 increases (Figure 4c).

3.2.3. CO and CO_2. Carbon monoxide is a toxic, odorless, and invisible gas that is emitted primarily because of incomplete combustion of carbonaceous material. In general, CO is not considered important for CFPPs because the fuel generally undergoes nearly complete combustion. However, as MSW replaces coal, the relative importance of CO could increase. Carbon dioxide is a GHG that is of interest because of its environmental impacts and environmental regulations in industrialized nations regarding its control. Carbon sequestration, carbon capture, and carbon storage are some of the current categories in environmental controls aimed at reducing the amount of anthropogenic CO and CO_2 emissions. Panels d and e of Figure 4 show that the amounts of CO and CO_2 released are a function of the fraction of MSW in the co-combustion process and the amount of moisture in the MSW, respectively.

For all MSW, the amount of CO_2 in the flue gas gradually increases with moisture but decreases with the MSW fraction. Kaplan et al.[3] showed that the use of MSW could decrease CO_2. As CO_2 increases with moisture, CO decreases. Increasing the mass fraction of MSW also causes a strong increase in CO (Figure 4d), except when M is highest. This suggests that accessibility to carbonaceous material is hindered within MSW, resulting in incomplete combustion. Although the relative increase in CO, as shown in Figure 4 is almost 6-fold, CO is still considered insignificant because its concentration is still relatively small compared to other pollutants. From Figure 4e, the increase in CO_2 with the moisture content could be associated with conditions favoring the water−gas shift reaction (where CO combined with water yields more CO_2 and H_2).

3.2.4. PEI and GHG Emissions for MSW Scenarios. The WAR results for each 100% MSW scenario and coal are shown in Table 3 for NO, NO_2, CO, CO_2, and SO_2. The total PEI includes the summation of all eight parameters used to determine environmental or human health hazards. PEI was calculated using the scaled mass flow rate. The trends for the PEI are therefore a result of the scaled mass flow rate. The total PEI among the four pollutants varies widely, from ∼4 (NO_2) to 7663 (NO) PEI/h, showing NO having the worst potential environmental impact of the pollutants studied for the conditions used. The impact of MSW composition on the PEI was insignificant, because the PEI was nearly constant for each MSW scenario. Higher PEI should be avoided, because the

Table 3. U.S. EPA WAR Model PEI Analysis for Each Pure MSW Scenario, Calculated Using Pre-APC Concentrations for CO and CO_2 and Post-APC Concentrations for NO, NO_2, and SO_2[a]

	total PEI/h														
	NO^{sc}			NO_2^{sc}			CO^{sc}			CO_2^{sc}			SO_2^{sc}		
	$M = 10.1$	$M = 25$	$M = 40$	$M = 10.1$	$M = 25$	$M = 40$	$M = 10.1$	$M = 25$	$M = 40$	$M = 10.1$	$M = 25$	$M = 40$	$M = 10.1$	$M = 25$	$M = 40$
MSW 1	7410.70	7410.29	7409.37	4.41	4.98	6.21	105.01	52.98	16.01	29.87	30.63	31.18	89.27	89.26	89.24
MSW 2	7410.63	7410.18	7409.21	4.51	5.11	6.42	94.26	46.62	13.75	30.03	30.73	31.21	89.27	89.26	89.23
MSW 3	7410.68	7410.25	7409.29	4.44	5.03	6.32	101.61	50.20	14.63	29.92	30.68	31.20	89.27	89.26	89.24
MSW 4	7410.73	7410.32	7409.38	4.37	4.94	6.20	109.42	54.52	16.00	29.80	30.61	31.18	89.27	89.26	89.24
MSW 5	7410.58	7410.11	7409.07	4.57	5.21	6.61	88.30	42.38	11.89	30.11	30.79	31.24	89.27	89.26	89.23
coal I6	7663.52	7663.52	7663.52	8.31	8.31	8.31	18.14	18.14	18.14	45.75	45.75	45.75	2152.50	2152.50	2152.50

[a] PEI used the scaled mass flow rate of each pollutant (as derived from the scaled volumetric flow rate).

externalities associated with adverse environmental impacts are variable and costly to individuals and government.

The WARM model accounts for GHG emissions. It is used to determine the net CO_2 equivalents (CO_2e) associated with material reallocation (including transportation, non-biogenic CO_2, and avoided GHG emissions). Negative values denote GHG emission reductions or carbon storage, and net GHG emissions are estimated to be negative for all biogenic sources of carbon (paper and wood products and organics).[23] The net metric tons of CO_2e for each MSW constituent material for different disposal methods are shown in Figure 6a; additionally a mixture consisting of an equal distribution of plastics and organics is shown. It should also be noted that Figure 6a has five categories listed in the *x* axis, with one being average MSW (MSW 1); however, MSW 1 is comprised of more than the summation of the other four categories listed in Figure 6a and should not be expected to equal the averaging of those other four categories. The complete breakdown of MSW 1 is given in Table 1. Both the material and the disposal process are important in determining potential GHG emissions. In all cases, recycling and composting should be encouraged because of their favorable impact on GHG releases. For the mixture of plastics and organics and for plastics alone, combustion is the worst option, while for organics alone and for paper, landfilling is the worst option. For the average MSW, combustion offers an improvement over landfilling with respect to GHG impacts (Figure 6a). The clear implication of Figure 6a is that average MSW has a higher metric ton of CO_2e ($MTCO_2e$) per ton of material when the landfill is used as the final disposal method instead of combustion. This can be caused by the inherent nature of the material composition and its ability to form GHGs in various process methods.

For each MSW scenario, panels b and c of Figure 6 juxtapose the contributions of different MSW constituent materials to CO_2e for combusting and landfilling, respectively. Results show that to reduce $MTCO_2e$ per day, it is better to combust MSW 4 (reduced plastics; total = −531.1 $MTCO_2e$/day), MSW 3 (reduced organics; total = −238.7 $MTCO_2e$/day), and MSW 2 (reduced paper; total = −94.5 $MTCO_2e$/day) while landfilling MSW 5 (reduced paper and organics; total = −105.3 $MTCO_2e$/day). MSW scenario 1 can have benefits of being processed either way. In considering Figure 6, it is important to note that the data in Figure 6a is per ton, while the data in panels b and c of Figure 6 are based on the daily rates. Therefore, scaling up to the daily amount causes the larger values exhibited in panels b and c of Figure 6. Figure 6a provides a summary of how each recyclable influences the net $MTCO_2e$ per ton of material for each process, with plastics showing the largest benefit by recycling and smallest benefit by combustion.

3.3. Economic Implications for Recycling or Composting.

Each of the five MSW scenarios used in this study reduced reusable material in the MSW composition through recycling or composting (Table 1). The purpose of economically evaluating the impacts of recycling and composting was to determine if the profit and, subsequently, the APC expenditures were significantly impacted by substituting MSW for coal. Actual expenditures, revenues, and profits depend upon highly proprietary information for each plant; therefore, absolute values are not publicly available or necessary for the objective of this research. In addition, because all revenue and expenditure streams were not evaluated in this study, the profit is not necessarily representative of what a real CFPP earns. However,

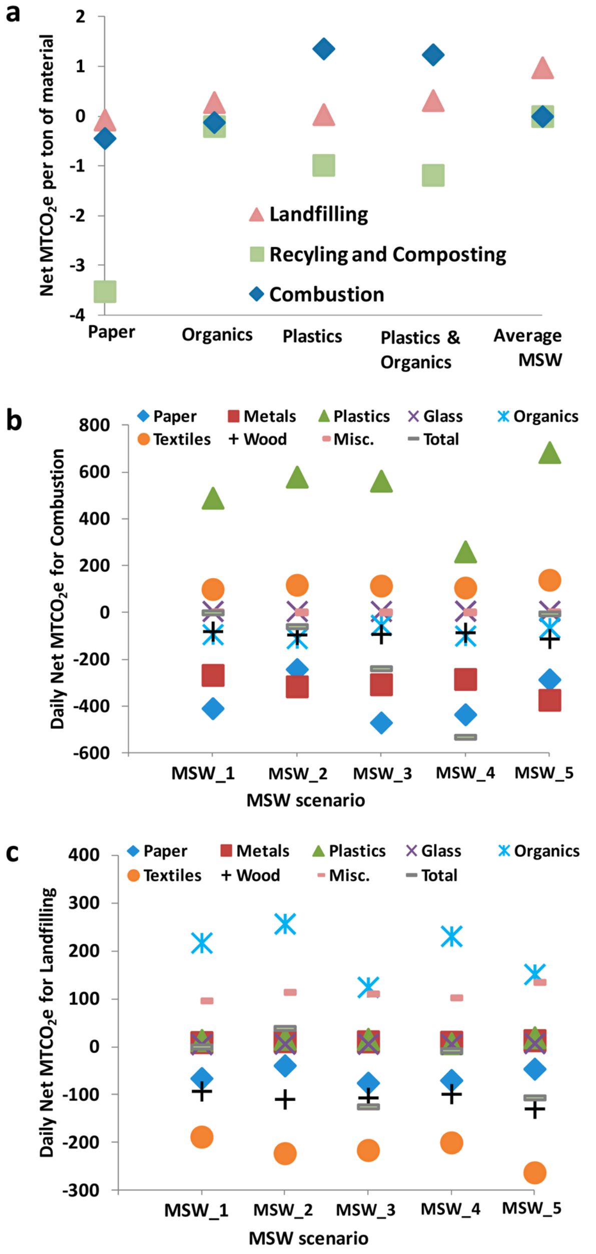

Figure 6. U.S. EPA WARM model results, with different *y*-axis labels for each graph. (a) Net emissions of metric tons of CO_2e ($MTCO_2$e) per ton of MSW constituent material. (b) Contributions of individual MSW constituent materials to daily net $MTCO_2$e emissions for each MSW scenario for the combustion process. Note that the total mark for MSW 1 (0 $MTCO_2$) is completely hidden and MSW 5 (−4.44 $MTCO_2$) is partially hidden, as the values are very close to the miscellaneous mark. (c) Contributions of individual MSW constituent materials to daily net $MTCO_2$e emissions for each MSW scenario for the landfill process. Negative values denote GHG emission reductions or carbon storage; net GHG emissions are estimated to be negative for all biogenic sources of carbon (paper, wood products, and organics). Net emissions consist of transportation to combustion facility, non-biogenic CO_2, and emissions of N_2O minus avoided GHG emissions.[23]

Table 4. Annual Average Change in Profit, as Compared to Coal I6[a]

	change (%) in profit		
	M = 10.1	*M* = 25	*M* = 40
MSW 1	−20.09	−24.36	−28.67
MSW 2	−20.57	−24.76	−28.98
MSW 3	−21.69	−25.70	−29.73
MSW 4	−21.90	−25.88	−29.88
MSW 5	−22.61	−26.46	−30.34

[a] Derived from eq 7. See the Supporting Information for further source information.

the relative changes in the profit, expenditures, and revenues of using one of the MSW scenarios with coal I6, as compared to the CFPP, are realistically obtainable and are reported for this study. Results derived from eqs 5−7 can be found in Table 4 for the change in profit using MSW in lieu of coal and in Table 5 for the impacts on APC costs using MSW. See Table S4 of the Supporting Information for data and references used in the economic evaluation.

In each MSW scenario used in lieu of coal I6, there was a reduction in profit the CFPP earned, ranging from ~20 to 30%, as shown in Table 4. From Table 4, each MSW scenario offers a different change in net profit and some are more dependent upon moisture than others. The change in net profit is directly tied to MSW composition and moisture, with higher moisture of MSW being associated with a larger reduction in profit. MSW 5 (recycled paper and compost organics) showed the largest reduction in profit when it is used in all moisture scenarios, while MSW 1 (the national average) minimized the reduction in profit. For this reduction in profit, however, the amount can vary with the MSW composition. Incentives to use MSW may include taxation on externalities, such as pollutant emissions, and granting credits for renewable fuel use.

The change in expenditures and revenues can be partially attributed to the value of the recyclable materials, the heating value associated with each MSW scenario, and the costs associated with operating APC devices (Table 5). Altering these parameters can allow MSW to become a more economically viable fuel source. From Table 5, the annual emission costs are reduced: up to ~3% for NO, ~20−47% for NO_2, and ~95% for SO_2, when MSW is used.

Reducing emission costs can also result from the proposed CO_2 tax, as shown in Table 5. The proposed average carbon dioxide tax, β, was $40.01 per ton of carbon dioxide, as derived within the limits of previous work.[37,38]

4. SUMMARY AND CONCLUSIONS

The results from this study are useful to discern practices that warrant further investigation for a municipality, CFPP, or regulatory body based on emissions, energy content of the fuel, and costs associated with implementing the recycling and composting programs. It should be stressed that this study is not conclusive as to what would occur in a commercial parallel co-firing CFPP. While co-combustion is an alternative disposal method for MSW, it is not primarily used to produce large quantities of energy, although energy production is a useful byproduct of MSW combustion. The conclusions of this study are as follows: (1) Heating values are influenced by the MSW composition, in a non-uniform pattern, depending upon the MSW scenario category reduced. (2) One cannot reliably predict for all cases that a reduction in an element will linearly reduce a particular pollutant; thus, target reduction of a pollutant may require more thorough analysis of reaction kinetics and plant-operating conditions. (3) SO_2 and NO concentrations decrease with an increase in the fraction of MSW; however, the type of MSW used did not yield largely

Table 5. Annual Average Change in Emission Operational Costs for Each Scaled Pollutant, as Compared to Coal I6[a]

	change (%) in emission costs, as compared to coal I6											
	NO^{sc}			NO_2^{sc}			CO_2^{sc}			SO_2^{sc}		
	M = 10.1	M = 25	M = 40	M = 10.1	M = 25	M = 40	M = 10.1	M = 25	M = 40	M = 10.1	M = 25	M = 40
MSW 1	−3.30	−3.30	−3.32	−46.87	−40.09	−25.22	−34.72	−33.04	−31.85	−95.85	−95.85	−95.85
MSW 2	−3.30	−2.65	−2.66	−45.68	−38.43	−22.69	−34.37	−32.84	−31.78	−95.85	−95.85	−95.85
MSW 3	−3.30	−1.99	−1.99	−46.53	−39.45	−23.88	−34.61	−32.95	−31.81	−95.85	−95.85	−95.85
MSW 4	−3.30	−1.32	−1.33	−47.36	−40.55	−25.42	−34.86	−33.09	−31.85	−95.85	−95.85	−95.85
MSW 5	−3.30	−0.66	−0.67	−44.96	−37.23	−20.39	−34.18	−32.70	−31.72	−95.85	−95.85	−95.85

[a] The APC devices included selective catalytic reduction (SCR) for NO_x and flue gas desulfurization (FGD) for SO_2. Costs include but are not limited to reagent usage, catalyst replacement, waste disposal, and electricity consumption. For the calculation of change in emission, operational costs for CO_2 were obtained for a proposed carbon dioxide tax of $40.01 per ton of CO_2. See the Supporting Information for further source information. CO is excluded in the economic analysis because values for its recovery and expense are not reliably obtainable.

variable results. (4) MSW composition impacts the NO_2 concentration. The concentration of NO_2 is dependent upon moisture, with low moisture decreasing NO_2 more steeply than high moisture as the mass fraction of MSW in the feed increases. (5) CO emissions increase with a decreasing moisture and an increasing mass fraction of MSW. CO_2 emissions depend upon both the moisture content and MSW composition. (6) PEI varied by pollutant and was independent of the MSW composition and moisture for SO_2, slightly dependent upon the moisture content for CO_2, and heavily dependent upon moisture for NO_2 and CO. PEI for NO was not dependent upon moisture. (7) $MTCO_2e$ per day for each MSW scenario varies by material as well as the final disposal method. MSW 4 (reduction in plastics) provided lower CO_2e emissions when combusted, whereas MSW 5 (reduction in paper and organics) fared better in a landfill. Combining recycling or composting initiatives could have a more profound influence on the heating value and should be studied on a case-by-case basis. (8) The use of MSW as a co-fuel to coal will cause a decrease in both profit and emission costs. The extent varies with MSW composition and moisture.

Other portions of the proximate analysis, such as volatile matter and fixed carbon, also could have an impact on emissions and heating value, although they were held constant in these simulations. Further investigation to determine the influence that a particular course of action for recycling or composting would have on emissions, heating values, and costs should be pursued by municipalities prior to policy implementation.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Aspen property parameter DHFGEN values (Table S1), heat capacity coefficients (Table S2), ultimate analysis of the MSW scenarios, on a dry basis (Table S3), economic parameters and references (Table S4), scaled mass flow rates of NO, NO_2, CO, CO_2, and SO_2 (Table S5), and normalized and scaled flue gas ratios for MSW 2−MSW 5 (Figure S1). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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