Environmental Implications of Municipal Solid Waste-Derived Ethanol

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We model a municipal solid waste (MSW)-to-ethanol facility that employs dilute acid hydrolysis and gravity pressure vessel technology and estimate life cycle energy use and air emissions. We compare our results, assuming the ethanol is utilized as E85 (blended with 15% gasoline) in a light-duty vehicle, with extant life cycle assessments of gasoline, corn-ethanol, and energy crop-cellulosic-ethanol fueled vehicles. We also compare MSW-ethanol production, as a waste management alternative, with landfilling with gas recovery options. We find that the life cycle total energy use per vehicle mile traveled for MSW-ethanol is less than that of corn-ethanol and cellulosic-ethanol; and energy use from petroleum sources for MSW-ethanol is lower than for the other fuels. MSW-ethanol use in vehicles reduces net greenhouse gas (GHG) emissions by 65% compared to gasoline, and by 58% when compared to corn-ethanol. Relative GHG performance with respect to cellulosic ethanol depends on whether MSW classification is included or not. Converting MSW to ethanol will result in net fossil energy savings of 397−1830 MJ/MT MSW compared to net fossil energy consumption of 177−577 MJ/MT MSW for landfilling. However, landfilling with LFG recovery either for flaring or for electricity production results in greater reductions in GHG emissions compared to MSW-to-ethanol conversion.

Introduction

Recent sharp increases in petroleum prices have sparked renewed interest in alternative automobile fuels, especially renewable fuels such as ethanol. Ethanol is an excellent light-duty vehicle (LDV) fuel that can be used in conventional vehicles in blends of up to 10% ethanol and 90% gasoline (E10), while flexible fuel vehicles, of which there are more than five million in the United States today, can run on mixtures containing as high as 85% ethanol blended with 15% gasoline (E85). A total of 16.3 billion L of ethanol, 95% of which was produced from corn, were used as a LDV fuel in the U.S. in 2004. While corn is expected to continue to be a major feedstock for fuel ethanol, ethanol produced from cellulosic feedstocks such as woods, grasses, and organic fractions of municipal solid waste (MSW) is emerging as an attractive option because of developments in conversion technology, lower feedstock costs, and higher potential for fossil fuel displacement and reduction in greenhouse gas (GHG) emissions compared to corn-ethanol (*1*, *2*).

MSW is an especially appealing feedstock for ethanol, because cellulosic materials such as paper, wood, and yard waste form about 60% of the dry weight of a typical MSW stream, and diverting these fractions for ethanol conversion would help address not only the problem of MSW disposal, but also contribute, albeit marginally, toward diversifying energy sources. In 2001, U.S. households generated 208 million metric tons (MT) of MSW of which 116 million MT were landfilled (*3*), which, assuming a conservative yield of 66 L of ethanol/MT of MSW, can potentially supply 7.7−13.7 billion L of ethanol. Further, unlike other cellulosic feedstocks, MSW has an already well-established collection system, and is available at a negative cost. The tipping fees charged by landfills to accept MSW ranged from $15 to $100/MT with a national average of $36/MT in 2002 (*4*, *5*). As a result, the economics of converting MSW into ethanol are considered attractive (*6*) and several companies have already attempted pilot testing and commercial planning/implementation (e.g., *7*−*10*).

However, it is not obvious whether the production and consumption of MSW-ethanol is environmentally superior to the production and consumption of gasoline or ethanol from corn or cellulosic materials from dedicated energy crops. Similarly, it is not obvious whether converting MSW into ethanol is environmentally better than simply landfilling. Life cycle assessment (LCA) provides an appropriate, comprehensive framework to analyze such questions about relative environmental performance because LCA takes a "cradle to grave" approach and considers the environmental effects over the entire life cycle, covering raw material extraction, production, use, and disposal stages of a product (*11*, *12*). A number of prior studies have carried out LCAs of alternative fuels and their use in LDV (see ref *13* for a survey). Several of these studies compare gasoline with corn-ethanol and ethanol from woody and herbaceous cellulosic biomass (e.g., *2*, *14*−*17*). However, none of the existing studies analyze environmental implications of MSW-ethanol. Similarly LCAs of traditional MSW management practices have been conducted by several authors (e.g., *18*−*21*). The U.S. Environmental Protection Agency (USEPA) has developed a model called WARM that evaluates the life cycle environmental impacts associated with several traditional MSW management options including landfilling (*22*). However, none of the above considers MSW to ethanol conversion as a waste management option.

This paper addresses this gap in the extant literature and examines the following questions: (i) What are the life cycle environmental burdens associated with using MSW-ethanol as an LDV fuel? (ii) How do MSW-ethanol-fueled LDVs compare from a life cycle energy and emissions perspective, with LDVS fueled with gasoline or with ethanol produced from corn or cellulosic biomass from energy crops? (iii) How does MSW-ethanol compare from a lifecycle energy and emissions perspective with landfilling?

Method

Scope and Functional Unit. Our analysis is based primarily on U.S. data sources, waste collection practices, technological

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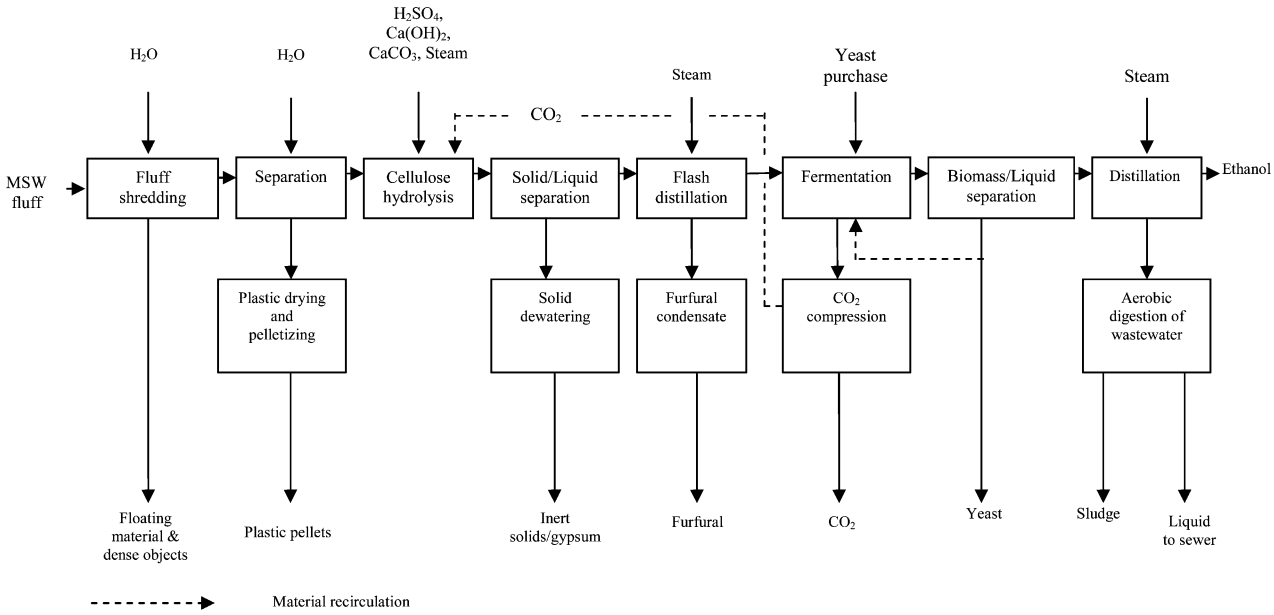

FIGURE 1. Schematic representation of MSW to ethanol conversion technology (adapted from ref *8*).

parameters, and LCA models. We develop an LCA model of MSW-ethanol following the conventional LCA approach documented by the International Organization for Standardization (ISO) (*11*, *12*). We assume that MSW is a waste that needs to be disposed of and do not consider energy use and environmental implications of the processes and products that generated the MSW; i.e., the boundary of our LCA assumes availability of MSW as a feedstock without any prior associated/allocated environmental burdens. For example, none of the environmental burdens associated with paper production, distribution, and use are allocated to the waste paper used as a feedstock in ethanol production.

We use two different functional units in our analysis because we make two different comparisons. When comparing ethanol from MSW with gasoline, corn-ethanol, and celluosic biomass ethanol as LDV fuels, we use one kilometer (km) of vehicle travel as the functional unit. When comparing landfilling and converting to ethanol as waste management options for MSW, we use one MT of wet MSW-fluff as the functional unit. (MSW-fluff refers to the organic residual remaining after conventional extraction of commodities that can be recycled, e.g., aluminum, glass, steel, and plastics, from raw MSW.)

We quantify renewable and non-renewable (fossil fuel and petroleum) energy use, and GHG and air pollutant (AP) emissions. The GHG considered are CH_4, N_2O, and CO_2 and these are weighted by their 100-year global warming potentials in calculating CO_2 equivalents (CO_2 equiv) (*23*). The AP considered are volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter less than 10 micrometers in size (PM_{10}), and sulfur oxides (SO_x). We do not investigate the emissions to water and soil. Energy use and emissions associated with the construction and demolition of the ethanol facility are not included because the allocated emissions and energy use per functional unit from these long-lived assets are likely to be small and LCA studies that we use for comparison also do not include them. We also do not consider other waste management options such as composting.

Life Cycle Inventory. We model a MSW-to-ethanol facility with the capacity to treat 24 MT of wet MSW-fluff per hour using dilute acid hydrolysis and gravity pressure vessel (GPV) technology. The life cycle model incorporates individual modules for MSW collection and hauling, MSW classification, pretreatment, chemicals manufacturing and transportation, MSW-fluff conversion to ethanol, treatment of the coproducts (wastewater, gypsum, and plastics), and use of ethanol as E85 in LDVs. A brief description of these steps follows, and more details are provided in section A1 in Supporting Information.

We model MSW collection and hauling using diesel trucks and estimate the average hauling distance assuming a waste generation density of 2.85 MT MSW/km^2. We model the classification process, where marketable aluminum, glass, steel, and plastic materials are extracted leaving MSW-fluff as the residual, based on Broder and Barrier (*7*). MSW-fluff to ethanol conversion is based on a gravity pressure vessel (GPV) process developed by GeneSyst Inc (*8*). A schematic representation of the GPV process is shown in Figure 1. The main steps in the conversion are the following: MSW-fluff shredding and separation, continuous dilute acid hydrolysis under high temperature, high-pressure conditions in a GPV (a long vertical heat exchanger) to convert the cellulose fraction into sugars, fermentation to convert the sugars into ethanol, and distillation to produce fuel-quality ethanol. We assume an overall yield of 84.5 L of ethanol/MT of wet MSW-fluff. More detailed performance data for the MSW-ethanol facility, including conversion efficiencies at various stages are provided in Section A1 of Supporting Information. Our model also includes secondary processes for treating various coproducts and wastes, such as plastic drying and pelletizing, solids dewatering, furfural condensation, CO_2 compression, and wastewater treatment. Ethanol transportation and distribution activities are modeled based on estimates from Wang (*2*). Life cycle data on the chemicals used during the hydrolysis of the feedstock are from NREL (*24*), ESA and EFMA (*25*), and Sargent and Lundy (*26*). The data for the wastewater treatment stage are from Edeline (*27*), Vandevenne (*28*), and Pardo (*29*). For the vehicle use phase, we assume that ethanol is blended with gasoline as E85 and used in a displacement-on-demand spark ignition conventional drive (E85 DOD SI CD) LDV with a fuel economy of 11.0 L gasoline equivalent/100 km. The vehicle is assumed to meet the Tier 2 Bin 5 emissions standard. These vehicle specifications are from a General Motors Corporation (GM) study (*1*).

For the LCA model, we first estimate the onsite, direct energy consumption and the fuel mix for each of the life cycle stages, and then use Argonne National Laboratory's GREET model (*2*) to determine the life cycle renewable and non-renewable energy use and emissions associated with

TABLE 1. Energy Use and Emissions Associated with the Life Cycle Stages of MSW Conversion to Ethanol[a]

parameter	MSW col-haul.	MSW classifi-cation	fluff pretreat.	chemical manufact.	chemical transp.	ethanol product.	waste-water treat.	lime treat.	plastic treat.	ethanol transp.	ethanol distrib.	total without MSW classifi-cation	total with MSW classific-ation
Energy (MJ/MT wet MSW-fluff)													
total energy	23.8	594	57	14.3	21.8	166	4.1	10.9	117	26.9	4.5	447	1041
fossil fuels	23.5	510	49	13.9	21.7	150	3.6	9.3	100	26.9	4.5	403	913
petro-leum	12.1	7.9	0.8	9.4	20.1	9.9	0.1	0.1	1.6	25.1	4.2	83	91
Air pollutant emissions (g/MT wet MSW-fluff)													
VOC	0.68	0.98	0.09	5	1.05	93	54	0.02	0.19	1.35	0.14	155	156
CO	0.79	14	1.33	1.49	3	40	115	0.25	3	4	0.60	170	184
NO_x	2.99	83	8	12	23	97	77	1.53	16	32	1.78	272	355
PM_{10}	0.71	5.42	0.52	86	0.64	8	10	5	3	0.87	0.05	114	119
SO_x	2.15	164	16	63	1.69	41	11	3	32	3	0.13	173	337
Greenhouse gas emissions (g/MT wet MSW-fluff)													
CH_4	1.85	0.89	0.09	76.00	1.84	121	2.40	0.02	0.18	2.28	0.38	206	207
N_2O	0.03	0.82	0.08	0.02	0.04	1.05	0.01	0.02	0.16	0.05	0.01	1.46	2.27
CO_2	1644	43440	4171	19798	1659	55111	297	795	8584	2069	343	94472	137912
total GHG	1694	43702	4196	21554	1713	58204	354	800	8636	2136	355	99642	143344

[a] Total greenhouse gas emissions (Total GHG) are expressed in terms of CO_2 equiv; col-haul = collection and hauling; pretreat. = pretreatment; manufact. = manufacturing; transp. = transportation; product. = production; treat. = treatment; distrib. = distribution. Totals may not add due to rounding.

this fuel mix. All the electricity requirements at the facility are assumed to be met from the U.S. grid, while required steam is generated on site using natural gas boilers. Next, we include the direct emissions from various processes in the ethanol facility, production of chemical inputs, and LDV use, and estimate the life cycle emissions associated with a MSW-ethanol E85 LDV. Although MSW to ethanol conversion process yields many coproducts such as recovered materials, CO_2, furfural, and gypsum, etc., that are potentially marketable with or without further processing, to be conservative, we do not include any credits for these coproducts in our life cycle calculations for MSW-derived ethanol. Similarly, we assume that the residual decomposition products of lignin are disposed.

We compare the life cycle environmental burdens associated with the MSW-ethanol LDV with those from LDVS fueled by gasoline and ethanol produced from corn or cellulosic biomass. The life cycle energy use and emissions data for the comparative fuels and vehicles are from the comprehensive LCA study of alternative fuels conducted by GM (*1*). In addition, we compare the life cycle implications resulting from the conversion of MSW-fluff to ethanol with results from the USEPA's WARM model for three typical U.S. landfill systems, namely, landfill with no landfill gas (LFG) recovery, landfill with LFG recovery for flaring, and landfill with LFG recovery for energy production (*22*).

Results and Discussion

The estimated life cycle energy consumption, GHG, and AP emissions per MT of wet MSW-fluff input for each of the stages of the MSW to ethanol process are shown in Table 1. The MSW classification step is a major contributor to the life cycle energy use and GHG emissions, followed by ethanol production and chemical manufacture.

There is some debate as to whether the MSW classification step should be included in the analyses. For example, Broder and Barrier (*7*) include MSW classification in their analysis, while Sakamoto (*4*) and GeneSyst (*8*) assume that the facility will receive sorted MSW-fluff from an existing materials recovery facility. From a life cycle system boundary perspective, the relevant question is whether MSW classification is carried out only because MSW is being converted to ethanol, or if the classification would have happened even if MSW was managed in other ways. While conversion to ethanol would definitely require classification and separation, separation of recyclables is likely to occur prior to landfilling as well, either because it is economically feasible due to the value of recovered materials or because of legal mandates for prior separation. Hence, we report the life cycle emissions both with and without the classification step (last two columns of Table 1) and discuss the implications.

Comparison of MSW-Ethanol with Gasoline, Corn-Ethanol, and Cellulosic Ethanol as LDV Fuels. Table 1 reports estimated life cycle emissions associated with converting one MT of wet MSW-fluff into ethanol. However, the question of policy interest is how does MSW-ethanol compare on the basis of life cycle energy use and emission burdens per km driven, with other LDV fuels, specifically gasoline, corn-ethanol, and cellulosic-biomass ethanol? To address this question, we first convert the life cycle energy use and emissions shown in Table 1, to a per MJ of ethanol output basis, assuming an ethanol yield of 84.5 L/MT of wet MSW-fluff and a lower heating value of 21.16 MJ/L for ethanol. We then assume the ethanol produced is blended as E85 and used in the LDV specified previously. We calculate the total life cycle "well-to-wheel" (WTW) energy use and emissions per vehicle km traveled (VKT). The WTW data for the gasoline used for blending with ethanol are from GM (*1*).

The estimated WTW energy use and emissions per VKT using MSW-ethanol are shown in columns 2 and 3 of Table 2. We compare these estimates with the WTW results for low-sulfur (30 ppm) reformulated gasoline, corn-ethanol, and cellulosic biomass (assumed 50% herbaceous/50% woody feedstocks)-ethanol from GM (*1*), shown in the next three columns of Table 2. Key parameters and assumptions for these pathways in GM (*1*) are summarized in Section A2 of the Supporting Information. In our LCA calculations, we follow the Intergovernmental Panel on Climate Change guidelines (*30*) and exclude direct emissions of CO_2 resulting from the fermentation process and ethanol combustion in the vehicles, assuming that the carbon that is emitted is from renewable biomass sources and was fixed recently through photosynthesis. Further, GM's estimates include credits for coproducts such as distiller's dried grains and solubles in

TABLE 2. Well-to-Wheel Energy Use and Emissions for Light-Duty Vehicles[a]

parameter	MSW-ethanol no classification	MSW-ethanol with classification	LS FR-gasoline (GM (*1*))	corn ethanol GM (*1*)	cellulosic ethanol GM (*1*)
			Energy use (kJ/Km)		
total energy	4456	5348	4473	5792	7481
fossil fuels	1767	2528	4458	3104	1326
petroleum	1168	1180	3994	1267	1269
			Air pollutant emissions (g/Km)		
VOC	0.36	0.36	0.21	0.25	0.25
CO	2.69	2.71	2.49	2.56	2.66
NO_x	0.54	0.66	0.25	0.48	0.52
PM_{10}	0.20	0.20	0.05	0.17	0.07
SO_x	0.29	0.53	0.10	0.22	0.01
			Greenhouse gas emissions (g/Km)		
CH_4	0.41	0.41	0.41	0.44	0.17
N_2O	0.02	0.02	0.02	0.16	0.10
CO_2	38	103	328	223	63
total GHG	54	119	343	280	96

[a] LS-FR = Low sulfur federal reformulated gasoline. Total greenhouse gas emissions (Total GHG) expressed in terms of grams of CO_2 equiv. Cellulosic ethanol assumes 50% woody/ 50% herbaceous feedstock as per GM (*1*). All ethanol is utilized as E85.

corn-ethanol production, and for electricity produced from lignin combustion in cellulosic-biomass-ethanol.

The relative performance of MSW-ethanol (Table 2) depends on whether MSW classification is included or not. However, even if the classification step is included the life cycle energy use per VKT for MSW-ethanol is less than that of corn-ethanol and cellulosic-ethanol. The WTW total energy use for MSW-ethanol is essentially the same as that for gasoline, if MSW classification is excluded. But these energy use numbers do not include any credits for recovered materials during the classification stage. Adding credits for recovered materials can significantly reduce life cycle energy use for MSW-ethanol. For example, the USEPA estimates that life cycle energy savings from recovering and recycling 1 kg of aluminum from MSW are 197.8 MJ (*22*), and on average 3.49 kg of aluminum was recovered per MT of MSW generated in the U.S. in 2001 (*3*). Hence, credits of 690 MJ/MT of MSW for recovery and recycling of aluminum alone would offset the energy of 594 MJ/MT MSW used in the classification step. Hence substitution of gasoline with MSW-ethanol will reduce overall energy use.

From the row labeled "petroleum" in Table 2, it can be seen that even without any such coproduct credits, energy use from petroleum sources for MSW-ethanol is lower than for the other fuels, indicating that converting MSW to ethanol can contribute toward reducing dependence on foreign oil and improving energy security. It should be noted that 1040 kJ/km (life cycle energy including 933.8 kJ contained in gasoline) of petroleum use in all three ethanol vehicles comes from the gasoline blended in E85. In terms of global warming potential, MSW ethanol even with classification, can reduce net GHG emissions by 65% compared to gasoline, and by 58% when compared to corn-ethanol. Relative GHG performance with respect to cellulosic ethanol depends on whether MSW classification is included or not. Although including the MSW classification related emissions will reduce the GHG emission benefits of MSW-ethanol, adding coproduct credits for recovered materials will more than offset the GHG emissions associated with the classification step. For example, the estimated GHG emission savings per kg of aluminum recovered and recycled from MSW are 16.23 kg CO_2 equiv (*22*), and on average 3.49 kg of aluminum was recovered per MT of MSW generated in the U.S. in 2001 (*3*), i.e., a total of 56.7 kg CO_2 equiv credits compared to GHG emissions of 43.7 kg CO_2 equiv per MT of MSW associated with classification.

Well-to-wheel AP emissions from MSW-ethanol appear to be higher than those of gasoline, corn-ethanol, and cellulosic-ethanol. It can be seen from Table 1 that the majority of these emissions arise from MSW classification and recovery operations, ethanol production, and wastewater treatment at the ethanol conversion facility, indicating that local air quality may be a concern around these facilities and appropriate emission control systems may be necessary to reduce these air quality impacts.

Comparison with Landfilling as a Waste Management Option. A second policy-relevant question is, whether it is better, from an energy and emissions perspective, to landfill MSW or convert it into ethanol. We compare the MSW to ethanol conversion with three types of landfilling options, namely landfilling without LFG recovery, landfilling with LFG recovery for flaring, and landfilling with LFG recovery for energy. Since we are evaluating MSW conversion to ethanol as a waste management alternative to landfilling, and our functional unit is one MT of MSW-fluff managed by different methods, we treat the ethanol produced as a coproduct and adjust the total energy and GHG estimates per MT MSW-fluff (reported in the last two columns of Table 1), by appropriate coproduct credits.

We consider two alternative assumptions in estimating these coproduct credits for ethanol produced, first that the ethanol produced displaces an energy-equivalent amount of gasoline (i.e., 84.5 L of ethanol produced from MSW will displace 56.75 L of gasoline), and second that the ethanol displaces an equal amount of corn-ethanol. The displacement, in reality, will be a function of the relative prices, government policies, and vehicle fleet characteristics. For example given the conditions in the United States in 2005; retail gasoline prices of over $0.80/L, a mandate for more than doubling the use of ethanol as an automobile fuel under the Energy Policy Act of 2005, continuing subsidies for ethanol production, and existence of a large fleet of E85 flexible fuel vehicles, it would be logical to assume that the incremental production of MSW-ethanol would displace gasoline rather than corn-ethanol. However, if corn prices were to increase significantly or gasoline prices were to decline substantially, MSW-ethanol may displace corn-ethanol. Hence we analyze both alternatives.

These coproduct credits represent the avoided energy consumption and emissions from the production of gasoline and corn-ethanol displaced by MSW ethanol. We use well-to-vehicle-fuel-tank (WTT) emission and energy use estimates

TABLE 3. Fossil Energy Use and Greenhouse Gas Emissions: MSW to Ethanol Compared with Landfilling

scenario	net fossil fuel energy use (MJ/MT wet MSW fluff)	net GHG emissions (kg CO_2 eq./ MT wet MSW fluff
MSW to ethanol no classification gasoline displacement	−1830	−66
MSW to ethanol with classification gasoline displacement	−1320	−22
MSW to ethanol no classification corn-ethanol displacement	−907	−27
MSW to ethanol with classification corn-ethanol displacement	−397	16
landfill with LFG recovery for electricity	177	−463
landfill with LFG recovery for flaring	577	−337
landfill with no LFG recovery	577	337

[a] Energy use and emissions for landfill options estimated from WARM model (*22*); LFG = landfill gas; MSW to ethanol scenarios with gasoline displacement include a credit of 1788 MJ/MT wet MSW-fluff which represents the fossil energy content of the gasoline displaced.

for gasoline and corn-ethanol from GM (*1*) and calculate coproduct credits for 56.75 L (1788 MJ) of gasoline or 84.5 L (1788 MJ) of corn-ethanol displaced. (Section A3 in Supporting Information shows the WTT estimates). Displacing gasoline with MSW-ethanol will further reduce net fossil energy consumption by 1788 MJ. Gasoline displacement will also reduce net GHG emissions associated with vehicle operation because the CO_2 emissions from MSW ethanol are from biomass carbon previously fixed through photosynthesis. Hence we provide additional GHG credits for the gasoline displacement scenario of 71.6 g CO_2/MJ of gasoline displaced, or a total of 128,802 g CO_2/MT of wet MSW-fluff. The life cycle net fossil energy and GHG emissions per MT MSW-fluff converted to ethanol after the coproduct credits are shown in the top four rows of Table 3. (Section A4 of Supporting Information provides detailed calculations.)

For the landfilling options, we draw on the results from the WARM model (*22*). The model estimates life cycle fossil energy use and GHG emissions for various combinations of waste management practices, materials being handled, landfill characteristics, and waste transportation distances. However, the main limitations of the WARM model are that it only considers fossil energy use and GHG emissions, and reports only the total life cycle emissions. Furthermore, the model makes several key assumptions that are critical for interpreting our comparisons. These include the following: (a) when organic matter is landfilled, anaerobic bacteria degrade it partially, producing CH_4 and CO_2: CH_4 is counted as an anthropogenic GHG because degradation of the biomass would not result in CH_4 production if the biomass was not landfilled, while CO_2 generated is not counted as a GHG because CO_2 would be produced through natural decomposition even if the waste was not landfilled; flaring of LFG without energy recovery will hence reduce net GHG emissions; (b) carbon in un-decomposed organic matter is stored in the landfill, and GHG credits are provided for this carbon sequestration; (c) all plastics are non-biodegradable, do not generate CH_4 when landfilled, and no GHG credit is given for carbon sequestered in landfilled plastics because the carbon is assumed to be of fossil origin; and (d) when LFG is recovered for energy, it displaces electricity corresponding to the U.S. electricity grid mix and equivalent coproduct credits are provided.

The life cycle fossil energy use and GHG emissions reported by the WARM model for the landfilling options are shown in the last three rows of Table 3. The fossil energy use for landfilling with energy recovery is lower than landfilling without energy recovery. However, because of carbon sequestration credits for undecomposed organic matter and conversion of anthropogenic methane emissions into biogenic CO_2 emissions via flaring, landfilling with LFG recovery for flaring shows negative GHG emissions (−337 kg CO_2 equiv/MT wet MSW-fluff). The carbon credits are even higher in the case of LFG recovery for energy, because the recovered energy is assumed to displace electricity generated by the U.S. grid which is dominated by coal generation with high GHG emissions.

As can be seen in Table 3, converting MSW to ethanol will result in significant fossil energy savings compared to landfilling with or without LFG recovery for energy. These fossil energy savings are substantially higher when the produced ethanol displaces gasoline. The net GHG emissions from MSW-ethanol conversion are negative for all scenarios, except the last when the MSW classification step is included and the produced ethanol is assumed to displace corn-ethanol. However, landfilling with LFG recovery either for flaring or for energy recovery results in even greater reductions in GHG emissions compared to MSW to ethanol conversion. The main reasons for better GHG performance of landfilling with LFG recovery are the carbon sequestration credits provided for un-decomposed organic materials, and coproduct GHG credits for electricity.

Sensitivity Analysis

The ultimate yield of ethanol from MSW depends on the composition of incoming MSW and the efficiencies of conversion from cellulose to glucose during hydrolysis, glucose yield after neutralization, and glucose to ethanol conversion during fermentation. Fermentation inhibiting toxins commonly found in biomass hydrolyzates such as furfural, weak acids (i.e., levulinic, acetic, and formic), and phenolic compounds are generally major concerns. However, in the GPV process, the amount of toxins generated is much lower due to rapid (less than 10 s) hydrolysis, compared to the slow, lower-temperature acid hydrolysis. Proposed excessive liming during fermentation is shown to improve yields (*31*). Furthermore, an optional activated carbon adsorption step can be used (not modeled) between the post-GPV clarification and fermentation steps to extract organics along with formic acid, phenolics, and furfurals. The reported glucose fermentation efficiencies range from 38% (*32*) to 90% with advanced technology (*16*). We have conservatively assumed a fermentation efficiency of 44% and an overall yield of 84.5 L of ethanol/MT of wet MSW-fluff in our base case analysis. However, we also analyze scenarios where the efficiency of the conversion of cellulose to glucose ranges from 38% to 91% and the efficiency of the solid/liquid separation ranges from 63% to 95%, resulting in ethanol yields ranging from 46 to 166 L/MT of MSW-fluff. Under these scenarios, the net fossil energy use with classification ranges from −330 to −3436 MJ/MT wet MSW-fluff (for 46 and 166 L/MT wet MSW-fluff, respectively). Without classification, the corresponding results range from −841 to −3947 MJ/MT wet MSW-fluff. With classification, total GHG emissions range from 42 to −167 kg CO_2 equiv/MT wet MSW-fluff (for 46 and 166 L/MT wet MSW-fluff, respectively). Without classification, the respective results range from −2 to −211 kg CO_2 equiv/MT wet MSW-fluff. Comparing these results with the fossil energy and GHG emissions associated with landfilling with LFG recovery for energy (177 MJ/MT wet MSW-fluff and −463 kg CO_2 equiv/MT wet MSW-fluff), it can be seen that

improvements in ethanol yield significantly reduce net fossil energy use and GHG emissions, which is mainly due to the larger volume of gasoline being displaced (through higher ethanol output). However, even after assuming the highest ethanol yield of 166 L/MT, MSW to ethanol conversion results in higher net GHG emissions compared to landfilling with LFG recovery.

Discussion

Our results indicate that the net life cycle energy used in producing MSW-ethanol is less than the energy used for producing corn-ethanol or cellulosic biomass-ethanol. More importantly, the use of energy from petroleum sources for MSW-ethanol is lower than that for gasoline, corn-ethanol, and cellulosic-ethanol, which suggests that using MSW-ethanol can reduce petroleum consumption. In terms of global warming effects, MSW-ethanol performs better than corn-ethanol and gasoline. Similarly, converting MSW into ethanol instead of landfilling will result in significant fossil energy savings. These savings are substantially higher when the ethanol displaces gasoline. However, if the policy goal is to reduce GHG emissions, landfilling with LFG recovery either for flaring or energy recovery might be a better alternative than converting MSW to ethanol, primarily because of carbon credits for undecomposed organic matter and electricity displaced.

Our study is subject to limitations arising both from the life cycle model of MSW to ethanol that we have developed and the other life cycle models utilized for comparative analyses. These limitations need to be taken into account when drawing inferences. Currently, no commercial facilities that convert MSW to ethanol are operating. Our model of MSW to ethanol conversion is primarily based on projected performance of a proposed plant. These performance data are based on pilot studies (*7*, *8*, *33*). There exist a number of competing technologies for each of the processing steps in ethanol conversion, namely pretreatment, hydrolysis, fermentation, and distillation, and technologies that combine these processes, for example, simultaneous saccharification and fermentation (SSF). While our analysis is based on a specific plant configuration that represents "state-of-the-art" in our judgment, the performance parameters of an operating, commercially viable, conversion plant may differ from our projected performance. Similarly, parameters such as waste densities, transportation distances, and emission control system performance may differ across plants depending on plant size, scale economies, and local regulations. We do not carry out formal analyses of these uncertainties, but report sensitivities with respect to key parameters such as ethanol yield and inclusion of a classification step. The limitations of the WARM model are described in detail in ref *22*. While the GM study (*1*) is a comprehensive study of alternative fuels, it suffers from common limitations inherent to any LCA, both practically and conceptually as discussed by Jolliet et al. (*34*). These limitations extend to our study as well.

Producing ethanol from MSW can contribute to reducing dependence on non-renewable petroleum resources and reducing GHG emissions. However, the overall impact of MSW-ethanol is expected to be limited, mainly because of limited availability of MSW as a feedstock. The estimated annual quantity of ethanol that can potentially be produced from MSW ranges from 7.7 to 13.7 billion L, compared to 530 billion L of motor gasoline consumed in the United States in 2005. Hence, MSW-ethanol is likely to play a relatively minor role in fuelling the U.S. LDV fleet and in alleviating some of its environmental impacts. However, MSW-ethanol can augment the diversity of the domestic energy resource base, help mitigate the impact of potential fuel supply disruptions, and improve energy security.

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Supporting Information Available

Detailed process description and selected performance data for the MSW-to-ethanol facility; summary of assumptions and key parameters in the life cycle assessment of corn ethanol, cellulosic ethanol, and crude oil gasoline pathways in the 2005 General Motors study; well-to-tank energy use and emissions associated with MSW-ethanol, low-sulfur Federal reformulated gasoline, corn ethanol, and cellulosic ethanol; detailed calculations for the results shown in Table 3. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Brinkman, N.; Wang, M.; Weber, T.; Darlington, T. *Well-to-Wheels Analysis of Advanced Fuel Vehicle Systems − a North American Study of Energy Use, Greenhouse Gas, and Criteria Air Pollutants*; Final Report; Argonne National Laboratory: Argonne, IL, 2005; http://www.transportation.anl.gov/pdfs/TA/339.pdf.

(2) Wang, M. *Greenhouse Gases, Regulated Emissions, and Energy used in Transportation (GREET) model Version 1.6*; Center for Transportation Research, Energy Systems Division, Argonne National Laboratory: Argonne, IL, 2006.

(3) U.S. Environmental Protection Agency. *Municipal Solid Waste in the United States: 2001 Figures and Facts*; U.S. Environmental Protection Agency: Washington, DC, 2003; http://www.epa.gov/epaoswer/non-hw/muncpl/pubs/msw2001.pdf.

(4) Sakamoto, O. The financial feasibility of municipal solid waste to ethanol conversion. Master of Science Thesis, Department of Agricultural Economics, Michigan State University, MI, 2004.

(5) Repa, E. W. Solid Waste Disposal Trends. *Waste Age* **2000**, *31*, 4, 262−265.

(6) Joshi, S.; Sakamoto, O.; MacLean, H. L. Feasibility of MSW to Ethanol Conversion, Presented at 27th Symposium on Biotechnology for Fuels and Chemicals, Denver, CO, May 1−4, 2005.

(7) Broder, J. D; Barrier, J. W. *Municipal solid waste and waste cellulosics conversion to fuels and chemicals. April 1990−September 1992*; Final report, Volume I: Summary report; Tennessee Valley Authority Biotechnical Research Department: Muscle Shoals, AL, 1992.

(8) Genesyst International Inc. (GII). *MSW fluff conversion to alcohol*; GeneSyst Inc.: Hudson, OH, 2004; http://www.genesyst.com/Ethanol_from_Waste/MSW_Conversion.htm (accessed 2/20/06) Also available on request from James Titmas (e-mail GenSyst@aol.com).

(9) Hegedus, N. Political victory leaves much for Masada to do. *Times Herald Record*, Dec 10, 2003; http://www.recordonline.com/archive/2003/12/10/nhmasada.htm.

(10) Fox, P.; Fentes, J.; Bogner, D. P. *Market development program for refuse to alcohol plants in Arizona*; Final report; Western Regional Biomass Energy Program (WRBEP): Denver, CO, 1999; Contract 55015.

(11) International Organization for Standardization. *ISO 14040: Environmental management: Life cycle assessment - Principles and framework*; International Organization for Standardization: Geneva, Switzerland, 1997.

(12) International Organization for Standardization. *ISO 14041: Environmental management: Life cycle assessment - Goal and scope definition and inventory analysis*; International Organization for Standardization: Geneva, Switzerland, 1998.

(13) MacLean, H. L.; Lave, L. B. Evaluating automobile fuel/propulsion system technologies. *Prog. Energy Combust. Sci.* **2003**, *29*, 1−69.

(14) Wang, M.; Saricks, C.; Wu, M. *Fuel cycle fossil energy use and greenhouse gas emissions of fuel ethanol produced from US Midwest corn*; Argonne National Laboratory: Argonne, IL, 1997.

(15) Kadam, L. *Environmental life cycle implications of using bagasse-derived ethanol as a gasoline oxygenate in Mumbai (Bombay)*; Prepared for the National Energy Technology Laboratory,

Pittsburgh, PA and USAID, New Delhi, India; NREL/TP-580-28705; National Renewable Energy Laboratory: Golden, CO, 2000.
(16) Sheehan, J.; Aden, A.; Paustian, K.; Killian, K.; Brenner, J.; Walsh, M.; Nelson, R. Energy and environmental aspects of using corn stover for fuel ethanol. *J. Ind. Ecol.* **2003**, *7* (3−4), 117−146.
(17) Farrell, A. E.; Plevin, R. J.; Turner, B. T.; Jones, A. D.; O'Hare, M.; Kammen, D. M. Ethanol can contribute to energy and environmental goals. *Science* **2006**, *311* (5760), 506−508.
(18) Solano, E.; Ranjithan, S. R.; Barlaz, M. A.; Brill, D. E. Life cycle based solid Waste Management − I: Model development. *J. Environ. Eng.* **2002**, *128* (10), 981−992.
(19) Solano, E.; Dumas, R. D.; Harrison, K. W.; Ranjithan, S. R.; Barlaz, M. A.; Brill, D. E. Life cycle based solid Waste Management − II: Illustrative applications. *J. Environ. Eng.* **2002**, *128* (10), 993−1005.
(20) Thorneloe, S. A.; Weitz, K. A.; Nishtala, S. R.; Yarkosky, S.; Zannes, M. The impact of municipal solid waste management on greenhouse gas emissions in the United States. *J. Air Waste Manage. Assoc.* **2002**, *52*, 1000−1011.
(21) Ménard, J. F.; Lesage, P.; Deschênes, L.; Samson, R. Life cycle analysis of municipal organic Waste Management: landfill versus bioreactor. In *Proceedings of 10th World Congress on Anaerobic Bioconversion Answer for Sustainability*, Montréal, ON, August 29−September 2, 2004; Vol. 2, pp 602−610.
(22) U.S. Environmental Protection Agency. *Solid Waste Management and greenhouse gases − A life cycle assessment of emissions and sinks*, 2nd ed.; EPA530-R-02-006; U.S. Environmental Protection Agency: Washington, DC, 2002.
(23) Intergovernmental Panel on Climate Change (IPCC). *Third Assessment Report. Climate Change 2001: The Scientific Basis*; Cambridge University Press: New York, 2001.
(24) *Life-Cycle Inventory Database*; National Renewable Energy Laboratory: Golden, CO, 2004; http://hpb-1a.nrel.gov/lci.
(25) *Production of sulphuric acid − Best available techniques for pollution prevention and control in European sulphuric acid and fertilizer industries*; European Sulphuric Acid Association (ESA) and European Fertilizer Manufacturers' Association (EFMA): Brussels, Belgium, 2000; Booklet no. 3 − 8.
(26) *Dry flue gas desulphurisation technology evaluation*; Project number 11311-000; Sargent & Lundy LLC: Chicago, IL, 2002.
(27) Edeline, F. *L'épuration physico-chimique des eaux − Théorie et technologie*, Cebedoc Edition, 4th éd.; Tec & Doc Lavoisier: Paris, 1997 (In French).
(28) Vandevenne, L. Traitement des boues. In *Application des techniques d'épuration des eaux résiduaires industrielles*; Document Cebedeau, 2 Rue A. Stévart, 4000 Liège, Belgique, 1995 (In French).
(29) Pardo, P. E. *Séchage thermique des boues de stations d'épuration utilité et perspectives*; Document ENGREF; ENGREF centre de Montpellier, B.P.5093 - 34033 Montpellier cedex 01, 1998 (In French).
(30) Intergovernmental Panel on Climate Change (IPCC). *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3: The Greenhouse Inventory Reference Manual*; United Nations Environment Program, Organization for Economic Cooperation and Development, International Energy Agency: Paris, France, 1997.
(31) Green, M.; Shelef, G. Ethanol fermentation of acid hydrolysate of municipal solid waste. *Chem. Eng. J.* **1989**, *40*, B25−B28.
(32) Laughlin, T. J.; Coleman, D. R.; Kilgore, M. V.; Lishawa, C. L.; Meyers, W. E.; Eley, M. M. Development of a Process for Conversion of Municipal-Solid-Waste to Ethanol. *Biotechnol. Bioeng. Symp.* **1984**, *14*, 581−587.
(33) Broder, J. D.; Harris, R. A.; Ranney, J. T. Using MSW and industrial residues as ethanol feedstocks. *Biocycle* **2001**, *42* (10), 23.
(34) Jolliet, O.; Saadé, M.; Crettaz, P. *Analyse du cycle de vie - comprendre et réaliser un écobilan*; Presses Polytechniques et Universitaires Romandes, Collection gérer l'environnement, 2005 (In French).

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