Proceedings of ES2009
Energy Sustainability 2009
July 19-23, 2009, San Francisco, California USA

ES2009-90327

LIFE CYCLE ANALYSIS OF AUTOMOTIVE ETHANOL PRODUCED FROM MUNICIPAL SOLID WASTE

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ABSTRACT

The trend of increasing petroleum prices has prompted the consideration of other fuels for transportation. Ethanol has received a great deal of attention based on the hope that it is possible to develop a sustainable and relatively environmentally responsible alternative to gasoline. Currently, the biofuels industry depends heavily on the use of cereal crops as the feedstock for the ethanol refineries. This practice, however, has led to concern over the diversion of food supplies to fuel supplies; price increases of corn and corn-dependent products (milk, beef, etc.) have already been blamed on the market forces pushing crops towards fuel production. Additionally, sufficient land water exist in the US for cereal crop-based biofuels.

Another method for producing ethanol uses waste products as the main feedstock. The waste can consist of anything fermentable – agricultural field remnants, yard clippings, and paper and food waste all are potentially inputs to the ethanol production process. An added benefit of such a system is the decrease in the amount of material that must be disposed in landfills or dumps.

This paper briefly discusses the conversion of municipal solid waste (MSW) to ethanol for use as an automotive replacement fuel.

ETHANOL FROM MSW

Research into the conversion of municipal solid waste into ethanol has been around for longer than one might think. The oil crises of the 1970s and 1980s prompted the U.S. Army to consider alternative sources of gasoline for its vehicles. In 1992 the Army studied the potential of converting the 20 tons of waste paper generated *daily* by the Redstone Arsenal.[1] Two different methods of producing the ethanol were considered: (1) sulfuric acid hydrolysis to convert the cellulose to fermentable sugars, and (2) enzymatic conversion. Both processes use conventional batch yeast fermentation to produce ethanol. The study concluded that the conversion of the cellulosic fraction of the MSW to useful and valuable byproducts would significantly reduce the burden on existing landfills, and that the production of fuel ethanol from MSW would help reduce dependence on imported liquid fuels. However, the technologies used in this study were deemed too immature and too problematic for wide-spread adoption.

In the subsequent years, a number of companies have worked on advancing the technologies for MSW conversion, spurred by the ever-increasing economic reward of finding a viable process for producing non-petroleum liquid fuels. The Masada Resource Group recently teamed with RJ Zapata and Associates to develop and operate a commercial-scale combined waste-to-ethanol and electricity production plant in the Dominican Republic. The plant, announced in December 2007, is expected to produce as much as 30 million gallons of ethanol per year.[2] Meanwhile, in late December 2007, BioGold Fuels Corporation licensed technology to separate organic from inorganic waste streams for eventual input to their biodiesel fuel process.[3] According to their press release, the company was “seeking to develop, acquire, license and commercialize patented and proprietary technologies that its management believes will allow a significant amount of municipal solid waste to be recycled into synthetic diesel fuel and other renewable fuels to address the $93 Billion diesel fuel market in the United States.” Clearly they believe that MSW provides a clear profit stream for producing biofuels.

Another method for producing fuels from MSW is the *Coskata* process currently promoted by General Motors. This process supplies anaerobic bacteria with carbon monoxide and hydrogen in a specialized reactor. CO and H_2 are produced by gasification, which can be done a number of different ways, depending on the feedstock material. The claim is that the feedstock can consist of materials including agricultural waste, crops, waste materials such as old tires, and municipal waste streams. The gasification is believed to be more efficient that the enzymatic reactions used in traditional ethanol production. GM's proposed demonstration plant is predicted to use plasma gasification. The Coskata process is also predicted to use about a third the water of conventional ethanol production methods.[4,5]

The plasma gasification techniques for producing the syngas used in the Coskata reactor are still under development. The French company Europlasma is developing plasma torches that could be used for this purpose. This is an extension of the use of similar technologies for vitrifying the dangerous waste products from power plants.

Europlasma is directing its goals towards the production of sulfur-free biodiesel since diesel fuel is more widely used in Europe. The company is working with grants from the French nuclear research body and is still in the research phase with no schedule for commercialization of the technology.

LIFE CYCLE ANALYSIS OF MSW-BASED ETHANOL

With this new emphasis on converting waste to fuels, it seems logical to consider the environmental implications of such a strategy. For the purposes of this study we will look only at the conventional (i.e., enzymatic reduction and fermentation) methods that are mature and in use around the world. The basic process is illustrated in Figure 1.

In 2007 the American Chemical Society published a seminal paper on this topic, authored by researchers from the University of Toronto and the University of Michigan.[6] In this paper a municipal solid waste-to-ethanol plant was modeled to estimate the energy use and perform and LCA study. The processing plant was a typical facility that used acid hydrolysis and gravity pressure vessel technology. The resulting ethanol was assumed to be used in an E85 blend. The MSW composition used in this study assumed cellulosic material composition (i.e., paper, wood, and yard waste) of about 60 percent.

The report concludes that the life cycle total energy use per vehicle mile with ethanol from MSW is less than that for ethanol from corn or cellulose. They also concluded that the MSW-ethanol use in vehicles reduces net greenhouse gas emissions by 65 and 58 percent compared to gasoline and corn ethanol, respectively.

The study also provides estimated energy and emissions for various stages of the MSW-to-ethanol cycle. These are listed in Table 1. The results are given for both with and without MSW *classification* (referring to the sorting and removal of non-fermentable materials prior to the hydrolysis stage).

The values given in Table 1 are given per metric ton (tonne) of wet MSW fluff. The authors also cite a yield of 84.5 liters of ethanol produced per tonne of feedstock. For the purposes of this study we consider MSW with classification but will not include the collection and hauling stage. Consequently, the total energy input is 1041 - 23.8 = 1017 MJ per metric ton. This results in a total upstream energy input of about 43,000 BTU per gallon.

In other words, the energy balance for MSW-based ethanol looks quite good compared to crop or cellulosic production, with an energy return on investment of about 1.75 to 1. The upstream emissions of carbon dioxide can be calculated as

$$\begin{aligned}&136270\,\frac{g\;CO_2}{tonne\;MSW}\times\frac{1}{84.5}\,\frac{tonne\;MSW}{liter}\\&\times\frac{1}{454}\,\frac{lb}{g}\times 3.78\,\frac{liter}{gallon}\\&\approx 13.4\;lb\;CO_2\,/\,gal\end{aligned}\qquad(1)$$

where the 136270 g CO_2 is the total emissions from Table 1 without the collection and hauling stage. Similarly, the emissions of SO_X, NO_X, and CH_4 are determined to be 0.033, 0.035, and 0.020 lb per gallon, respectively. When used in an E85 blend the emission numbers are 12.1, 0.029, 0.030, and 0.022 lbs per gallon for CO_2, SO_X, NO_X, and CH_4.

LIFE CYCLE ANALYSIS TOOL

These numbers are compared to an existing computer tool used for the analysis of vehicles[7]. This existing LCA tool is a spreadsheet-based method for calculating the cradle-to-grave life cycle emissions for automobiles, including vehicle material acquisition, assembly, fuel production and delivery, vehicle use, and disposal.

In the existing LCA tool, the upstream CO_2 emissions for corn-based E85 are about 64 percent of the numbers just calculated. However, the emission values given in Table 1 show CO_2 emissions for MSW-based ethanol dominated by the classification and the plastic treatment. Indeed, these two stages – not found in the corn ethanol calculations – combined make up 38 percent of the emissions, thus showing quite good agreement.

On the other hand, while the upstream CH_4 emission for E85 in the existing LCA tool (0.016 lb per gal) is close to that just calculated, the SO_X and NO_X values in the existing tool are 20 to 60 percent higher than those numbers from Kalogo et al. Again, we see that the SO_X and NO_X burdens from the classification and plastic treatment are significant, but not sufficient to explain the differences. *The reader is cautioned when comparing these two pollutants to earlier studies.*

VEHICLE ANALYSIS

The LCA tool was run using the upstream energy and emission values as just calculated. In addition, both the city and highway mileage was adjusted by the ratio of the energy content of E85 compared to gasoline (71 percent). The vehicle mass and composition for E85 runs remained the same as for the gasoline version. Table 2 shows the estimated life cycle emissions for an average midsize sedan, while Table 3 and Table 4 show similar results for an average midsize SUV and average full-size pickup truck, respectively. The assembly and raw material energy needs were assumed satisfied using national average values. Both gasoline and E85 vehicles are shown in these tables, where "MSW-85" refers to E85 produced from MSW

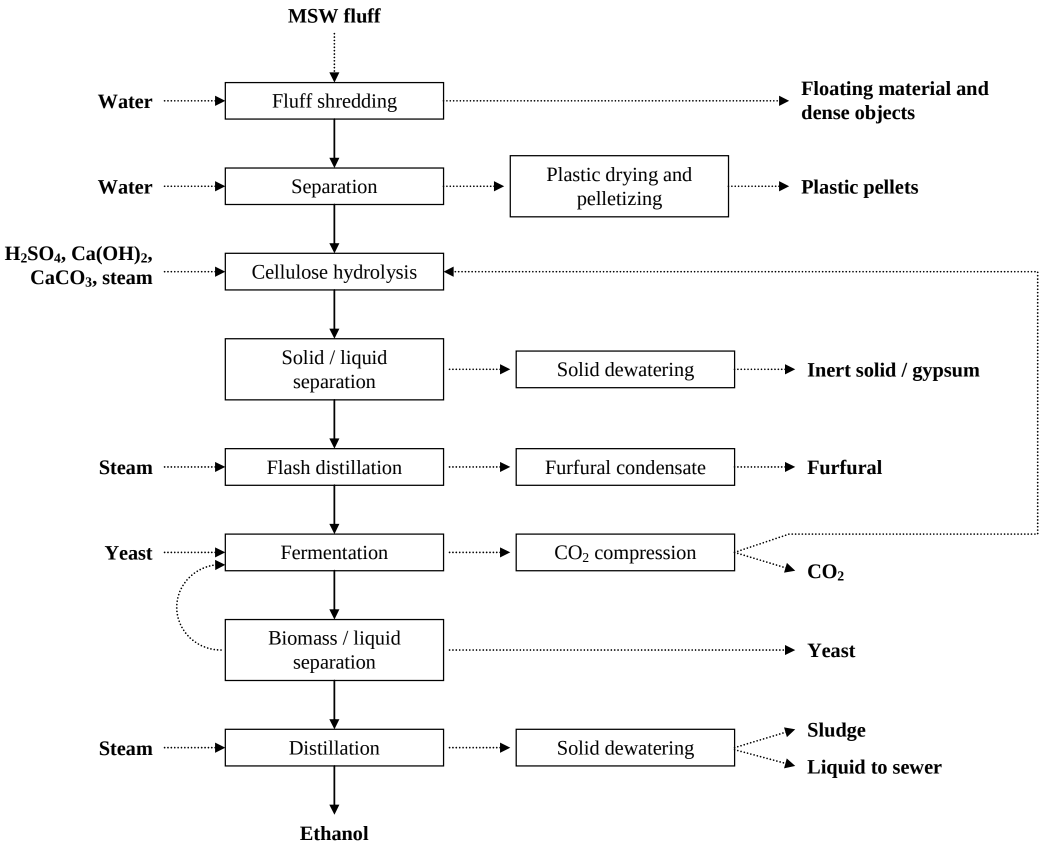

FIGURE 1 FLOW CHART OF ETHANOL PRODUCTION FROM MSW

TABLE 1 ESTIMATED ENERGY AND EMISSIONS FOR VARIOUS STAGES OF THE MSW-TO-ETHANOL CYCLE

(from Kalogo et al.)

	Energy (MJ/tonne wet MSW-fluff)			Air pollutant emissions (g/ tonne wet MSW-fluff)					Greenhouse gas emissions (g/ tonne wet MSW-fluff)			
parameter	***Total energy***	***Fossil fuels***	***Petro-leum***	***VOC***	***CO***	***NO_x***	***PM_{10}***	***SO_x***	***CH_4***	***N_2O***	***CO_2***	***Total GHG***
MSW collection & hauling	23.8	23.5	12.1	0.68	0.79	2.99	0.71	2.15	1.85	0.03	1644	1694
MSW classification	594	510	7.9	0.98	14	83	5.42	164	0.89	0.82	43440	43702
Fluff pretreatment	57	49	0.8	0.09	1.33	8	0.52	16	0.09	0.08	4171	4196
Chemical manufacturing	14.3	13.9	9.4	5	1.49	12	86	63	76	0.02	19798	21554
Chemical transportation	21.8	21.7	20.1	1.05	3	23	0.64	1.69	1.84	0.04	1659	1713
Ethanol production	166	150	9.9	93	40	97	8	41	121	1.05	55111	58204
Wastewater treatment	4.1	3.6	0.1	54	115	77	10	11	2.4	0.01	297	354
Lime treatment	10.9	9.3	0.1	0.02	0.25	1.53	5	3	0.02	0.02	795	800
Plastic treatment	117	100	1.6	0.19	3	16	3	32	0.18	0.16	8584	8636
Ethanol transportation	26.9	26.9	25.1	1.35	4	32	0.87	3	2.28	0.05	2069	2136
Ethanol distribution	4.5	4.5	4.2	0.14	0.6	1.78	0.05	0.13	0.38	0.01	343	355
Total without classification	447	403	83	155	170	272	114	173	206	1.46	94472	99642
Total with classification	1041	913	91	156	184	355	119	337	207	2.27	137912	143344

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TABLE 2 AVERAGE STANDARD MIDSIZE CAR

	Lifetime emissions in pounds							
	Gasoline, 15 mpg city / 32 highway				***MSW-E85, 11 mpg city / 23 highway***			
	CO_2 eq.	SO_x	NO_x	Hg	CO_2 eq.	SO_x	NO_x	Hg
Material production	13,654	54	24	0.00025	13,654	54	24	0.00025
Vehicle assembly	6,519	26	12	0.00003	6,519	26	12	0.00003
Fuel production / transport	37,106	30	35	-	115,215	258	273	-
Vehicle operation	123,862	12	114	-	26,462	3	95	-
Vehicle maintenance	5,064	20	9	0.00009	5,064	20	9	0.00009
Vehicle disposal	8,948	36	16	0.00017	8,948	36	16	0.00017
Total	**200,000**	**180**	**210**	**0.00054**	**180,000**	**400**	**430**	**0.00054**

TABLE 3 AVERAGE MIDSIZE SUV

	Lifetime emissions in pounds							
	Gasoline, 11 mpg city / 22 highway				***MSW-E85, 8 mpg city / 16 highway***			
	CO_2 eq.	SO_x	NO_x	Hg	CO_2 eq.	SO_x	NO_x	Hg
Material production	18,386	73	32	0.00034	18,386	73	32	0.00034
Vehicle assembly	8,777	35	16	0.00003	8,777	35	16	0.00003
Fuel production / transport	52,125	43	49	-	161,850	363	384	-
Vehicle operation	173,996	17	160	-	37,173	4	134	-
Vehicle maintenance	6,819	27	12	0.00013	6,819	27	12	0.00013
Vehicle disposal	12,049	48	22	0.00023	12,049	48	22	0.00023
Total	**270,000**	**240**	**290**	**0.00072**	**250,000**	**550**	**600**	**0.00072**

TABLE 4 AVERAGE FULL SIZE PICKUP

	Lifetime emissions in pounds							
	Gasoline, 10 mpg city / 20 highway				***MSW-E85, 7 mpg city / 14 highway***			
	CO_2 eq.	SO_x	NO_x	Hg	CO_2 eq.	SO_x	NO_x	Hg
Material production	21,343	84	38	0.00039	21,343	84	38	0.00039
Vehicle assembly	10,189	41	18	0.00003	10,189	41	18	0.00003
Fuel production / transport	58,950	48	55	-	183,042	410	434	-
Vehicle operation	196,778	19	181	-	42,040	4	151	-
Vehicle maintenance	7,916	32	14	0.00015	7,916	32	14	0.00015
Vehicle disposal	13,987	56	25	0.00026	13,987	56	25	0.00026
Total	**310,000**	**280**	**330**	**0.00083**	**280,000**	**630**	**680**	**0.00083**

COMPARISON WITH OTHER FUELS

In 2004 the Sanitation Department of the City of New York did an extensive study on different types of technologies for providing a value stream from the huge amounts of MSW generated by the New York metropolitan area.[8] This report included a large number of solicited responses from technology providers and specifically addressed the land and water use issues.

Generally, most of the facilities are quite small – a plant of a dozen acres or so is capable of processing several hundred tons of MSW per day. Likewise, many of these plants rely on the water inherent in the waste stream for process water and otherwise require only about 100 gallons per ton of waste. At about 77 liters (~20 gallons) of ethanol per short ton (the unit used in the NYC study) this is equivalent to about 5 gallons of water per gallon of ethanol, or about 65 gallons of water per MMBTU of ethanol, about 33 times less water than would be used in corn-based ethanol.

The land use would be equivalent to or less than the refineries needed for processing petroleum. Indeed, there is possible net benefit since the treatment of the MSW would reduce the amount of land required otherwise for landfill.

The carbon dioxide emission number of 13.4 pounds per gallon is equivalent to about 176 pounds of carbon dioxide (~48 lb C) per MMBTU of ethanol produced and delivered. However, according to Kalogo et al., there is a significant benefit due to the diversion of the MSW from the landfill. Their paper cites a total well-to-wheel value of 103 g CO_2 per km, equivalent to approximately 105 lb per MMBTU.

Table 5 expands upon earlier research[9] and describes the overall impact of MSW-based ethanol for transportation as compared to other conventional and alternative fuels. The water use and land use for MSW-to-ethanol production are relatively small, and certainly negligible compared to the requirements for crop-based ethanol.

TABLE 5 SUMMARY OF ENVIRONMENTAL AND ENERGETIC IMPACTS OF NOVEL FUELS

		Land use				Water use (gallons)		Energy ratio	CO$_2$ emissions[a]
Fuel source	**Transportation energy displacement**	**Acres[b]**	**Fraction of U.S. cropland**	**gallons of fuel per acre**	**MMBTU[e] of fuel per acre**	**per gallon of fuel**	**per MMBTU of fuel**	**BTU input per BTU of fuel**	**lb per MMBTU of fuel**
Conventional gasoline	**0-100%**	tens of thousands	very low	-	-	5	45	0.05	175
Conventional diesel	**0-100%**	tens of thousands	very low	-	-	10	80	0.09	175
Corn-based ethanol	**10%**	65 M	20%	370	28	170	2200	0.98	350
	25%	160 M	51%	370	28	180	2300	0.98	350
	50%	337 M	103%	360	28	220	2900	0.98	350
Cellulosic ethanol	**10%**	46 M	15%	515	39	146	1900	0.92	330
	25%	112 M	35%	515	39	146	1900	0.92	330
	50%	228 M	72%	510	39	149	1900	0.92	330
MSW-based ethanol	**0-100%**	tens of thousands	very low[d]	-	-	5	65	0.6	~105
Soybean biodiesel fuel	**10%**	253 M	80%	57	7	900	6900	0.76	180-220
	25%	380 M	120%	57	7	900	6900	0.76	180-220
	50%	1.2 B	390%	57	7	900	6900	0.76	180-220
Coal-to-liquid	**10%**	4,100	very low	~4.4 M	~500,000	3	24	~0.5	~380
	25%	10,300							
	50%	20,600							
Algaculture	**10%**	2.5 M	< 1%	6000	800	50	400	0.2	< 0; absorbs CO$_2$ from power plant
	25%	6.5 M	2%	6000	800	50	400	0.2	
	50%	13 M	4 %	6000	800	50	400	0.2	
Heavy crude	**0-100%**	a few thousand	very low	-	-	~10	~80	~0.25	~200
***In situ* oil shale**	**10%**	7,500[c]	very low	~20 M	~65,000	~6	~45	~0.15	~240
	25%	19,000[c]							
	50%	37,000[c]							
Tar sands	**10%**	48,000[c]	zero	~3 M	~350,000	~5	~38	~0.25	~180
	25%	120,000[c]							
	50%	240,000[c]							

[a] includes driving cycle; carbon emissions are calculated from the chemical composition of various fuels and the appropriate stoichiometric combustion equations with the consumption of CO$_2$ by photosynthesis (for biofuels) not included so that all fuels are compared on an equivalent basis.

[b] M = million; B = billion

[c] assumes ten years combined for in-ground retorting and productive well life

[d] possibly a negative number if one accounts for decreased use of landfill acreage necessary is MSW is used for fuel production

[e] MMBTU = million Btu

CONCLUSIONS

This paper provides a brief discussion of the conversion of municipal solid waste to ethanol for use as an automotive replacement fuel. The overall impacts of using ethanol in such a manner have been compared to traditional and other alternative fuels and it is determined that the use of municipal solid waste for producing ethanol for transportation fuels appears to be a technology worth considering for expansion. The overall energy balance compared to "traditional" fuel crops is considerably better and the carbon emissions are much less. In addition, the use of society's waste products to produce energy is attractive for any number of reasons including better use of the committed land and as an alternative to incineration.

Of perhaps greater importance is the availability of MSW as a feedstock. The use of an otherwise discarded resource is a more apt use of a resource than diversion of foodstocks to fuel as is the case with many crop-based biofuels.

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