Chapter 14 Biofuels and Bioenergy Production from Municipal Solid Waste Commingled with Agriculturally-Derived Biomass

4 authors:

Kevin Holtman
Georgia-Pacific Chemicals, LLC

David Bozzi
United States Department of Agriculture

Diana Franqui
United States Department of Agriculture

William J. Orts
United States Department of Agriculture

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Kevin M. Holtman, David V. Bozzi, Diana Franqui- Villanueva, William J. Orts

USDA- ARS- WRRC, 800 Buchanan Street, Albany, CA 94710

Corresponding author: William J. Orts bill.orts@ars.usda.gov

Abstract

The USDA in partnership with Salinas Valley Solid Waste Authority (SVSWA) and CR3, a technology holding company from Reno, NV, has introduced a biorefinery concept whereby agriculturally- derived biomass is commingled with municipal solid waste (MSW) to produce bioenergy. This team, which originally developed an autoclaving technology to pretreat MSW, has installed and operated a pilot- scale (2 T per batch) steam autoclave to evaluate its use for producing biofuels from waste biomass. Through this collaboration the SVSWA has arrived at the decision to commercialize autoclaving of their MSW with the intention of producing bioenergy from the cellulosic fraction from MSW. The autoclave has also been applied as a front- end technology to pretreat an array of different biomass feedstocks for energy production. Commingled feedstocks that have been test-autoclaved in this system include rice straw, wheat straw, grape pomace, olive industry waste, wax board, cardboard, food wastes, leafy vegetable wastes, and fast- food garbage. These streams were autoclaved and converted to bioenergy either alone and/or commingled with MSW. For each run the USDA research team provided data on the yields of methane production via anaerobic digestion versus ethanol yields via saccharification and fermentation; i.e., ethanol was produced from the isolated cellulose using typical commercial yeasts after dilute acid hydrolysis. In most cases results favored biomethane production as being more economically viable than ethanol production due to more efficient conversion and the scale of biomass availability. Specifically, the data from smaller scale operations generally point toward biogas production. The next step for the partnership is to demonstrate, at pilot scale, an anaerobic basin system developed at the USDA specifically for the purposes of producing biomethane from MSW commingled with agricultural wastes.

Introduction

The Renewable Fuel Standards set in 2007 mandated that 36 billion gallons of advanced biofuels be produced annually in the U.S. by 2022, with production of cellulosic ethanol to be established by 2010 as one source of this alternative fuel. The EPA has recently had to revise cellulosic ethanol targets in 2010 due to the reality that the industry lags behind schedule. Also, the scope of this mandate has been broadened to allow for alternative biofuels, beyond ethanol, to be considered as “ethanol equivalents”.

Herbaceous feedstocks have the potential to provide significant amounts of biomass to meet these mandated biofuels targets. In a report released by the US DOE and USDA in April 2005, commonly referred to as the “Billion Ton Report” (http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf) it was suggested that production of more than a billion dry tons of biomass per year is viable and would provide as much as 60 billion gallons of ethanol (or alternative fuels, perhaps). More specifically, the “Billion Ton Report” indicated a potential production of 1.36 billion tons of biomass per year, comprised of 428 million tons from annual crop residues, 368 million tons from forest residues and 377 million tons from 55 million acres of dedicated energy crops.

The Billion Ton Report provided the vision that a significant quantity of feedstock is available for future conversion to biofuels; however it did not lay out a plan for establishing the infrastructure for realizing this vision. Most traditional crops and most woody residue are only available on a seasonal basis in very specific regions. Significant breakthroughs must be realized to develop an infrastructure that will allow for sustainable growth of feedstock that then fits into a viable infrastructure for transportation, biomass pretreatment and conversion (T.L. Richard, Science, 329. no. 5993, pp. 793 – 796; 13 August 2010).

Utilizing agriculturally- derived biomass, with its seasonal availability, raises multiple issues that complicate infrastructure development, such as:

- Does the biomass change with age?
- Who handles transportation?
- Which party stores the feedstock, grower or biorefinery operator?
- Who takes on liability issues related to a guaranteed supply?
- Should the biorefinery operation be seasonal?
- What is the optimal transportation radius for supplying feedstock?
- Will lending agencies (bankers) provide the millions of dollars in funding needed for large scale biorefineries if the feedstock is variable?
- Will there be sufficient economic credits or incentives (carbon credits) if waste is diverted from landfills or sewage treatment facilities to produce bioenergy?

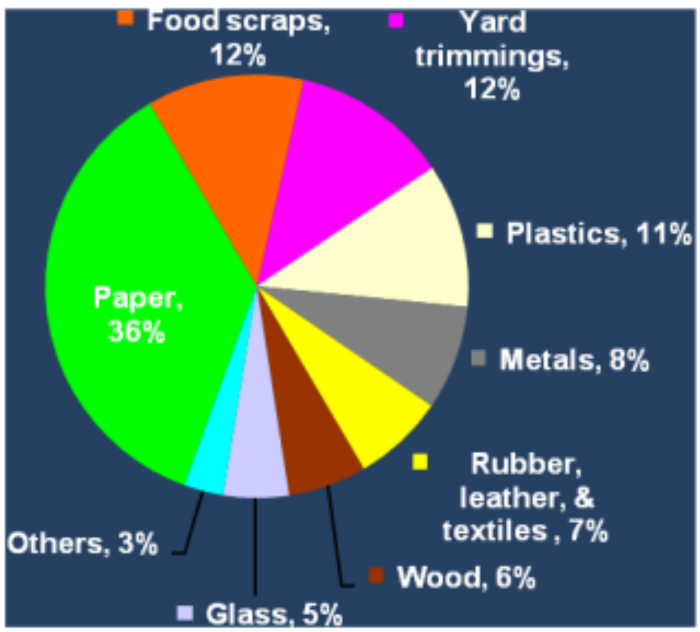

Figure 1: Composition of typical MSW in the U.S.

MSW as a Biofuels Feedstock

Utilizing MSW as a consistent feedstock provides answers to many of these infrastructure issues. For the most part, transportation routes, supply contracts, storage capacities, liability agreements, permitting rules, and cost structures are in place for MSW. As outlined in Figure 1, MSW is roughly 40% cellulose, much of it in the form of paper waste that has already been pulped and can be readily converted to sugars by hydrolysis. While MSW may be a viable feedstock for biofuels production, there is not enough biomass available to provide more than 10% of our U.S. domestic needs, at best. It is estimated that, in 2004, roughly 509 MM T of MSW was generated annually, with an estimated annual rate per capita of 1.3 tons[1]. At conservative conversion rates, this would result in less than 12 billion gallons of ethanol per year, less than 10% of the U.S. annual domestic gasoline usage of 138 billion gallons (http://americanfuels.blogspot.com/2010/04/2009- gasoline- consumption.html). The pulp fraction that can be fermented to ethanol represents only a small fraction (10- 20 %) of the total energy available in MSW, therefore the total impact of processing MSW cannot be measured simply by displacement of fossil fuel by ethanol. Dissolved organics derived primarily from food waste can be fermented to biomethane and used as a transportation fuel or green electricity, and the non- fermentable organic fraction (i.e., lignin) and non- biogenic (inorganic) fraction can be converted thermally to green electricity. As a result efficient use of this "waste" material can result in significant displacement of foreign oil and/or coal resulting in a significant savings in greenhouse gas emissions.

Commingled MSW with Agriculturally- Derived Biomass

Why commingle MSW with agriculturally- derived biomass for biorefinery development? In quick summary, MSW provides stability – both in consistency of supply and infrastructure development – while herbaceous feedstocks supply the potential for the quantities needed to meet our energy needs. MSW can be a reliable supplement to herbaceous feedstocks specifically because it is available on a daily basis through transportation networks that have been developed and optimized. Cellulosics from MSW after separation are comparable to commodity lignocellulosics and can be utilized to help jumpstart the cellulosic ethanol industry due to the relatively low cost of separation and the advantages related to locality and transportation. Availability is both consistent and predictable, with feedstock contracts usually held by single parties. Given these benefits, it is valuable to look more closely at initially utilizing this resource to start operation with the later potential of commingling MSW with herbaceous feedstocks, and identify what might be needed to assist operational application. This paper discusses a pilot study of commingling MSW with agriculturally- derived feedstocks for the production of either ethanol and/or biogas.

Case Study: Pilot- Scale Production of Bioenergy from Commingled MSW and Ag- Biomass

This section outlines technology to convert MSW and agriculturally- derived biomass to bioenergy at a pilot- scale operation in Salinas, California. Conversion is based on steam- processing biomass whereby unsorted incoming MSW, along with commingled biomass, is pressure cooked for ~30 minutes, and screened to separate the organic fraction from the remaining waste. Participating partners include researchers at the USDA, CR3 of Reno, NV, a technology holding company, and the Salinas Valley Solid Waste Authority (SVSWA). This team has installed a pilot scale MSW- autoclave to isolate uniformly the cellulosic fraction from MSW for biofuel research. The team has explored other technologies for end product development including a high- solids bioreactor system that can fully divert organic wastes into biomethane, as well as a pulp- washing operation that yields relatively clean cellulose for ethanol production or fiber sales in the secondary pulp market. Commercialization of the CR3 technology has been realized at facilities operated by Sterecycle, U.K, a licensing partner of CR3 that operates a 250 ton/day autoclave (see http://www.sterecycle.com/index.htm).

The key process toward this conversion is a two- ton/batch autoclave in which biomass is steam- processed at elevated pressure and temperature; a pretreatment process rendering output streams that are predictable and uniform. The autoclave developed and patented by CR3 consists of a horizontal rotary vessel with helical heating baffles that have been designed to externally heat the autoclave's contents, impart shear forces to the waste material, and facilitate breakdown (Figure 2, top left). This process converts MSW to a biomass source that is consistent on a daily basis, making it easy to augment this feedstock with agriculturally- derived biomass as it becomes available on a seasonal basis. MSW in Salinas has not been pre- sorted, although the SVSWA is active in its recycling efforts, therefore office paper, cans, bottles and boxes have been mainly segregated out of this waste stream. As such, this particular MSW stream (Figure 2, top right) is typically landfilled, and would be considered as a cost burden to most waste processors.

Figure 2. CR3 designed two- ton rotary autoclave operated by USDA at Salinas, CA showing (UL) the autoclave in the upright position for loading; (UR) loading of unsorted MSW; (LL) autoclaved MSW pulp commingled with different components of MSW pulp including unrecovered bottles and cans, and (LR) 3/8" screen accepts after trommelling containing a consistent high solids pulp that can be converted to bioenergy.

At the start of the process, MSW and commingled wastes are conveyed directly into the autoclave with only minor visual sorting; i.e., only large items such as durable goods – furniture, car batteries, appliances, etc. – are removed. The process consists of heating the vessel by the addition of direct steam with a corresponding pressure increase to 5 psig. Temperature is raised over a period of ~35 minutes to the operating temperature of 131oC (26 psig) via indirect heating oil, and the temperature is held constant for 30 minutes over which time the vessel is slowly rotated about the longitudinal axis. Rotation of the vessels results in (1) breakdown of the organic fraction into a moist pulp rich in cellulose; (2) cleaning and sterilization of non- organics (metals and glass) and "stiff" plastics, such as PET bottles; and (3) reduction in volume of the input waste material. At the end of the residence period, a flash- vacuum reduces the pressure to 10 psig and then the vessel is reheated to 24 psig over 10 min. The vessel is then evacuated to 0 psig and finally - 20" Hg via a jet eductor system.

Steam autoclaving is applied here to recover all of the waste cellulosic material contained in MSW (and commingled ag- derived biomass) that would not normally be recycled. The solids discharged from the autoclave are reduced in volume by as much as two- thirds relative to their original volume, and have the appearance of high consistency pulp fibers commingled with recyclable materials, pellets of plastics, and miscellaneous dirt. After autoclaving, the contents of the autoclave, which appear as a pulp material (Figure 2, lower left) are dropped into trommel screening system fitted with 3/8", 1/2", and 1" rotating screens. The organic fraction of autoclaved biomass is readily separated from the non- organics through simple size- sieving in a standard rotating trommel screen. Recovery of metals and high- melting plastics can be completed via this non- intrusive trommelling. The majority of the pulp fiber passes through the 3/8" screen and is overwhelmingly lignocellulosic in nature commingled with small debris and ash (Figure 2, lower right). In fact, the "accepts" from the 3/8" screen represents nearly 60 % of the material entering the autoclave (50 % of the volume), and after washing is arguably one of the least expensive sources of cellulosic pulp, which is then available for biorefinery development.

Advantages of this process are as follows:

- Autoclaving alone reduces the volume of the MSW stream by >60%, which implies significant landfill volume savings;
- Screening after autoclaving removes larger recyclable feedstocks, such as metals, glass and stiff plastics (PET bottles) not recovered during recycling protocols;
- Autoclaving and screening isolates organics such as food waste and a cellulose- rich pulp that is virtually the "cheapest" source of cellulose available for bioenergy conversion;
- Liquids isolated from this processing, along with much of the remaining solids, are rich in food waste and volatile solids for easy biological conversion to methane. This stream can be converted to methane via high- solids anaerobic fermentation very efficiently.

- The cellulosic- rich pulp can be converted to multiple biofuels including ethanol, methane, or "3rd generation" fuels as they become commercially viable.
- Biomass feedstocks can be readily commingled with cellulose isolated from MSW as they become available.
- The infrastructure is in place for collection and transportation of MSW.
- Two streams isolated from the MSW, the cellulose- rich pulp and the solubilized organic fraction can each be utilized to produce bioenergy. The USDA has worked with partners to provide data on converting MSW- derived cellulose to ethanol, showing yields of ~50 gals per ton of cleaned pulp using commercially available enzymes in a process that has yet to be optimized.

Rice Straw Conversion by Hot Water Treatment

The autoclave technology outlined for MSW pretreatment can also be utilized as a pretreatment system for non- cellulosic agricultural wastes. The USDA's efforts have focused on "green" techniques for pretreating biomass with strict directives to reduce water use and utilize all byproducts, such methane from solubilized organics stream. As a result, hot water pretreatment (HWP) was applied for enhancing the enzymatic hydrolysis of MSW and other biomass sources. HWP is referred to by multiple names including autohydrolysis, which explains the fundamental reaction mechanisms that occur as cellulose and hemicellulose are broken down and made more accessible to enzymes. Autohydrolysis is essentially subjecting the given substrate to high temperature (~200 oC) and high pressure (~300 psig). Although the pH is neutral at STP (standard temperature and pressure), acetyl groups from the hemicellulose are cleaved at higher temperature to produce acetic acid groups, dropping the pH slightly to ~4.5 and making the solution slightly acidic. These conditions at high temperature prove favorable for two mechanisms of cellulose hydrolysis.

Results of HWP experiments at different residence temperatures, varying between 190 and 230 oC and times from 10- 60 minutes are presented in Table 1. In this study, hydrolysis was performed using Celluclast 1.5 L and Novo 188 enzyme solutions (Novozyme) in 500 mL shake flasks at 55 oC. Ethanol production was achieved using an overnight seed culture of Ethanol Red yeast TM (Fermentis, France).

	Residence temp.(0C)	Residence time (min)	Severity Factor (R_o)	Cellulose Converted (%)	Cellulose to fermentation (t/1000 tpd basis)	Ethanol yield (gal/d)
Untreated	-	-	-	12	43	7,747
RS- 1	190	10	3.65	67.5	188	33,868
RS- 2	195	30	4.27	62.3	190	34,307
RS- 3	195	60	4.58	55.9	169	30,432
RS- 4	205	30	4.57	53.3	169	30,465
RS- 5	210	15	4.41	51.4	145	26,202
RS- 6	210	20	4.54	73.5	208	37,560
RS- 7	215	30	4.86	46.6	146	26,263
RS- 8	225	30	5.16	51.7	186	33,494
RS- 9	230	20	5.13	34.4	79	14,199

Table 1. Yields from enzyme hydrolysis and fermentation and estimations of the yields of ethanol from rice straw on a 1000 tpd OD basis.

These data show that autoclaving and/or varied HWP pretreatments can be applied to convert rice straw to ethanol at reasonable yields.

Autoclaving Commingled Streams: MSW with Agriculturally- Derived Biomass

The USDA has applied their autoclaving technology to an array of feedstocks as a pretreatment toward a consistent biorefinery operation. These include:

- Rice straw + MSW
- Raw waste / activated sludge
- Grape pomace
- Waxboard (beer box and lettuce boxes)
- Green/yard waste
- Commercial MSW

Biomethane Production

One life- cycle analysis published in Science (J.E. Campbell, et al. Science 324, 1055, 2009), concluded that converting biomass to electricity to run electric cars is more efficient than running cars on biomass converted to ethanol. Biomass- derived electricity produces an average 81% more transportation miles and 108% more emissions offsets per unit area cropland than cellulosic ethanol. The team in Salinas, (the USDA, CR3 and SVSWA) has carried out experiments comparing the conversion of these autoclaved commingled biomass streams into ethanol and biogas via anaerobic fermentation. Figure 3 depicts the biomethane production from a continuously stirred reactor (CSTR) fed a combination of commingled cellulosic MSW and rice straw at an organic loading rate of 1 kg/m3 d. The inoculant was the mixed liquor obtained at a municipal wastewater treatment facility and acclimated to cellulosic MSW.

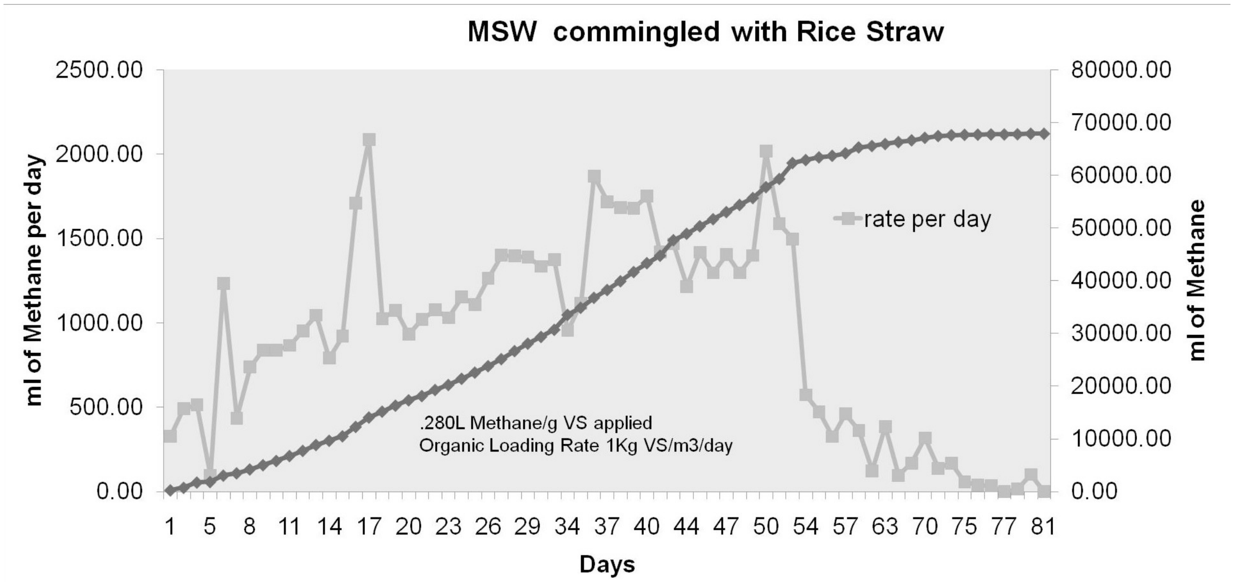

Figure 3. Methane production of autoclaved MSW commingled with rice straw using a high solids biogas reactor.

Research indicates that very high biomethane yields are available both from cellulosic MSW and biomass, however because of their nature (cellulose encrusted in lignin) longer retention times are required for their decomposition. Figure 4 shows the biomethane production from a 20 g plug feed of rice straw to the CSTR described above. Yields with the acclimated population have routinely been in the range of 385 mL CH4 per gram of biodegradable volatile solids (BVS).

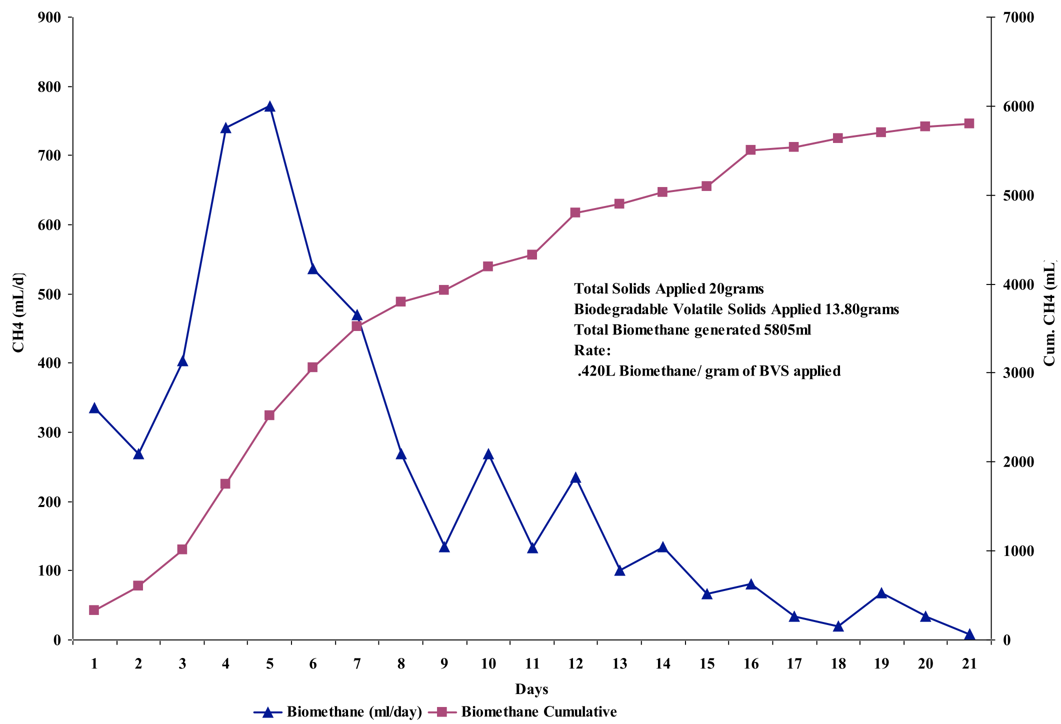

Figure 4: Biomethane production from a 20 g plug feed of rice straw to a CSTR

In order to maximize biomethane production from cellulosics, longer retention times are required as compared to food waste which is overwhelmingly the substrate utilized in this field. To minimize capital costs, high solids systems are highly preferable for cellulosic substrates. The USDA has developed a high solids system anaerobic system that embodies several advantages over current technologies employed for biogas production from MSW. The system depends on semi- continuous batch operation in which feedstock is fed at regular intervals while maintaining a hermetic seal to allow for anaerobic digestion of the reactor's contents during the feeding process.

The autoclave system yields 450- 500 lb of dry cellulosics per ton of incoming MSW at 40- 50 % solids. The pulp is to be diluted and fed continuously into high solids anaerobic digesters, with recycled permeate or gray water to obtain high solids (15- 20 %) fermentation conditions. Manure has a high nitrogen content and can be used to properly amend the carbon to nitrogen (C:N) ratio of the cellulosics; thus addition of manure or chicken litter to the basin is a desirable scenario to avoid chemical alteration of the C:N ratio. Laboratory experiments have determined that the entire fermentable fraction of the cellulosics (cellulose, hemicellulose) can be completely fermented within a 40 day time period. The method thus eliminates the cellulosics from MSW and reduces the time period for its destruction (which occurs naturally in a landfill) from 20- 50 years to 40- 120 days. Cellulosic residue such as rice straw can be shredded and commingled with the MSW pulp prior to feeding to allow for incorporation. The residuals from the basin represent a humic- like substance that can be used as an organic soil amendment (especially with enhanced C:N ratio) and can be used to restore nutrient poor soils. Metals analyses to this point have indicated that the soil amendment is well below EPA 503 regulations for compost.

This process is to be demonstrated at the SVSWA Crazy Horse Landfill and as the project that has been (described here) proves viable, SVSWA could scale to commercial for the production of biomethane. A preliminary study indicated that at 500 TPD incoming MSW the process would produce ample biogas to operate the facility, fuel the waste hauling fleet, and provide excess for sale to the surrounding community. As LNG or CNG, biomethane burns much cleaner than diesel, can displace those requirements for fossil fuel, and is a GHG negative (CO_2 saving) fuel alternative. Methane-derived fuels are amongst the lowest carbon fuels and life cycle analysis indicates that at 500 TPD incoming Salinas could avoid the emissions of 14,000 tons of CO_2 equivalent greenhouse gases over a 20 year operating period. Alternatively biogas can be utilized for green electricity production and can be used to displace coal providing a clean pathway to fueling electric cars.

Care has been taken to accommodate agricultural wastes into the feedstock. However, the economic viability of the system being developed in Salinas depends on the reliability of MSW production, with the existing infrastructure of the waste industry to create a platform feedstock. Agricultural wastes are only to be added if the transportation radius and collection mechanism are logical and if there is no other higher value use alternative. The system accepts both cellulosic and non-cellulosic agricultural wastes, making it a perfect fit for the Salinas Valley as the region produces 25,000 tons per year of processing waste and pre- packaged food products that have gone beyond shelf life. These materials are to be incorporated with the MSW feedstock with no modification and the autoclave will free their contents from the packaging. Cellulosic wastes, on the other hand, can be milled to reduce particle size and mixed with the high solids pulp prior to slurrying the feed to the anaerobic basins. Other wastes such as manure can be fed either directly or slurried with the cellulosic ag- wastes. As a result the anaerobic basins can be utilized to produce biomethane from a multitude of waste streams. Parallel basins that do not incorporate municipal wastes can be operated successfully and the residuals can be readily applied to food producing lands to return nutrients to the soil, completely integrating the farming community operations. This latter example of the basin's utility provides a sustainable option for producing energy in California's rice country. The pilot scale basin to be built in Salinas, CA will be in essence a prototype on- farm basin and will provide a good estimation of the economics of the system at this scale.

Biomethane yields achieved in the laboratory are in the range of 155 ethanol gallon equivalents (EGE) per ton of dry MSW pulp. Biomethane is scalable, has a reasonable capital investment, and thus is applicable on- farm and in rural communities as are predominately encountered in the U.S. Nationally biomethane could represent as a replacement fuel nearly 10 billion (EGE) annually based solely upon MSW. If produced locally from local waste materials including municipal wastes, biomethane will actually be a negative GHG emission fuel based upon well- to- wheel analysis. It is the USDA's mission to provide added value to existing agricultural operations, to open up pathways for new products, and to create jobs particularly in rural communities. Biomethane gas (BMG) can be produced in both rural and urban areas, it can be easily transported via pipeline to its ultimate destination for processing, and thus it can provide a distributed system capable of efficiently delivering energy from rural agricultural areas to urban centers with high energy demand.

If future biorefineries are to follow the trends shown by the corn- ethanol industry they require huge capital investments. The typical corn- ethanol facility increased from under 50 million gallons per year in 2004 to over 100MM gal/yr by 2006 [Todd Alexander and Marissa Leigh Alcala, Ethanol Producer Magazine, April 2006]. Moving cellulosic ethanol technology from the laboratory to a commercial- scale biorefinery is an expensive proposition and banks have appeared reluctant to fund these high- risk projects using first- of- a- kind technologies. With costs for moderate- scale demonstration plants ranging upwards of $80 million, and costs for significant commercial facilities (100 MM gal/yr) over $150 million, funding has proven problematic. To bridge this financing gap, the U.S. Department of Energy (DOE), along with the U.S. Department of Agriculture, have sponsored several granting programs; for example they announced that over $240 million in grants were awarded for nine small- scale cellulosic biorefinery projects in 2008, each ranging from $25 to $30 million. Despite this progress, ethanol from herbaceous feedstocks and/or waste has yet to prove commercially viable on a large scale for a host of reasons, including higher costs of enzymes (relative to corn- ethanol), low ethanol yields, and high separation costs as a result of low yields.

Ramping up cellulosic ethanol production will require major changes to grow, handle, transport and store the immense quantities of biomass - lignocellulosic feedstocks such as switchgrass, crop residues, forest wastes, and solid wastes - necessary to continually feed biorefineries and/or electric power generation stations. A recent article in Science (T.L. Richard, Science 329, 793, 2010) concludes that bioenergy from biomass has the potential to provide up to 60 percent of the world's primary energy, with estimates of a 50 percent reduction in greenhouse gas emissions by 2050. Such an exponential increase in bioenergy production in less than 40 years will need to be accompanied by a huge expansion of infrastructure.

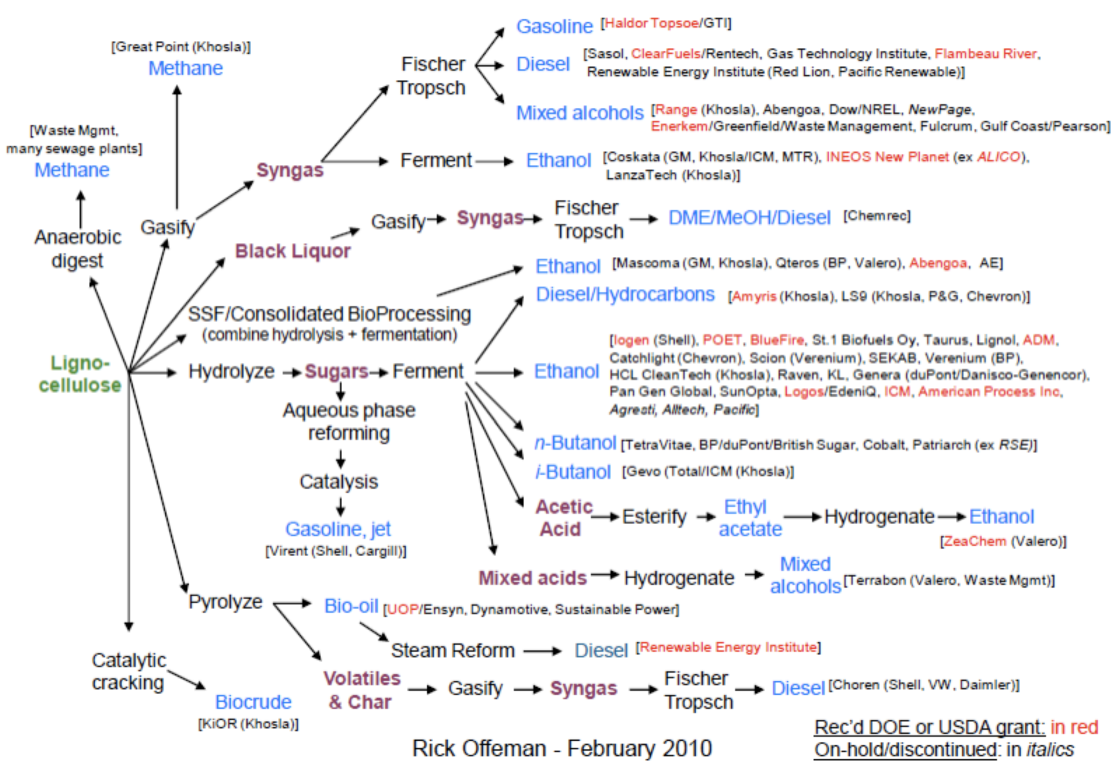

Figure 5. A listing of companies involved in biofuels production from lignocellulosic feedstock based on their processing methods.

Figure 5 is a listing of companies involved in biofuels production from lignocellulosic feedstock, outlining production of so- called 2nd and 3rd generation fuels in groups based upon their differing conversion technologies. Many promising technologies are represented within this listing. This figure neatly highlights the fact that all scenarios for biofuel production from biomass depend on providing the "cheapest" source of sustainable carbon on a consistent basis. Arguably, waste feedstocks are "cheap" sources of carbon, provided their pretreatment is appropriate for use within the processes outlined in Table 1. Rather than paying for feedstock, most waste treatment facilities are paid to "get rid of" waste, with typical tipping fees for MSW in the U.S. roughly $22- 40/ton.

Pulp isolated from MSW could feed virtually every one of these processes (2nd or 3rd generation fuels) since it is such a cost effective source of lignocellulose. Considering that ratepayers fund a tipping fee to landfill this waste, the cost of conversion, roughly $25 to $50/ton means that MSW can provide inexpensive biomass to this entire industry.

Summary

The uniform streams isolated from autoclaved MSW, either alone or commingled with agriculturally- derived biomass, have been converted to ethanol and biogas. It has been shown that MSW can be a platform feedstock for an integrated biorefinery to produce high yields of transportation fuel and/or methane depending on the needs of the local community. In one model scenario, we developed plans for an integrated biorefinery that utilizes three strategies; (1) biomethane production of volatile organics, (2) ethanol production via conversion of sugars derived from cellulose- rich pulp obtained from MSW, and (3) complete recycling of all metals and cans from the MSW with little additional labor. Large- scale commercial application of this specific autoclaving technology is being performed by Sterecycle, U.K, a licensee that operates a 250 ton/day autoclave (see http://www.sterecycle.com/index.htm).

The goal of this project is to establish the viability of a scaled- up system for effectively diverting the organic component of MSW from landfills and converting it to meaningful volumes of biomethane or ethanol. The first economic benefit of this process is diversion of nearly all of the organics from landfill operations. The second opportunity is resale of recycled metals and high- melting plastics obtained from autoclaved MSW after trommelling. The biggest economic driver for utilizing waste as a biomass source is the economic security of turning these societal costs into value- added products. Landfill costs (tipping fees) are increasing yearly, with costs surpassing $40/ton. Diversion of tipping fees adds financial security to economic risk assessment, since MSW in the proper situation is essentially available at the cost of pretreatment. Additional incentive is the recognition that tipping fees will likely get significantly higher with time due to relative scarcity of land and public sensitivity to landfills in their neighborhoods. As populations densities increase, tipping fees increase rapidly; for example tipping fees in Europe and Japan are significantly above $100/ton, with costs projected toward $200/ton by 2015.

In locales that cannot provide the amount of biomass required for an economical cellulosic ethanol plant, other technologies are possible. In rural communities, particularly those with low densities of agricultural residues (and, thus a large transportation radius), anaerobic digestion is potentially more attractive because it is not as dependent on scale. Biomethane from digestion can be sold to utility companies as natural gas, can run turbines for electricity production or can be liquefied and used as a transportation fuel. With a minor modification to the fuel system, liquefied biomethane can displace diesel in heavy duty vehicles and dramatically reduce their carbon foot- print. Swedish automobile manufacturers, led by Volvo, have begun marketing fleets of trucks that run on biomethane derived from an increasing number of filling stations that are connected to waste facilities (http://www.automotiveworld.com/news//80530- sweden- volvo- to- start- methane- diesel- tests- in-february).

References

1 BioCycle April 2006, Vol. 47, No. 4, p. 26, http://www.jgpress.com/archives/_free/000848.html