Chapter 13

Municipal Solid Waste as an Advanced Biofuels Feedstock – A Brief Summary of Technical, Regulatory, and Economic Considerations

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Abstract

Renewable energy technologies are being looked at as significant new sources to meet our current and future energy needs. Investments in research, development, and deployment of cellulosic biomass sources and conversion technologies for both power and transportation fuels are underway and will continue to grow. Some challenges include: securing cost-competitive reliable sources of quantities large enough to meet our energy needs; carrying capacity of infrastructures to harvest/collect, sort, and pre-process biomass feedstocks and transport and store products; technologies capable of converting these into consumable cost-competitive energy products; and ensuring environmental and public health protection and benefits. Much attention is given to agriculturally derived feedstocks; however a diverse range of wastes, including municipal solid wastes (MSW), sewage sludge, food processing wastes and manures, also have potential to serve as advanced biofuels feedstock. These materials can be converted using a variety of technologies. Although they present some challenges, they also potentially present significant environmental and economic benefits for farmers, municipalities, and industries. This paper looks more closely at MSW as a potential feedstock, identifying a number of technical, economic, environmental, and public health questions for which future research, analysis, and demonstration are needed.

Introduction

The Energy Independence and Security Act mandated an increase of 36 billion gallons per year (BGY) of renewable fuels be blended into our transportation fuels by 2022. Cellulosic biomass sources are expected to provide 16 BGY (or 44%) of that total. Cellulosic feedstocks, including agricultural plant residues, wood, perennial grasses and other crops grown specifically for fuel production, and secondary materials derived from industrial processes such as sawdust and paper pulp, have the potential to be converted to biofuels. Another feedstock that has not been given as much attention is municipal solid waste. These oftentimes overlooked resources can be a reliable supplemental feedstock given their consistent generation and availability, and existing infrastructures of storage and transportation networks. Use of wastes can often translate into indirect environmental and economic benefits, having the potential to transform materials with high management costs into potentially high revenue-generating feedstocks. Municipal solid waste (MSW) and construction and demolition debris (CDD) diverted from landfills avoids generation of methane gases that would otherwise occur in a landfill. In the State of Maine, diverting post-recycled or non-reusable portions of waste has resulted in an 85-90% reduction in landfilling needs, helping to extend the lifetime capacity of the landfill. Use of MSW for energy products, including advanced biofuels, presents a number of potential benefits and co-mingling this continual source of feedstock may be a good supplement to other seasonally produced cellulosic feedstocks. This paper frames a number of technical, environmental, regulatory, and economic considerations in looking at the feasibility of MSW waste as an advanced biofuel feedstock for future research consideration.

A number of technical, economic, environmental, and social/political factors need to be considered in understanding benefits and challenges of using MSW. Technical considerations include regional reliability of wastes, characteristics of the waste, and compatibility with and efficiency of conversion technologies. Environmental performance, including air and water emissions, greenhouse
gases, and waste generation can affect both costs and public acceptance. Economic factors include infrastructure costs to collect, transport, and convert wastes compared to infrastructure for other management options, such as recycling, waste- to- energy conversion, composting, and/or ultimate disposal; and comparative economics of its use for fuels versus power and/or other products.

State and national regulations and policies may also limit the use of wastes. Under EPA’s recently promulgated Renewable Fuel Standard, advanced fuels must be derived from feedstocks that meet the definition of renewable biomass. Producers can use separated MSW (defined as material remaining after separation actions have been taken to remove recyclable paper, cardboard, plastics, rubber, textiles, metals, and glass) as feedstock to generate Renewable Identification Numbers (RINs) for their fuel. In essence, this translates largely to yard and food wastes and construction and demolition wood debris.

Technical Considerations

Technical and economic feasibilities are often inter- dependent when considering feedstock/ conversion/energy product options. As a result, proof of concept, and cost- effective pilot scale demonstrations, and commercial scale implementation of feedstock/conversion pathways have, understandably, been priorities for research. However, it is important to characterize and understand other factors to operationalize feedstock production and use, including infrastructures needed to harvest, collect, process/pre- treat, and transport feedstock. Availability, reliability, composition, and density of feedstock supply will all affect technical and economic efficiencies. These considerations are briefly discussed for MSW as a potential supplemental feedstock.

Availability and Reliability of Feedstock

It is estimated that as much as 60 BGY of renewable fuels could be produced from a billion dry tons of biomass. The “Billion Ton Report,” released in April 2005 by the U.S. Department of Energy and the U.S. Department of Agriculture, indicates 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, along with grain and other miscellaneous sources. (These estimates most likely will change once the revised DOE study, “Biomass as Feedstock for a Bioenergy and Bioproducts Industry: An Update to the Billion- Ton Annual Supply” is completed and published.

Agricultural residues and energy crops vary geographically (Figure 1), are produced seasonally, and are dependent on a number of factors including precipitation, nutrients, and climate. Seasonal availability of biomass requires periodic harvest and siting of land for longer- term storage of biomass for year round use.

![Biomass Resources of the United States](http://www.nrel.gov/gis/images/map_biomass_total_us.jpg)

Figure 1. Biomass Resources of the United States; Total Resources by County, found at:
http://www.nrel.gov/gis/images/map_biomass_total_us.jpg
In contrast, although waste generation rates, composition, and how they are managed also vary geographically, they are continually generated, regardless of environmental variables, and infrastructures are well established to collect, sort, and manage these materials.

BioCycle estimated that, in 2004, more than 509 Million Tons (MT) of municipal solid waste (MSW) was generated annually, with an estimated annual rate of 1.3 tons per capita. EPA has estimated that in 2008, 251.3 MT of waste was generated. Although analyses and estimates of the amounts of waste and how it is managed vary, there are large quantities of waste available regionally.

However, not all this waste would be available or qualify as feedstocks for advanced biofuels, given other uses for these wastes and national policies. In 2008, the U.S. recycled 33.2% of its wastes and combusted 13% for power. Wastes that would otherwise be diverted to landfills may present the greatest opportunities for use as feedstocks. In 2008, 54% or 135 MT of all wastes generated were landfilled. However, as mentioned above, only separated MSW free of recyclable paper, cardboard, plastics, rubber, textiles, metals, and glass will meet the renewable fuel standard. Therefore, infrastructure to separate recyclables and composition of the waste stream are critical. To date, much of the separated MSW that would be considered renewable biomass feedstock for advanced biofuels do not have high recycling rates relative to other biogenic wastes. (See Figure 2). Infrastructures for collecting these wastes and markets for these materials are not as well developed as markets for paper, plastic, glass, and metal wastes. Wood, wood packaging, food wastes, and yard wastes combined would amount to more than twice as much tonnage as paper and paper board biogenic wastes. Use of these wastes would help divert these wastes from the landfill helping to also preserve landfill capacity, while not diminishing recycling of other wastes for other purposes.

Availability of MSW for advanced biofuels will also depend on a number of other factors, including: BTU value, moisture, size of the waste; infrastructures to collect, sort, pre-treat, and transport the materials; distance between the source of materials and conversion facilities; how the waste is managed; and the economics of these different management options. Although economic fluctuations and population growth or decline influence the amount of MSW generated, (e.g., in some cities and towns waste generation varies based on tourist season population shifts), in general, generation rates for a particular region or county is and can be well measured and predictable. It is more difficult to develop national estimates, given discrepancies in definitions of types of wastes and the life cycle of those wastes, and inaccurate and/or inconsistent reporting by all local governments.

In 2005, 167.8 Million Tons of total MSW was generated, having an average heat content of 11.73 Million BTU/Ton. Of the total MSW generated, 105.58 Million Tons (63%) was biogenic (comprised of food wastes, wood, textiles, leather, yard trimmings, newsprint, paper, and containers and packaging). This biogenic portion of waste contributed 56% of that heat content, containing 167 trillion BTU.
Existing waste management trends will influence volumes of waste available for other purposes. Wastes can be recycled, combusted in Waste-to-Energy power facilities, converted to other energy products, composted, or landfilled. Depending on the price for recyclable materials, waste can be viewed as a commodity, or when landfilled, as a cost. Several studies have demonstrated that recycling materials is more beneficial in reducing life cycle greenhouse gases - by reducing demand on energy and material resources, and by diverting it from landfills - thereby reducing landfill methane gas generation.\textsuperscript{12,13} It is a national policy to first encourage waste minimization, then reuse, recycling, and composting, followed by conversion to energy or landfilling. The National Recycling Coalition and U.S. EPA claim that a 32% recycling rate of MSW reduced the generation of 200 Million tons of GHGs, (about 3% of the nation’s total carbon footprint).\textsuperscript{14}

![Figure 3. Total MSW Generation (by Material), 2008](image)

EPA’s Regulatory Impact Analysis in support of the Renewable Fuel Standard Program’s Final Rule projected that in 2022, paper would comprise 24.5% of MSW, wood 5.6%, yard trimmings 12.8%, and food scraps 15.1%, with moisture content of 10%, 20%, 40%, and 70%, respectively.\textsuperscript{15,16,17} Additionally, it estimated that only 8 million dry tons of construction and demolition debris (CDD) would be available for biofuels, based on population estimates and assumptions that 50% of this waste stream would be contaminated and un-useable. In total, of an estimated 44.5 million dry tons of MSW and CDD wood waste available, only 26 million dry tons would be used to produce 2.3 ethanol-equivalent billion gallons of fuel (assuming 90 gal/dry ton ethanol conversion yield for urban waste in 2022).\textsuperscript{18}

Utilization and management of waste varies regionally, (Figure 4) and varies even more by state.\textsuperscript{19} For example, in 2006, the State of Maine recycled as much as 32% of their wastes (increasing to 38% in 2008) and converted about 32% of their wastes to energy, landfilling 25% and exporting the remainder.\textsuperscript{20,21} By contrast, in another region of the U.S., New Mexico only recycled 9% of its waste in 2006, landfilling 91%, with no waste-to-energy conversions.\textsuperscript{22} In States with low recycling rates, opportunities may exist to use yard and food wastes and construction demolition wood debris as feedstocks. This new use could improve the economics of waste management and possibly increase recycling rates, in addition to energy use.
Given variability of agricultural feedstocks, it may be advantageous to consider how waste is managed regionally and co-mingle plant derived biomass with other steadily generated feedstocks, such as MSW.

**Availability Questions**

- Does seasonal availability of plant derived feedstocks affect contracts and liabilities for suppliers and biorefineries?
- Are separated MSW streams (i.e., yard and food wastes and CDD) truly continual in supply?
- Would including a continual supply of separated MSW improve liabilities?
- Would farmers and farm owners be positively, negatively, or neutrally impacted by separated MSW being another feedstock source?
- How do biorefineries overcome the challenge of seasonal biomass availability? Does it affect their business and operational plans or their ability to secure funds from lending institutions?
- What controls can be devised to improve availability of separated MSW? Plant derived feedstock?

**Composition of Feedstock**

On average, a pound of MSW contains an average heating value of 5,100 BTUs. However, in actuality, the amount of BTUs that can be extracted from a waste stream is dependent on the composition of the waste.

MSW is a heterogeneous mixture of materials from diverse sources. Depending on the composition of the mixture and whether and how it is separated, it will have varying biogenic content and heat value. Although there are great quantities of MSW available, only the biogenic portion (e.g., wood, yard trimmings, paper, and food wastes) would qualify as a renewable fuel source according to the amended Renewable Fuel Standard (RFS2). Biogenic wastes will vary in composition (i.e., volumes and sizes, energy, moisture, and chemical content). These characteristics will determine the energy input...
needed to process the wastes (e.g., collection, separation, densification, dewatering, shredding, etc.) and compatibility with conversion technologies, and will ultimately determine air and greenhouse gas life cycle emissions and net energy output.

The heat value of the waste would determine its value as a biofuel feedstock. Heat values vary considerably for different waste materials (see Table 1). The biogenic heat value of MSW has been consistently higher than the non-biogenic portion, but has decreased significantly (from about 67% in 1989 to 56% in 2005) as a result of plastics replacing paper in packaging and other consumer goods. Of the biogenic portion, the largest percentage of BTUs comes from containers and packaging (16%). Other biogenic wastes contribute less BTU content to the waste stream (food waste contributing 8%, textiles 7%, wood 6%, paper 6%, news print 5%, and yard trimmings 4%).

Plastics (which are not considered biogenic) contain the highest BTU content. Paper waste mixed with plastics would have a very high heat value, since plastics have BTU content ranging from 16.5 Million BTU/ton to 38 Million BTU/ton (see Table 1), followed by paper wastes (which are biogenic). Therefore, there has been some thought to co-mingle plastics with other biogenic wastes. However, there are several reasons not to co-mingle plastics with any biogenic wastes for energy production, particularly paper. First, paper has one of the highest recycling rates and economic values for use as recycled material (Table 1). Second, there is a robust global market for recycling plastics, (55¢ - 89¢/lb). Third, incineration of plastics in MSW, particularly at low oxygen levels, is associated with the generation of Polycyclic Aromatic Hydrocarbons (PAHs) emissions, which are carcinogenic, and will require stringent air pollution control devices. Fourth, as previously discussed, under EPA's Renewable Fuel Standard Program, feedstocks containing plastics in a MSW stream will not be considered as a renewable biomass source.

It is preferable to continue recycling plastic and paper wastes. In 2008, Americans recycled about 61 million tons of wastes, composted 22.1 million tons, and combusted about 32 million tons (13%). Nationally, in 2008, the U.S. recycled and composted 1.5 pounds of the 4.5 pounds of waste generated per person per day and combusted (with energy recovery) or discarded the remaining 3 pounds per person per day. Given environmental, GHG, and economic benefits, increasing the recycling rate even further is a national goal.

However, if post-recycling residual wastes have high biogenic and BTU content, they could be used as energy feedstocks. These residuals are typically landfilled, at a cost. Therefore, recycling infrastructures and use of waste as energy feedstock could be compatible. An analysis done by the County of Los Angeles Department of Public Works, and the Los Angeles County Solid Waste Management Committee’s Alternative Technology Advisory Subcommittee outlined some of the key considerations in siting a facility and using existing infrastructure to use waste as an energy feedstock while not compromising recycling rates. Being able to divert at least 50% of the MRF residual away from the landfill was a critical factor.

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</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene terephthalate (PET)</td>
<td>20.5</td>
<td>10,250</td>
<td>30.05 MT</td>
<td>2.12 MT (7.1%)</td>
<td>27.93 MT (92.9%)</td>
<td>712.2 M BTU</td>
</tr>
<tr>
<td>High density polyethylene (HDPE)</td>
<td>19</td>
<td>9,500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>16.5</td>
<td>8,250</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low density polyethylene/Linear low density polyethylene (LDPE/LLDPE)</td>
<td>24.1</td>
<td>12,050</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Polypropylene (PP)</td>
<td>38</td>
<td>19,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>35.6</td>
<td>17,800</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Rubber  26.9  13,450  7.41 MT  1.06 MT (14.3%)  6.35 MT (85.7%)  131.1 M BTU (assuming an average 20.65 M BTU/ton)
Leather  14.4  7,200  1.89 MT  1.06 MT (53.3%)  10.48 MT (90.4%)  144.6 M BTU
Textiles  11.8  6,900  16.39 MT  0.8 MT (5.6%)  14.81 MT (90.4%)  148.1 M BTU
Wood  10  5,000  13.7 MT  0.8 MT (6.5%)  12.37 MT (85.7%)  131.1 M BTU
Food  5.2  2,600  31.79 MT  0.8 MT (2.5%)  30.99 MT (90.4%)  144.6 M BTU
Yard Trimmings  6  3,000  32.9 MT  21.3 MT (64.7%)  11.6 MT (35.3%)  69.6 M BTU
Newspaper  16  8,000  77.42 MT  42.94 MT (55.5%)  34.48 MT (44.5%)  450.6 M BTU (assuming an average 13.07 M BTU/ton)
Corrugated Cardboard  16.5  8,250  77.42 MT  42.94 MT (55.5%)  34.48 MT (44.5%)  450.6 M BTU (assuming an average 13.07 M BTU/ton)
Mixed Paper  6.7  3,350  77.42 MT  42.94 MT (55.5%)  34.48 MT (44.5%)  450.6 M BTU (assuming an average 13.07 M BTU/ton)
Other  20.5  10,250

Biogenic wastes have a lower heat value than plant derived cellulosic biomass and would most likely be suitable as a supplemental feedstock. DOE’s Biomass Feedstock Composition and Property Database lists the BTU content per pound of all herbaceous feedstocks, by variety type. The Switchgrass variety Alamo shows a range of 7,927 BTU/lb to 8,223 BTU/lb (Table 2).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Million BTU/Ton</th>
<th>BTU/lb</th>
<th>Region</th>
<th>Million Acres</th>
<th>Yield Scenario (Dry T/a)</th>
<th>BTU Available</th>
<th>Yield Scenario (Dry T/a)</th>
<th>BTU Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switchgrass</td>
<td>15.8</td>
<td>7,927 – 8,223</td>
<td>North Central</td>
<td>200</td>
<td>4.8</td>
<td>15,168 M BTU</td>
<td>6.0</td>
<td>18,960 M BTU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>960 MT</td>
<td>North East</td>
<td>36</td>
<td>4.3</td>
<td>2,445.8M BTU</td>
<td>5.3</td>
<td>3,014.6 M BTU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>154.8 MT</td>
<td>South Central</td>
<td>64</td>
<td>5.9</td>
<td>5,966.1M BTU</td>
<td>7.4</td>
<td>7482.9 M BTU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>377.6 MT</td>
<td>South East</td>
<td>22</td>
<td>6.9</td>
<td>2,398.4M BTU</td>
<td>8.6</td>
<td>2,989.4 M BTU</td>
</tr>
</tbody>
</table>

Composition of Waste Questions
- Given the BTU value and quantities of separated MSW, are they abundant and rich enough to consider as either an independent or supplemental feedstock?
- What are the thermal effects of co- mingling separated MSW with other plant derived biomass?
- Would some types of separated MSW be preferable over others?

Infrastructures
An optimal transportation radius for transporting biomass feedstock from field to a biorefinery is usually dependent on quantities available, mode of transport and infrastructure available, along with costs to harvest and transport it and price paid for the materials. Similar factors are considered for waste, however, hauling distances for wastes are influenced by a variety of factors, including local capacity to manage the waste, waste management contracts, inter- and intra- state transportation policies, and a hauler and waste management facility’s ability to recover costs of hauling through...
tipping fees. Although these decisions may seem complex, infrastructures to collect, sort, process, manage, and treat MSW and transportation routes, collection, and transfer stations are, in most locations, already well established and operational in the U.S. Regulations and business plans for waste transport are also already well established and practiced.

Municipalities that have made significant investments in recycling infrastructure will strive to maximize recycling rates. Recycling infrastructures separate out recyclable material from non-recyclable either at the curb or separated at Materials Recovery Facilities (MRFs). Although modifications to these infrastructures may be needed to further sort or pre-process wastes (e.g., electricity interconnects, water supply, sewer, and increased transportation access), their existence greatly reduces the capital costs required for essential pre-sorting of wastes for use as energy feedstocks.32

However, as shown in Figure 4, above, some regions of the country landfill significant amounts of wastes rather than recycling them. Opportunities to use non-recycled waste could also exist if capital costs were available to increase infrastructures that could effectively separate out biogenic from non-biogenic wastes. Infrastructures to separate these wastes could additionally spur more recycling. Combined recycling and recovery of energy laden materials could present economic advantages to a community, under certain scenarios. Cost-sharing between a municipality, waste management company, and biofuels producer could, therefore, potentially help increase the use of waste for energy, while also, increasing recycling rates. A better understanding of the economic and business opportunities for this kind of arrangement is needed.

Wastes can be converted to power and heat, using combustion and thermochemical conversion technologies (e.g., gasification and pyrolysis), or converted to biofuels using thermochemical or biochemical processes (e.g., acid hydrolysis and fermentation). When waste is combusted to generate power, recyclable waste and non-combustible wastes are separated out, with the remaining combustible waste converted into “Refuse Derived Fuel (RDF)”. RDF processing often includes further crushing, shredding, separation of non-combustibles, and pelletization of combustibles into a homogeneous fuel. According to an NREL study, “on average, 75%–85% of the weight of MSW is converted into RDF and approximately 80%–90% of the BTU value is retained. This leaves RDF with a higher heating value of 4,800–6,400 BTU/lb, which is approximately half of the BTU value of the same weight of coal.33 Densification of this feedstock results in more homogeneous physical and chemical characteristics, lower pollutant emissions, and less oxygen required during combustion.34

Once separated, the pre-treatment requirements of separating and shredding wastes for combustion is somewhat similar to those needed for gasification or pyrolysis; however they differ significantly from the dilute acid, steam-explosion, and/or enzyme hydrolysis pretreatment used to break down the hemicelluloses and cellulose prior to the fermentation process. Separation, shredding, size reduction, removal of toxics, etc., for either process and acid and/or enzyme hydrolysis could occur both prior to and at the biorefinery.

Distances for transport of the wastes from collection and pre-processing to the biorefinery, availability of various modes of transport (trucks, rail, or barge), and costs will also be important considerations of whether wastes can be a viable feedstock. The throughput capacity of the facility to process the waste and delivery and production schedules will also affect location and the need for and availability of storage capacity. Co-locating separation facilities with biorefineries would eliminate transportation and storage costs but capital costs for a separation facility and costs to store and dispose of non-biogenic wastes would be incurred. A number of pilot demonstrations have entered into agreements with municipalities to co-locate separation facilities at or in close proximity to biorefineries. (See discussion under Conversion Technologies).

Long-term contracts between municipalities and the waste management sector for managing wastes are another essential component of the infrastructure for using wastes as feedstocks. Municipalities need assurances that capacity exists to manage their wastes, and waste management companies need waste flow assurances for long-term operational planning of land, equipment, labor and securing capital costs for expansions. These contracts ensure recycling, waste-to-energy
conversions, composting and/or landfilling of a municipality’s or region’s wastes at a relatively stable tipping fee, and will be a critical factor in securing wastes as feedstocks.

Tipping fees vary considerably from state to state. In 2006, Massachusetts and New Jersey had the highest landfill tipping fees of $79 and $72 per ton, respectively, while Montana and Texas had the lowest, both at about $25/ton.\textsuperscript{35} Tipping fees for waste- to- energy (WTE) are usually considerably higher in states that have WTE facilities.\textsuperscript{36} Often, waste flow contracts involve importing wastes beyond the boundaries of the county or state in which a waste management facility is located or exporting wastes beyond where they were generated. States can be net importers or exporters of waste depending on infrastructures and economics.

It would be essential to understand how waste flows are secured and whether there is flexibility in existing contracts to divert some wastes for energy purposes. If wastes are imported from another state, it would be prudent to know whether that state was also considering waste as a potential energy source.

**Infrastructure Questions**

- Are existing infrastructures capable of pre-treating waste to the appropriate size for gasification, pyrolysis, or fermentation, or would this occur at the biorefinery?
- How will tipping fees and existing long-term contracts affect diversion of separated MSW for biofuels feedstocks?
- How do Renewable Portfolio Standards and competition for MSW as waste-to-energy feedstock and/or recycling impact use of separated MSW for biofuels feedstocks?
- Will states with extensive recycling infrastructure expand their capacity to increase markets for separated MSW as an advanced biofuels feedstock?
- Will states lacking recycling infrastructures use new markets for separated MSW as an opportunity to initiate recycling? What benefits and liabilities would occur?

All these factors will influence the feasibility of using these feedstocks for biofuels production, for producing power or being recycled into other products.

Economic analyses that consider a variety of scenarios and specific regional characteristics (types and volumes of wastes, available infrastructures and contracts, and distances) are needed to identify how to optimize transport and separation infrastructures.

Several transportation questions arise in considering use of wastes and co-mingling wastes with other biomass feedstocks.

- Would co-mingling of herbaceous feedstock and wastes affect decisions on optimal transportation distances?
- Would infrastructures to haul waste compete with infrastructures to haul herbaceous feedstocks?
- Would synchronization of delivery of feedstocks be needed? If not, what role would the biorefinery play in coordinating use and/or storing both these feedstocks?

**Conversion Technologies**

Biochemical, thermochemical, and chemical conversion platforms used to convert non-waste biofuel feedstocks can also be used to convert a variety of wastes, producing similar products. (See Table 3). All conversion methods require that the MSW be pre-shredded.
Table 3: Potential Waste Feedstocks for Biofuels

<table>
<thead>
<tr>
<th>Waste Type</th>
<th>Processing Required</th>
<th>Conversion Technologies</th>
<th>Product(s)</th>
<th>Amount Generated in U.S. Per Year (Million Tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogenic portion of municipal solid waste, including food wastes</td>
<td>Separation of recyclables (metals, glass, plastics, paper)</td>
<td>Hydrolysis &amp; fermentation</td>
<td>Ethanol, butanol, and microbially-produced alternative fuels</td>
<td>~105.58</td>
</tr>
<tr>
<td></td>
<td>Shredding of biogenic portion of wastes</td>
<td>Gasification</td>
<td>Syngas, ethanol, methanol, butanol biodiesel gasoline</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pyrolysis</td>
<td>Syngas, biodiesel, gasoline</td>
<td></td>
</tr>
<tr>
<td>Food wastes, including waste oils and greases, food processing wastes</td>
<td>Collection prior to disposal</td>
<td>Transesterification</td>
<td>Biodiesel</td>
<td></td>
</tr>
</tbody>
</table>

The biochemical and thermochemical platforms each rely on different catalysis systems. Biochemical conversions rely on biocatalysts, such as enzymes and microbes, as well as heat and chemicals to convert biomass to an intermediate sugar substrate that is then fermented to produce ethanol and other products. Thermochemical conversions rely on heat and/or physical catalysts that convert biomass to a gas or liquid, depending on the technology, and is then further converted to a fuel, power, or other chemical products.

Biochemical processes include anaerobic digestion and fermentation.

Anaerobic digestion of wastes uses microbes to convert wastes to methane and carbon dioxide in an oxygen free environment. This process requires that the MSW be shredded, inoculated, mixed with water, pulped, and fed into a reactor vessel. The composition of products is determined by the composition of feedstocks used and control of the process, (e.g., temperature, pH, oxygen, carbon/nitrogen ratio, mixing, retention time). Size and consistency of the feedstock is an important variable, since decomposition and availability of the feedstock’s organic materials is a critical first step in anaerobic digestion. Large polymers of organic materials are broken down through bacterial hydrolysis into smaller monomers of sugars and amino acids, followed by acidogenic bacteria further converting them into volatile fatty acids. Other acetogenic bacteria further convert these fatty acids into acetic acid, hydrogen, ammonia, and carbon dioxide, which are then converted by methogens to methane and carbon dioxide. The methane and carbon dioxide can further be used to produce energy products, including power and biofuels. This method is more suitable for high moisture content wastes, such as food wastes.\(^{37}\)

Fermentation, in contrast, is an aerobic process. Various processes can be used to pretreat / deconstruct cellulose, including steam, enzymatic and/or acid hydrolysis. Dilute acids solubilize the hemicellulose and render the cellulose available for enzymatic hydrolysis and saccharification. Enzymatic hydrolysis converts cellulose to simple sugars such as hexose, pentose, and glucose, which is then used as a substrate for further fermentation by microbes to produce a variety of alcohols, including ethanol and butanol.

Pyrolysis and gasification are two thermochemical processes used to convert a variety of biomass feedstocks, including the non-fermentable lignin portion of cellulose, yielding diverse products that yield a variety of fuels, chemicals, and power.

Gasification requires that the waste feedstock be chipped or hammer milled to a particle size of 10- mm to 100- mm in diameter and have a lower moisture content similar to other biomass feedstocks, so that it can be auger-fed into the gasifier.\(^{38}\) Processing refuse derived fuel helps to reduce the moisture content of MSW feedstock. Gasification occurs at higher temperatures (1,800ºF) with oxygen or air and catalysts. This process results in a syngas comprised of CO, H2, CO2, H2O, N2, and hydrocarbons, and...
small amounts of impurities (e.g., tars, sulfur, nitrogen oxides, particulates, and alkali metals). Gas cleanup is needed to remove followed by gas conditioning to remove hydrogen sulfide (H2S) and optimize the H2/CO ratio for fuel synthesis. The composition of the waste could influence the need for syngas cleanup. This syngas, which has a low to medium energy content, undergoes fuel synthesis either using catalysts or microbes. The choice of catalysts and the H2/CO ratio, or choice of subsequent fermentation of syngas by microbes, will determine the products to be produced. Diesel and alcohols (including methanol, propanol, butanol, and ethanol) can be produced through gasification, as well as other chemicals. Additionally syngas can be used for turbine power.

Heating values of waste feedstocks will vary based on both the moisture content of the waste, how it is pre-treated (e.g., densified), and the technology that it is converted in. Pacific Northwest National Labs (PNNL) compared the amount of MSW and/or RDF (densified and processed MSW fuel) that would be needed to get the same energy equivalent product output in a similar sized gasification unit as poplar wood biomass. “A 2,200 dry short ton per day biomass fed facility would require approximately 2,400 dry short tons per day of dry MSW or 2,300 dry short tons per day of dry RDF to supply the same quantity of stored energy to the gasifier.” However, moisture content influences energy output as well. Considering that RDF has higher moisture content than conventional biomass and MSW has even significantly higher moisture content than conventional biomass, it was found that approximately 2,755 and 3,300 short tons per day of RDF and MSW, respectively, would be needed to supply the same quantity of stored energy to the gasifier as conventional biomass.

The composition and contaminants in wastes will also affect catalysts during gasification of wastes. MSW can potentially contain sulfur, chlorine, fluoride, arsenic, phosphorous, mercury, and cadmium – which all can potentially interfere with catalysts used during gasification.

Pyrolysis occurs in the absence of oxygen with or without catalysts, and at lower temperatures than gasification, and can result in diesel and gasoline fuels.

Esterification is a chemical process that can convert oil laden food wastes, such as waste greases, to biodiesel. There are several processes by which esterification can occur:
1. Base catalyzed transesterification with alcohol
2. Direct acid catalyzed esterification with methanol
3. Conversion of oil to fatty acids followed by acid catalysis resulting in alkyl esters
4. Glycerolysis

Basically, triglycerides are broken down into glycerol (glycerin) and free fatty acids (carboxylic acids). The free fatty acids are esterified using methanol, producing biodiesel and the by-product, glycerol. However, free fatty acids and glycerol can also react with each other to form glycerides. The above processes vary in controlling conditions for optimal yield of biodiesel and minimization of glycerides.

The source of feedstock has some effect on the quality of biodiesel produced, since the nature of the three long-chain fatty acids in triglycerides is determined by the fat or oil source. For that reason, biodiesel composition can vary considerably and therefore is tested to verify that it meets ASTM specifications and further registered with the U.S. EPA. Product quality and vehicle performance is best ensured when there is a complete transesterification reaction, and successful removal of any glycerin, catalyst, alcohol, and free fatty acids. The final biodiesel product is often analyzed for trace metals and pesticides, polycyclic aromatic hydrocarbons, chlorinated polycyclic hydrocarbons and aflatoxins.

Issues, such as throughput, feedstock characteristics, by-products, and environmental emissions will determine the economic feasibility of using certain technologies to convert certain feedstocks.

Landfill Methane Generation via Anaerobic Digestion - Besides diverting wastes prior to disposal, anaerobic digestion in existing landfills also generates methane. This biogas can be collected, and upgraded for use as a fuel in heavy duty vehicles. Roughly 58% of all landfills already have landfill gas (LFG) recovery operations in place. However, there are multiple limitations to this as a biofuels source, including the need to purify, store, and distribute the biogas, at a significant cost. Additionally, it is not certain that a sufficient number of vehicles would be available to use this biogas.
Although this paper focuses on MSW, a variety of other wastes can also be converted using these technologies. Manures and sewage sludges are most suitable for anaerobic digestion, given their high moisture content. Dewatering them for use in thermochemical processes, while feasible, would result in high energy inputs and high GHG outputs from pre-treatment.

A surprising number of biofuel facilities have partnered with either communities or waste management companies to use MSW to produce biofuels.

- **Enerkem Mississippi Biofuels in Pontotoc, MS**, is a facility that will sort, upstream recycle, and pre-treat MSW, construction and demolition wood, and agricultural and forest residues for thermochemical conversion to a syngas that will further be processed into 20 million gallons ethanol, plus methanol, and plastics, annually. The Enerkem and Three Rivers and Waste Management Authority partnership is constructing the facility using 2009 funding from the U.S. Department of Energy.
- **Enerkem** has also partnered with the largest ethanol producer in Canada, Greenfield Ethanol, to convert 100,000 metric tons of sorted MSW annually into 10 million gallons of ethanol using gasification, and is expected to be operational sometime in 2011.
- **Masada OxyNol** plans to hydrolyze and ferment 275,000 tons per year of sorted MSW to produce 9.5 million gallons per year of ethanol at their facility currently under construction in Middletown, NY.
- **Fulcrum BioEnergy** is constructing a 10.5 million gallon per year commercial scale facility (Sierra Biofuels Plant) in Nevada. It plans to thermochemically convert post-recycled MSW to a syngas and further process it into ethanol.
- **Agresti Biofuels LLC** is planning to co-locate a facility adjacent to the Pike County, KY landfill where it will sort recyclables, cellulosic materials, and metals and use fermentation to convert the cellulose into ethanol.
- **BlueFire Ethanol**’s process is designed to convert MSW wood and other agricultural residues into ethanol, using strong acid hydrolysis and fermentation. Plans include multiple plants with capacities up to 55 million gallons per year with the first facility located in Lancaster, CA.
- **Taylor Biomass Energy** plans to separate recyclables from 1,000 tons per day of MSW and thermochemically convert the 275 remaining tons to syngas followed by conversion to either ethanol or power.
- **Coskata** plans to have a 50 million to 100 million gallon ethanol plant up and running using integrated thermochemical and biochemical technology to convert wood chips and expand to MSW, tires, and other waste. Feedstock is first thermochemically converted to syngas and then feeds this syngas to anaerobic microbes to produce ethanol. Coskata has a bench scale pilot in Warrenville, IL and a larger 40,000 gallon per year operational pilot plant in Madison, PA, with plans for a commercial scale 50 Million gallon per year plant in 2011.
- **Choren**’s gasification process followed by a Fischer-Tropsch process produces diesel using a wide variety of feedstocks, including biogenic wastes.
- **POET** has expanded beyond corn ethanol to cellulosic ethanol conversion technology with $80 million funding from DOE. This process is capable of using MSW, along with energy crops, stover, and wood chips. This 25 million gallons per year facility in Emmetsburg, Iowa will be operational in 2011, starting with corn cobs as feedstock but presumable expanding to other feedstocks, including wastes. POET is also looking into use of landfill methane in Sioux Falls, SD.
- **Biogas Energy Project at the University of California at Davis** has successfully converted eight tons of food waste per week in the San Francisco area and is licensed for use by Onsite Power Systems, Inc., in Davis.

**Conversion Technology Questions**
• How does using MSW affect conversion efficiencies, energy output, and environmental emissions and wastes? Are facilities that are using waste as a feedstock measuring these outcomes? Should they?
• Whether and when should MSW be used as an energy feedstock vs. recycling?
• What are the Life Cycle outcomes (for GHG and air emissions) associated with using waste as an energy feedstock vs. recycling?
• Do facilities and communities have common goals for optimizing economics, environmental, and social outcomes?
• Is anyone performing life cycle assessments for various feedstock/ conversion technology/ energy products that include wastes or co- mingling wastes?
• How does composition of the wastes and operating conditions of the conversion technology affect air emissions?

Environmental Performance

Life cycle GHG emissions will vary based on the infrastructure used to collect, sort, manage, and convert wastes. U.S. EPA’s Office of Research and Development has developed a life- cycle inventory database for North America and decision support tool (DST) for site- specific applications that includes GHG, other air and water emissions, and waste associated with MSW operations. This tool can compare quantitative life cycle assessments of GHG, other air, water, and waste emissions from various waste management infrastructures (e.g., non- sorted vs. sorted curb collection, square miles collected, fleet types, sorting facility types, and end- use of wastes) to determine optimal waste management options. One comparison that has not been studied to date is the use of wastes as an energy source for biofuel production compared with other uses and management options.

Emissions from municipal waste combustors are well characterized and concerns have been raised about toxic emissions, such as dioxin, furans, mercury, lead, cadmium, and products of incomplete combustion. However, operational conditions of this technology are significantly different than pyrolysis and gasification. Gasification technologies operate at greater efficiencies than MSW combustors at lower oxygen levels and produce a variety of value added products beyond electricity, including liquid fuels and chemicals. Emissions from thermochemical conversion of MSW can include air pollutants, such as oxides of nitrogen and sulfur (NOx and SOx), hydrocarbons, carbon monoxide (CO), particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), and greenhouse gases such as CO2 and CH4. Studies have shown that PAH generation is influenced by temperatures in either the combustion or gasification zones of conversion technologies, post- combustion gas temperatures, residence times, and levels of oxygen. Studies to characterize the differences between combustion, gasification, and pyrolysis are needed. The combustion process involves oxygen reacting with volatile products and char to form carbon dioxide and carbon monoxide. The gasification process occurs as the char reacts with carbon dioxide and steam to produce carbon monoxide and hydrogen. Pyrolysis occurs at lower oxygen levels. Understanding how these and other differences affect emissions from various wastes would be important to know for permitting facilities using wastes as feedstocks.

If pyrolysis and gasification technologies used only biogenic portions of the waste, it would be expected that volatile heavy metals and toxic emissions, such as dioxins and furans, would differ compared to waste combustion. Fugitive gas and dust emission levels would also vary with control strategies, operational practices and level of maintenance of a facility.

Organizations and communities have already equated gasification and pyrolysis to municipal solid waste combustion. Characterization of air, water, and waste emissions from all MSW waste conversion technologies is needed to differentiate use of wastes for fuel from the stigma of MSW combustion technologies for improved public acceptance.

Environmental Performance Questions
• What research is already being conducted to characterize the environmental performance of various conversion technologies using different feedstocks and under varying operating conditions?
What research is being conducted to compare environmental performance of using wastes as a biofuel feedstock vs. power vs. recycling vs. landfilling?
What life cycle assessments are needed?
Does waste as a feedstock result in significantly different environmental emissions?
Are public concerns about thermochemical conversion units justified? What information and dialogue needs to occur to increase our common understanding of their performance, benefits, and concerns?

Regional and State Considerations of Wastes as Feedstock

Several States and regions have been assessing which feedstocks would be available for either direct use in biofuels or as an energy source to power a biorefinery. Several States (e.g., Massachusetts, California, and Ohio) have explored waste availability and its potential to meet regional energy needs either for power or transportation fuels. Further research is needed to understand the comparative impacts and benefits of various feedstock/conversion technology/product pathways for a variety of regionally specific goals, including GHG reductions, production of energy, air and water quality, natural resource conservation, jobs creation, and public health.

MSW is, in some instances, considered to be a renewable resource, and in others, not. Many States have qualified MSW as a renewable source for the purposes of State Renewable Portfolio Standards (RPSs), and the Energy Policy Act of 2005 includes MSW-derived electricity as a renewable energy resource, and EPA’s Renewable Fuel Standard final rule defines the biogenic portion of separated MSW (i.e., after separating out recyclables) as renewable. The American Recovery and Reinvestment Act of 2009 includes MSW as qualifying to receive tax credits for renewable energy production, and most current legislation defines MSW as renewable.

Towns, counties, regions, and states vary on recycling rates and which wastes are recycled and/or recovered for energy. Construction demolition and debris (CDD), food wastes and yard wastes are often not recycled due to budget and infrastructure constraints.

Given that wastes will have varying GHG, air, water, and waste life cycle footprints, determined by a variety of geographic, economic, and technical factors, it would be advantageous to compare specific waste(s) to other available feedstocks to identify those yielding optimal outcomes, such as cost-effectiveness, minimal GHG emissions, and other optimal environmental, economic, and social outcomes, per BTU produced.

Regional and State Consideration Questions

- Is there a perceived new market for yard and food wastes and CDD as feedstock for biofuels?
- Will States increase recycling efforts of yard and food wastes and CDD?
- What would be critical considerations for states to increase recycling rates, including economic, political, environmental, social benefits and/or concerns?

Regulatory Considerations

Under EPA’s recently promulgated Renewable Fuel Standard, advanced fuels must be derived from feedstocks that meet the definition of renewable biomass. Producers can use separated MSW (defined as material remaining after separation actions have been taken to remove recyclable paper, cardboard, plastics, rubber, textiles, metals, and glass) as feedstock to generate Renewable Identification Numbers (RINs) for their fuel.

Renewable fuel producers must report and maintain records concerning the type and amount of feedstocks used for each batch of renewable fuel produced. Producers are required to quantify the portion of the final renewable fuel volume that qualifies as cellulosic biofuel for purposes of generating RINs, using a carbon-14 dating test method that quantifies the fossil fuel portion of the final fuel and determines the remaining non-fossil fuel portion as cellulosic biofuel. Where the renewable portion of the fuel cannot be determined based on the relative energy content of the renewable biomass and fossil feedstock, the producer is required to determine the biogenic fraction of the renewable transportation fuel via ASTM D6866 (a method that tests the biobased content of solid, liquid, and gaseous samples using radiocarbon analysis).
For separated MSW streams to quality, they must be collected according to a plan submitted to and approved by U.S. EPA. This plan includes:

1. The location of the municipal waste facility from which the separated food and yard waste is collected.
2. Extent and nature of recycling that occurred prior to receipt of the waste material by the renewable fuel producer;
3. Identification of available recycling technology and practices that are appropriate for removing recycling materials from the waste stream by the fuel producer; and
4. Identification of the technology or practices selected for implementation by the fuel producer including an explanation for such selection, and reasons why other technologies or practices were not.

**Regulatory Questions**

- Does the requirement that only separated wastes, (not containing recyclable plastics and paper), be used for advanced biofuels feedstock affect whether yard and food wastes and CDD are used for biofuels?
- Does this policy create an unfair advantage for waste to be used for biofuels feedstocks compared to waste- to- energy conversion for power?
- Does the requirement spur new infrastructures for separation of yard and food wastes and CDD?
- Has a comprehensive life cycle analysis of emissions (toxics and GHG), resource inputs, and infrastructure needs been performed that would help identify optimal use of wastes for energy products?

**Economic Considerations**

Economics will determine the availability of waste as feedstocks compared with other uses. Economics will determine acceptable distances to haul wastes from point of generation to biorefinery, whether pre- treatment is feasible, and the scale of conversion operations. The gross energy value of the feedstock used and efficiencies of the conversion technology will also affect net energy and costs.

Economics of waste as a feedstock differs considerably from conventional biomass feedstocks. MSW disposal and conversion facilities charge a tipping fee that is determined by landfill owners and operators (which can be owned privately or by local governments), based on the cost to otherwise dispose, recycle, compost, or combust the waste; whereas, costs for conventional biomass vary based on market values. Tipping fees vary significantly depending on location. As mentioned earlier, local waste management capacity (for landfills, recycling, composting, or combustion) and its ability to attract management of out- of- state waste will affect tipping fees and availability of MSW, both for local and out- of- state generated wastes. In 2004, tipping fees ranged from $24.06 per ton in the south to $70.06 per ton in the Northeast.  

Any processing of the MSW to produce a more manageable material will add cost to the overall conversion process, creating an economic trade- off between feed preparation costs and conversion technology capital and operating costs.

**Economic Questions**

Understanding all variables affecting economic feasibility is essential to determine whether MSW is a competitive feedstock. These include:

- Comparing tipping fees for wastes to be used for power vs. fuels vs. recycling vs. landfiling
- Comparing tipping fees for wastes as feedstock vs. market prices of conventional biomass
- Cost to use or expand existing infrastructures for hauling, sorting, processing, and storing
- What the net cost or cost- saving for recycling vs. using MSW as a biofuels feedstock is? What the determining factors are?
- Distances between supply, sorting infrastructures, and conversion technologies
- More detailed cost analyses for a variety of scenarios, including:
  - availability and costs of various types of wastes that considers collection and sorting
• costs to pre-treat wastes in either existing infrastructures or newly acquired infrastructures
• distances between waste generation, sorting and pre-treatment, and biofuel producers and costs of transport and storage infrastructures
• impact of these costs on tipping fees, if relevant
• comparison of these costs to using other biomass or co-mingling waste with other biomass.
• relationship between scale of facility and economics of tipping fees, if any, and
• identify minimum capacity of conversion technology below which the economics of using MSW is not viable.

Conclusion
Given the seasonal availability of plant derived feedstocks, and the continual supply and established infrastructure for MSW, it may be advantageous to consider use of separated MSW as an advanced biofuels feedstock.

However, a deeper understanding of the technical, economic, environmental, and social systems that generate and manage MSW is needed to identify which circumstances will result in the most sustainable arrangement. A sustainable outcome will include optimum economic gains, technical efficiencies, environmental protection, and social well-being where symbiosis exists between the biofuels system and other systems.

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