U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Waste-to-Energy from Municipal Solid Wastes

August 2019

REPORT

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Nomenclature or List of Acronyms

ABF	Agile BioFoundry Consortium
ANL	Argonne National Laboratory
BTU	British Thermal Units
BETO	Bioenergy Technologies Office
CAPEX	capital expenditures
CF	capacity factor
ChemCatBio	Chemical Catalysis for Bioenergy Consortium
CHP	combined heat and power
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FOM	fixed operation and maintenance costs
GWh	gigawatt hour
HTL	hydrothermal liquefaction
kWh	kilowatt hour
LCOE	levelized cost of electricity
LFG	landfill gas
MSW	municipal solid waste
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	research and development
SBIR	Small Business Innovation Research
USDA	U.S. Department of Agriculture
VGO	vacuum gas oils
VOM	variable operation and maintenance costs
WTE	waste-to-energy

Executive Summary

The U.S. Department of Energy (DOE) has assessed potential research and development (R&D) activities that could improve the economic viability of municipal solid waste-to-energy facilities. DOE recognizes that sorted municipal solid waste (MSW) and related feedstocks constitute a present disposal problem for municipalities and similar entities. Improving waste-to-energy conversion in existing facilities and developing technologies for next generation facilities is important to localities across the country as they explore more cost-effective solutions to waste disposal.

MSW starts out as a complex mixture of food waste, glass, metals, yard trimmings, woody waste materials, non-recyclable paper and plastic, construction and demolition waste, rags, and sludge from wastewater treatment. MSW presents numerous challenges when used as a feedstock for energy production: it has low energy content, high moisture, heterogeneous composition, and despite its abundance—the average American produces 4.4 pounds per day—it is highly distributed across the United States making it difficult for traditional approaches to reach economies of scale in many parts of the country.

Incineration and anaerobic digestion represent two existing types of MSW waste-to-energy facilities in the United States. Both require prior separation of recyclables to achieve optimal resource recovery and can produce electricity, heat, or both. However, high operating costs and high-level of competition from alternative sources make the production of heat and power from MSW economically challenging. DOE identified several R&D opportunities to improve the economic viability of existing MSW waste-to-energy facilities:

- **Develop waste preprocessing and handling strategies to reduce feedstock variability of MSW streams.** This allows for the most economical optimization of specific streams toward recycling, heat, power, fuels, and products. Research opportunities include characterization methods for high-precision sorting, development of quality control parameters, and pretreatment processes to remove contaminants.

- **Reduce operating costs and increase revenues in existing incinerator facilities.** These opportunities include advanced emissions control strategies to lower costs associated with environmental compliance, development of novel corrosion-resistant materials to reduce maintenance costs, and advanced separations to recover valuable materials from ash.

- **Enhance economic viability of existing anaerobic digestion facilities.** These opportunities include research of co-digestion strategies to enhance methane production and extend steady-state operation, low cost strategies for biogas cleanup to result in pipeline quality natural gas, novel thermocatalytic processes for the conversion of biogas and landfill gas to fuels and high-value co-products, and advanced reactor design and optimization of organisms to enhance biological conversion of gases to fuels and co-products.

DOE also identified several R&D strategies that might inform next generation waste-to-energy facilities in the United States. These technologies, while at an earlier stage of technology readiness, may provide cost-competitive alternatives that are better suited to the heterogeneous composition and distributed availability of MSW feedstocks. Many of these approaches enable the waste-to-energy facility to produce biofuels and co-products, which may provide enhanced revenues compared with existing facilities focused only on heat and power. DOE identified several R&D opportunities for cost-competitive waste-to-energy facilities:

- **Apply gasification technologies to sorted MSW to produce a syngas intermediate.** This includes developing biological conversion processes, which includes genetic engineering of more robust organisms to reduce separations costs, and advanced reactor designs to enable continuous operation. Thermochemical conversion research opportunities include the development of advanced catalysts with greater longevity and tolerance to impurities, as well as high-temperature, high-pressure gas clean-up strategies.

- **Lower capital costs of next generation anaerobic digestion systems that make high-value products.** These opportunities include developing anaerobic membrane bioreactors and transforming the chemistry of anaerobic digestion to produce short-chain organic acid intermediates that can be used to make higher-value fuels and commodity chemicals like acetone and naphtha.
- **Conversion of sorted-MSW to biocrude and derivative fuels.** These opportunities include modular hydrothermal liquefaction reactor designs to simultaneously process multiple waste streams and developing novel catalysis for sorted-MSW pyrolysis. Research opportunities also exist for the co-processing of biocrudes in existing petroleum refineries.
- **Enhance techno-economic viability of processes for currently unrecycled plastics.** More efficient transformation of existing polymers into high-value products could reduce the amount of plastics that go to landfills.

Production of biofuels and co-produced bioproducts from MSW feedstocks is at a much earlier stage of technological development than biopower. However, existing basic and applied research on producing biofuels and co-produced bioproducts from cellulosic materials, algae and other feedstocks can be leveraged to make MSW processes more cost effective.

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1 Municipal Solid Waste Resources in the United States

Municipal solid waste (MSW) in the United States is simultaneously a significant disposal problem in many locations and a potentially valuable resource. As shown in Figure 1, the United States produced more than 260 million tons of MSW in 2015, per Environmental Protection Agency (EPA) definitions. This equates to roughly 4.4 pounds per day per person.(1)

As shown below in Figure 2, 91.2 million tons (34.7 percent) of the EPA's total of 262 million tons is recycled and/or composted. Additionally, other organic materials, such as biosolids from municipal wastewater treatment facilities are also frequently disposed of in landfills. When MSW is disposed of in landfills, it generates biogas, which is mostly comprised of methane and carbon dioxide. When captured, this gas can be converted to power, heat, and/or other products.(2)

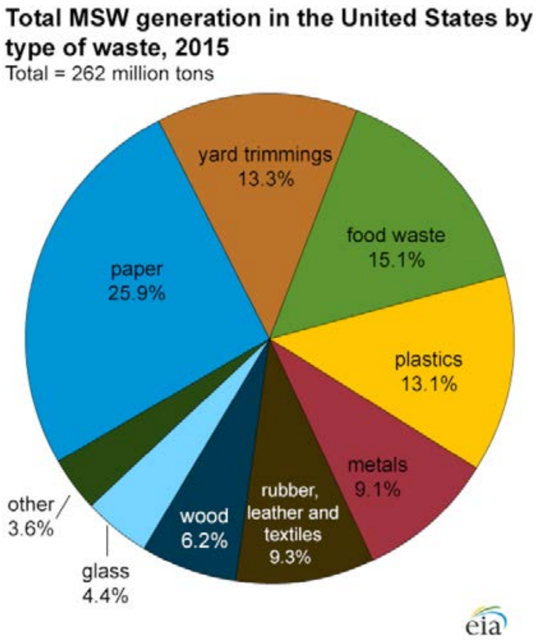


Figure 1. MSW generation(3)

This report focuses primarily on food waste, woody materials, yard trimmings, and nonrecyclable paper (see Table 1).

Table 1. Feedstocks Included in this Report

MSW as defined in this report	Not Included in this report's definition of MSW
Food waste	Glass
Woody waste materials	Recyclable metal
Yard trimmings	Other inorganic species found in MSW
Non-recycled paper	Commonly-recycled paper
Non-recycled plastics	Commonly-recycled plastics
Construction and demolition waste	
Textiles, leather, and mixed materials	
Sludge from municipal wastewater treatment	
Biogas derived from the above streams	

The components targeted in Table 1 total 60.5 percent of the 2015 MSW volume shown in Figure 1. In addition, construction and demolition wastes as well as sludges from municipal wastewater treatment are valuable target feedstocks, which the EPA does not include in its definition of MSW. Recent resource assessments find these two streams to contribute an additional 23.3 and 14.8 million dry tons, respectively, to the total waste feedstock available.(2, 4) Further analysis by the Pacific Northwest National Laboratory (PNNL) and others suggests that the EPA's estimates may understate the total volume of waste material disposed of in landfills by as much as 50 percent.(5, 6) Additionally, there are discrepancies between the amount of material that is theoretically recyclable, and the volumes that are "commonly recycled" per the definition in the Energy Policy Act of 2005,(7) and these differences are particularly pronounced for plastics.(8) In short, the EPA figures, while rigorously developed and widely cited, should probably be taken as a conservative lower bound in terms of resource potential.

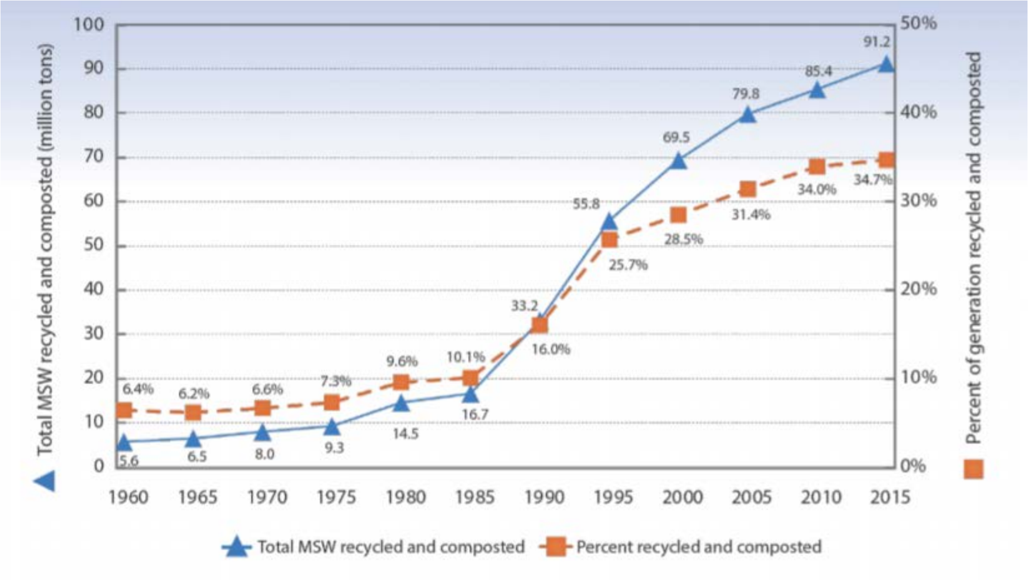


Figure 2. MSW recycling and composting rates, 1960-2015(9)

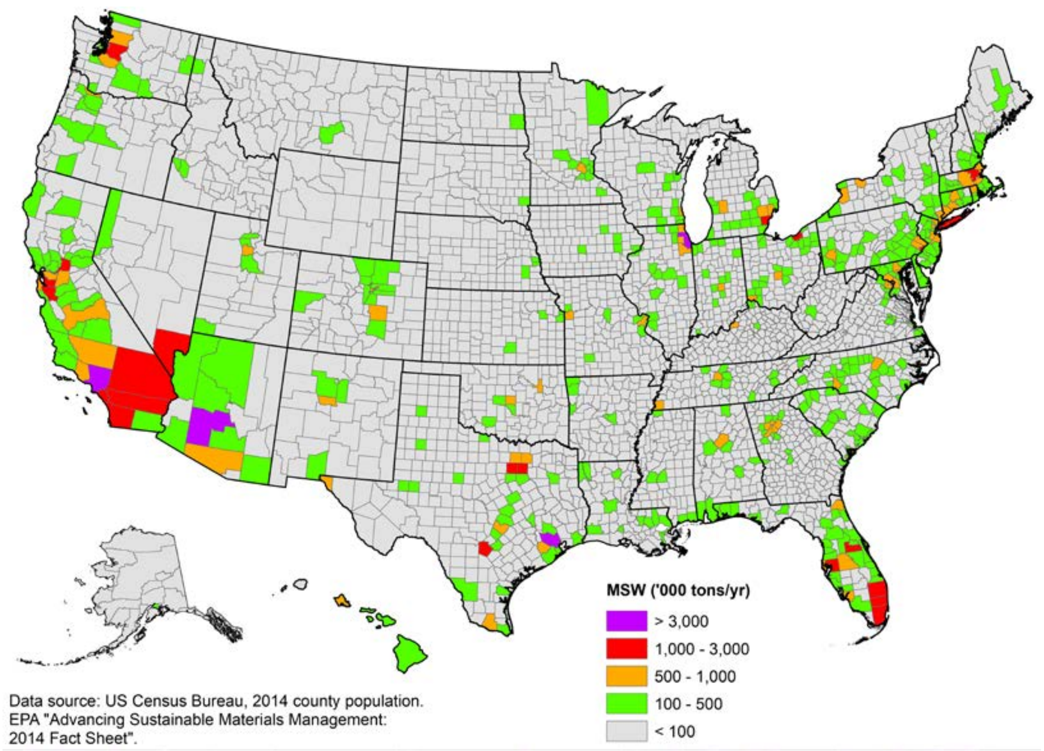
Recyclable paper, plastics, metal, glass, and other inorganic materials constitute 39 percent of the MSW stream and are not within the scope of this report. As shown in Figure 2, the recycled portion represents roughly 91 million tons, leaving 171 million tons that require either disposal or conversion to useful products per EPA estimates. For context, if the 171 million tons of unrecycled MSW was used to generate electricity at the efficiency rates of current WTE facilities, this volume would produce approximately 79 billion kilowatt hours (kWh), or 2 percent of current U.S. electricity generation. If the 171 million tons of unrecycled MSW was converted to a liquid fuel, the estimated yield would be 10 billion gallons, or 7 percent of U.S. gasoline consumption. Again, using alternative methodologies, other reliable sources estimate as much as 222 million tons available in 2013.(6) These two numbers are perhaps best viewed as lower and upper bounds of the range of potential resource quantities.

In any case, MSW poses several key feedstock challenges relative to other biomass streams, which result in increased costs and impair economic viability:

- **Relatively low energy content.** While the composition of MSW varies geographically and seasonally, the energy density is low—approximately 10-13 MMBTU/ton(10, 10a)—well below sub-bituminous coal at roughly 17-21 MMBTU/ton.(10a-14)

- **High moisture content.** Significant portions of MSW feedstocks are comprised of >75 percent water. Technologies that rely on the application of heat for conversion to either electricity or fuels are inherently disadvantaged as a high amount of energy is expended in heating or drying steps (i.e., evaporating the water beforehand). Energy intensive processes result in energy returns on investment and techno-economics that are unattractive because they require too much energy input.(15)

- **Diverse elemental composition.** Levels of nitrogen, sulfur, and ash species in MSW are well above those observed for other lignocellulosic feedstocks, and create criteria pollutants (e.g., oxides of nitrogen and sulfur) when combusted. For some fractions of MSW (e.g., yard waste and food waste), concentrations of nitrogen and sulfur can be up to 20 times higher than other lignocellulosic feedstocks such as corn stover and pine.(16) Additionally, the inorganic fraction of MSW tends to include chlorine, which can produce dioxins when combusted.(17) Technologies that are sensitive to these species and thus require intermediate clean-up and separation steps present techno-economic challenges for MSW feedstocks. The compositional variability is compounded, given that these waste streams (e.g., food waste, non-recyclable paper, and yard waste) are almost always comingled and individual municipalities can have significantly different waste sorting processes.
- **Distributed availability.** Figure 3 illustrates the geographic distribution of MSW generated in the United States. Densely populated urban areas (e.g., Los Angeles, New York City – the purple and red counties in the chart) generate significant quantities of MSW. These areas are thus prime locations for implementation of traditional, large-scale conversion technologies (e.g., mass burn steam cycle, anaerobic digestion) that require economies of scale to be economically viable. The orange and green areas may represent potential locations for a broad range of novel, smaller-scale waste-to-energy (WTE) technologies that match the scale of available MSW resources. Making this kind of distributed conversion approach economically viable is indeed an R&D challenge.



Data source: US Census Bureau, 2014 county population.
EPA "Advancing Sustainable Materials Management: 2014 Fact Sheet".

Figure 3. 2014 MSW generation in the United States

Map Source: NREL, May 2018

These key characteristics have shaped the history and current status of WTE strategies for MSW. Simultaneously, they inform the R&D options for investment, as discussed in Sections 3 and 4.

2 Status and Economics of Existing Municipal Solid Waste-to-Energy Facilities

Economic viability of facilities that manage and process MSW fundamentally depends on offsetting or exceeding the costs of operation with revenues.

Operation Costs:

- Fixed operating costs (salaries, depreciation, cost of capital)
- Variable operating costs (maintenance, utility usage, operation of emissions systems)
- Disposal of process wastes (ash from incineration, other unconverted waste).

Revenues:

- Tipping fees paid by waste producer
- Sales from electricity, heat, and steam
- Sales from other co-products (recovered metals, compost).

Both incineration and anaerobic digestion have a long history as management strategies for MSW in the United States and as alternatives to landfilling. Anaerobic digestion is applicable only to organic species found in MSW, whereas incineration works for all combustible materials. Both require prior separation of recyclables to achieve optimal resource recovery. Incineration and anaerobic digestion can produce electricity, heat, or both. However, existing market factors and rates make the production of heat and power economically challenging, particularly on the revenue side of the economic viability equation. Federal, state, and local policies may provide incentives for production of liquid and gaseous fuels such as, biogas and renewable natural gas, however, these policies are currently not equally available to incineration of waste streams to produce heat and electricity:

- **Lack of local demand for power.** Most often, it is more economically attractive to generate electricity for on-site use, thereby off-setting retail power purchases, than it is to sell electricity at wholesale rates into the highly competitive energy markets. The precise retail rates vary by state, time of day, and demand, but rates typically range from 2¢/kWh–7¢/kWh for the largest industrial customers to 8¢/kWh–11¢/kWh or more for retail consumers.(10a, 18) Many wastewater treatment plants with anaerobic digestion are in an advantaged position in this regard, as they have a substantial need for on-site electricity.(19, 20) However, this condition rarely applies to landfills and other MSW disposal facilities, which often do not have the same on-site electricity demands.

- **Competitiveness of electricity markets.** Long-term power purchase agreement prices have been trending much lower at the wholesale level due to the rapid deployment of natural gas, wind, and solar in recent years. For example, recent data shows contractual wind prices in the range of 2¢/kWh and solar at approximately 3¢/kWh, price points at which MSW-to-electricity is not competitive,(21, 22) as detailed further in Appendix B.(23) When there is need for peaking capacity in hour-ahead markets—and thus lucrative prices(24)—the increasing fleet of natural gas turbines is able to meet this demand. By comparison, incinerators and anaerobic digesters require long lead times for start-up, making them unable to react to and take advantage of sudden increases in electricity demand which result in short-term spikes in electricity prices.

- **Adjacent markets for heat.** Long-distance transportation of heat is not economically viable due to the required infrastructure investments and energy losses. Combined heat and power systems can provide additional revenues to MSW facilities when there are local applications for the heat, such as district heating systems, wastewater treatment plants, or various industrial processes.(25, 26) Unlike wastewater treatment plants, MSW facilities rarely have productive uses for the volumes of heat that would be produced, and are typically not in sufficient proximity to entities that might use this heat (e.g., district heating). This is particularly true in many of the opportunity areas, such as the green and orange counties illustrated in Figure 3.

- **Comparative generation costs.** Based on the limited amount of techno-economic analysis that is publicly available, MSW or biomass-based power generation can be among the most expensive options for producing electricity.(23) While the cited publication does not calculate the levelized cost of energy (LCOE) for MSW incineration, it does detail the elevated capital and operating costs that are significant components of that calculation.(27) Competing LCOEs for new generation capacity utilizing various technologies are listed in Table 2.[1]

Table 2. Selected Projected Costs of Electricity 2012-2022 (cents/kWh)

Solar (Photovoltaic)(22)	Onshore Wind(22)	Offshore Wind(22)	Natural Gas (Combined Cycle)(22)	Natural Gas (Combustion Turbine)(22)	Conventional Coal(28)	Biogas(29)
6.3	5.9	13.8	4.9	9.9	10.3	8.2–19.6

3 R&D Opportunities to Improve the Economic Viability of Existing WTE Facilities

As described in Section 2, the economic viability of MSW facilities requires that the revenues from any co-products and from tipping fees exceed the capital investments and operational costs (ash disposal, emissions controls, plant operation, etc.). In this equation, any co-product (ash, recovered metals, steam, electricity, biofuels, bioproducts, etc.) produced must be available at or below the market price for that product. Thus, to improve the economic viability of municipal solid waste-to-energy facilities, R&D could advance novel technologies and processes that lower capital requirements and operating costs or increase revenues from the production of valuable co-products. Section 3 describes R&D opportunities that can be implemented in existing MSW facilities to improve their economic viability by reducing operational costs and improving the marketability of co-products.

3.1 MSW Processing and Handling

Heterogeneity of MSW constitutes a significant barrier before any conversion process can be implemented. Thus, R&D in this area can be broadly-enabling for a variety of MSW facilities and processes. While most MSW processing facilities in the United States are highly automated to effectively separate co-mingled recyclables, the feedstock materials prior to conversion still require normalization through physical and/or chemical pretreatments, or they must be used in conversion processes that are insensitive to feedstock composition and properties.(30, 31) Physical properties, and therefore appropriate handling methods for MSW,

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[1] Note that the figures derived from reference 22 (EIA) are for plants coming on line in 2022, stated in 2017 dollars, while the coal number from reference 28 (also EIA) is for plants entering service in 2019, in 2012 dollars which have been converted to 2017 dollars using the CPI.

vary considerably over time, and are largely unstudied beyond changes in particle size, density, moisture uptake, and moisture holding considerations, most of which have been developed solely for anaerobic digestion applications.(32)

The implementation of physical and/or chemical pretreatments increases the overall processing cost but is usually necessary for high conversion rates. Several research and development opportunities exist to lower cost and improve precision of sorting, quality control, and pretreatment that can enable optimal handling of various components of MSW streams:

- Characterization methods of MSW to inform physical handling processes (e.g., separations, washing) for selective removal of inorganic materials. Optical, chemical, and other methods of classifying plastics represent opportunities as they could improve revenues through increased materials available for recycling.

- Development of discrete and quantifiable process quality control parameters relating feedstock composition to conversion performance attributes. This includes physical characteristics such as porosity of the material, compaction, and flow-ability of the MSW as well as attributes that affect downstream operations such as process yields, catalyst poisoning, and release of toxic emissions. Trade-off analysis is needed to identify upper and lower bounds of feedstock quality characteristics that can result in economic viability for downstream processes.

- Development of pretreatment processes (e.g., chemical, electrochemical, biological, or other hybrid options) to selectively remove problematic constituents at early process stages and reduce feedstock variability. This includes the development of systems that use relatively low levels of heat and oxygen to produce an improved biopower feedstock known as refuse-derived fuel. These processes (called torrefaction) can simultaneously improve the energy density of MSW, remove contaminants such as sulfur and chlorine, and improve the physical characteristics of refuse-derived fuel to make it more suitable for co-firing in coal plants.(33-37)

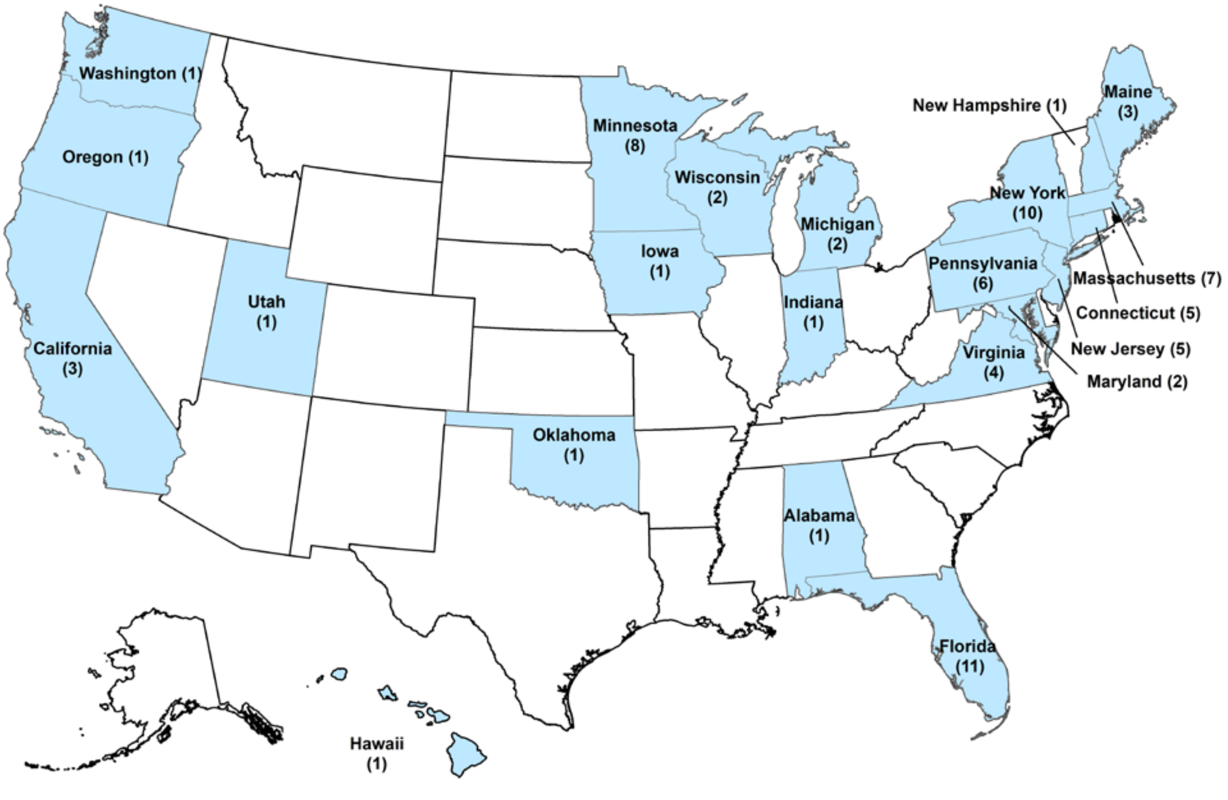
3.2 Advancements in Combustion/Incineration Systems

The use of incineration as a method of MSW disposal management dates back to the 19th Century with the first municipal incinerator constructed near Pittsburgh, Pennsylvania, in 1885.(38) By the early 1990s, there were more than 200 MSW incinerators in operation.(11, 38) Partly due to the more stringent air pollution control requirements enacted in the Clean Air Act amendments of 1990, the number of incinerators decreased to 97 in 2001, and continued downward to reach 77 facilities in 2016. A second reason for this decrease in facility count is due to low electricity prices, a key source of revenue for the viability of these plants. The remaining 77 facilities exist in 22 states, and more than half are located in the Northeast (Figure 4). While no new plants opened in the United States between 1995 and 2015, some expanded to handle additional waste and generate more energy. In 2015, the first new incinerator in 20 years was built and commissioned in Palm Beach County, Florida, and is considered the most advanced and cleanest WTE plant in North America due to its advanced combustion and pollution control measures.(39) However, the construction of this facility came at a significant capital cost, with a total project cost of $672,000,000.(40) While unique revenues and local policies exist for this facility (such as a mandate to manage the county’s waste, and the authority to levy property assessments as granted by the Florida State Legislature), the facility still represents a very expensive investment relative to other power generation facility types. Table 3 compares the cost of this facility relative to other utility-scale power generation options.

Table 3. Capital Costs for Typical Commercial-Scale Power Generation Facilities (in 2016 dollars)

	Palm Beach MSW Incineration Plant(40)	Ultra-Supercritical Coal(41)	Advanced Nuclear(41)	Natural Gas Combined Cycle(41)	Natural Gas Combustion Turbine(41)	Onshore Wind(41)	Photovoltaic - Fixed(41)
Nominal Capacity (MW)	100	650	2,234	702	100	100	20
Capital Cost ($/kW)	$6,720	$3,636	$5,945	$978	$1,101	$1,877	$2,671

Of the WTE facilities in existence today, the majority (59) generate electricity only, about 15 produce heat and power, and 3 plants export steam to local users.(42) Gross electric capacity is 2,547 megawatts (MW) and equivalent combined heat and power (CHP) capacity is 2,747 MW. Electricity generation by these WTE facilities has had a slight downward trend over the past 14 years with about 15 gigawatt hours (GWh) generated in 2001 to about 14 GWh in 2014.(42)



Data source: Energy Recovery Council 2016.
Data in parentheses shows number of plants in state.

Figure 4. States with WTE plants (incineration, refuse-derived fuel, and modular plants)

Map Source: NREL, January 2018

For the incineration facilities that remain, improvement in operating costs is necessary to maintain operability into the future. DOE identifies the following R&D opportunities to improve the economic viability of these existing facilities through improved co-product revenues as well as reduced operating and maintenance costs. Several R&D opportunities exist to reduce operating costs and increase revenues in existing incinerators facilities, such as advanced emissions control strategies, novel corrosion-resistant materials, and advanced separations to recover valuable materials from ash.

3.2.1 Deriving Incremental Value from Ash

Even when recycling is employed, approximately 5 percent of MSW by weight is metals. MSW preprocessing commonly recovers the most abundant ferrous and non-ferrous metals through the use of magnets and eddy-currents. Following incineration, ash is typically deposited in a landfill. The cost of this disposal is one of the largest operating costs that WTE facilities face. Development of resource recovery strategies to derive incremental value from ash while simultaneously reducing the disposal liability can thus aid existing operations.(43-45)

- Advanced separation processes for the recovery of precious and rare-earth metals.
- Long-term testing to evaluate the efficacy and safety incorporating incinerator ash for use in aggregate applications (e.g., concrete, asphalt).

3.2.2 Advanced Technologies for Reducing Incinerator Operation Costs

The development of corrosion-resistant materials, particularly with respect to chlorides at high temperatures can reduce operating costs of incinerator systems by reducing the frequency of system maintenance.(46-48) Cost-effective pollution control technologies are another key to improved economic viability. Opportunities in this space can leverage past R&D investments from the Office of Fossil Energy, Office of Nuclear Energy, and Advanced Manufacturing Office within the Office of Energy Efficiency and Renewable Energy (EERE) on materials development, research in the Vehicle Technologies Office within EERE, the Office of Basic Energy Sciences (BES) in the Office of Science, and the Environmental Protection Agency on emissions abatement. Possibilities in this area include, but are not necessarily limited to:

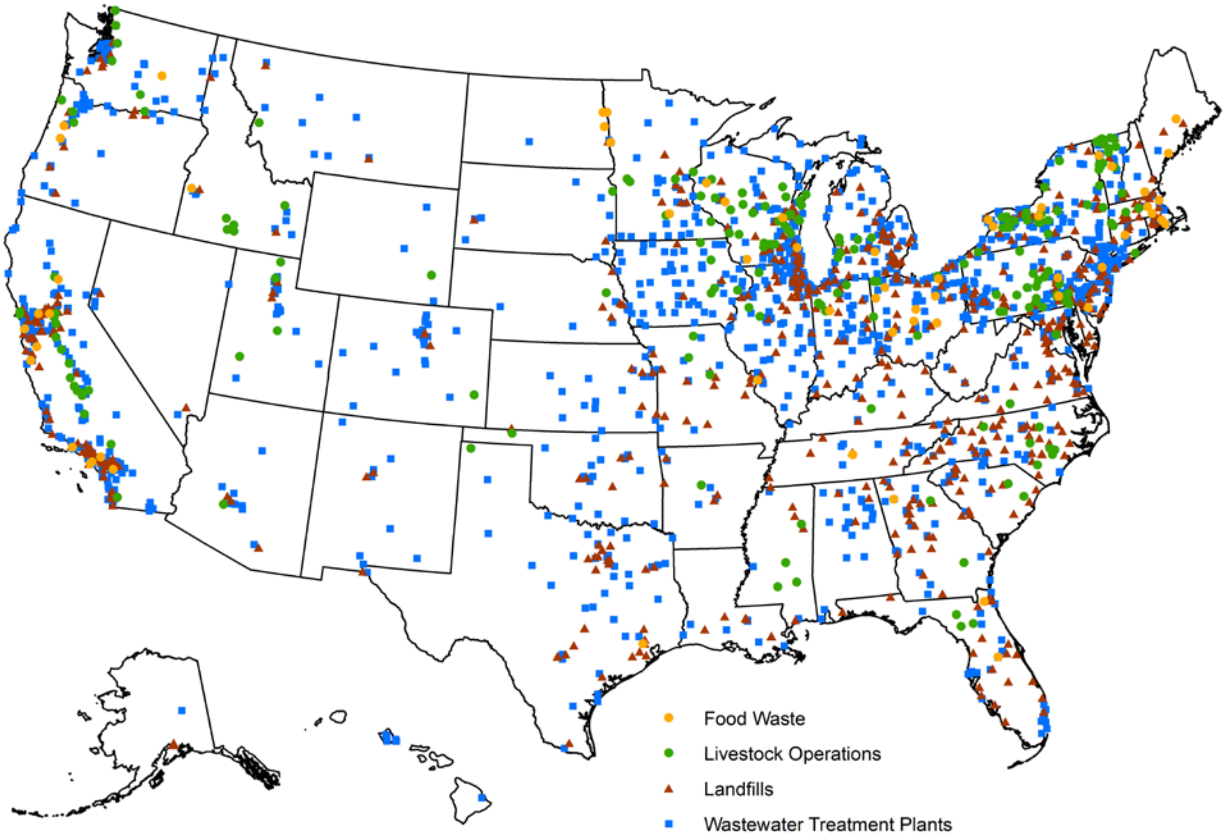
- **Development of catalysts to perform NO_x reduction at lower temperatures.** At present, waste gas streams require a reheating step that constitutes a major capital and operating cost associated with achieving emissions standards. Research and development of catalysts that perform these reduction chemistries at lower temperatures for greater than 2,000 hours would obviate the need for reheating. Further, an improved understanding of the relationships among catalyst structure, composition, operating conditions, activity, selectivity, and longevity would facilitate further progress.
- **Advanced materials to abate corrosion and fouling.** Typical materials of construction for piping, and heat exchangers are expensive alloys (e.g., Inconel) that increase the cost of construction by 3.9 times.(49) Development of novel materials including ceramics that can reduce maintenance times while achieving lower capital costs is a need for existing incineration facilities.

3.3 Advancements in Anaerobic Digestion Systems

Anaerobic digestion is a naturally occurring process that takes place under environmental conditions that are both oxygen-limited and have abundant supplies of organic material (e.g., landfills, anaerobic digesters, subterranean environments). Microbial organisms systematically deconstruct organic matter into volatile organic species. The final product is biogas, which is mostly comprised of methane and carbon dioxide. These processes are responsible for the generation of landfill gas from MSW. Given their diversity and long-term stability, these microbial communities are also very useful in the controlled processing of other organic wastes. Their use in wastewater treatment plants, for example, has become routine practice for larger facilities in the United States and worldwide. Many large dairies and swine farms also employ anaerobic digestion as a means of controlling excess volumes of manure beyond the local demand for beneficial uses such as fertilizer.

More than 2,200 sites in the United States are producing biogas via anaerobic digestion as illustrated in Figure 5.(2, 50, 51) The generated biogas can be combusted to produce heat and/or electricity but is often simply flared because the economic returns do not justify the required investments.(52) Several R&D opportunities have been identified to enhance economic viability of existing anaerobic digestion facilities, including:

- Research of co-digestion strategies to enhance methane production and extend steady-state operation.
- R&D in thermocatalytic processes for the conversion of biogas and landfill gas to fuels and high-value co-products. For example, novel catalysts which possess high activity and selectivity at low temperature and pressure could provide significant value.
- Advanced reactor design and genetic engineering of organisms to enhance biological conversion of gases to fuels and co-products.



Data sources: EPA AgStar, EPA Landfill Methane Outreach Program (LMOP),
EPA Region 3 Office of Materials Management, Water Environment Federation,
National Biosolids Partnership, American Biogas Council. Records at the end of 2017.

Figure 5. Operational biogas systems in the United States

Map Source: NREL, January 2018

3.3.1 Co-Digestion of Multiple Feedstocks

Anaerobic co-digestion is the process of combining multiple organic wastes simultaneously as a means of increasing methane yields. For example, high-energy materials such as fats, oils, and greases and food waste have at least three times the methane production potential of sludge and manure, and so are often added to wastewater and livestock digesters.(53) Co-digestion is becoming increasingly common in the United States, but data is limited for more diverse feedstock combinations, including many components present in MSW.(54, 55)

Specific opportunities within co-digestion are as follows and represent areas of potential collaboration with the U.S. Department of Agriculture (USDA):

- Analytical characterization of systems co-digesting a wider variety of materials including yard waste, food waste, crop residues, as well as manure in more rural areas.(56-58) Research could develop methods to inform the optimum mixing ratios to maximize biogas production from these systems.
- Long-term operations on co-digestion systems to inform digester operating characteristics and reduce the risk of process interruptions to anaerobic digester operators. Hypotheses around improved system balances and stability (e.g. carbon/nitrogen ratio, pH, dilution of inhibitory compounds) require extended experimental verification.(56)

3.4 Utilization of Biogas and Landfill Gas for Biofuels and High Value Chemicals

A significant number of existing landfill and anaerobic digestion facilities are actively producing biogas from sorted-MSW, as depicted in Figure 5. A collaboration among DOE, EPA, and USDA identified opportunities for more constructive utilization of this existing biogas, which includes the production of biofuels and bioproducts.(59, 60) Most traditional biogas applications view carbon dioxide (35-50 percent by volume) as either a diluting material for direct combustion or an impurity requiring removal for renewable natural gas and compressed natural gas applications. New processes beyond those typically employed to remove this carbon dioxide, such as pressure swing adsorption or amine adsorption contribute significantly to operational costs. Thus, the development of biological methods for removal of carbon dioxide or advanced synthetic sorbents constitutes a research opportunity for the utilization of biogas. Additionally, conversion strategies that use both the carbon dioxide and the methane in biogas offer the potential for significant improvement in overall carbon balances and product yields.

3.4.1 Thermochemical Conversion of Biogas

The commercial state of the art for converting methane into hydrogen, syngas, or other product intermediates is steam methane reforming. The process is commercially viable for fossil natural gas, after removal of natural gas liquids and other impurities. However, steam methane reforming is very energy and water intensive, requires economies of scale, and does not take advantage of the carbon dioxide in biogas, which suggests that alternatives might be explored:

- Advanced reforming strategies that utilize both the carbon dioxide and methane present in biogas. Combining traditional steam reforming with dry reforming, which utilizes carbon dioxide instead of steam, as well as the partial oxidation (~combustion) of methane to provide energy to drive these processes offers the potential to improve energy balances and economics.(61-69) Development of novel thermocatalytic and electrocatalytic processes suitable for biogas require greater understanding of the catalytic mechanisms involved in complex gas mixtures.

3.4.2 Biological Upgrading of Biogas

Within microbiology, methanotrophs are unique organisms that naturally consume the methane and carbon dioxide present in biogas and have demonstrated the ability to produce biofuel and bioproduct precursors.(70, 71) Through genetic engineering, these organisms can be modified to achieve higher product yields and other key technical parameters for economic viability. However, compared with other classes of organisms (e.g., Clostridia, E. coli, yeasts), the tools and methods for the genetic engineering of methanotrophs are less developed. Several R&D opportunities exist to improve the performance and viability of using methanotrophs and biological reactors for the conversion of biogas to biofuels and co-products:

- Develop genetic tools and organism transformation methods for methanotrophs to enable genetic engineering for improved carbon dioxide utilization and novel product pathways.

- Product toxicity, particularly when producing acidic compounds, is a significant challenge as acidic environments are toxic to many methanotrophic organisms. Possible strategies for overcoming these obstacles include but are not limited to the directed evolution of communities more robust at lower pH values, real-time separation of acidic products, and pathway engineering to produce strains that could thrive in acidic environments.
- Gas-liquid mass transfer is a considerable issue due to the low solubility of methane and imparts challenges to key cost drivers for gas phase fermentation systems. Research and development of novel reactor designs and fermentation methods that are compatible with these organisms could overcome this engineering bottleneck.

4 R&D Opportunities to Improve the Economic Viability of Next Generation WTE Facilities

R&D opportunities discussed in this section represent opportunities for development of new processes and strategies for deriving additional value from MSW. The approaches described herein are often at a much earlier stage of technological development compared to the opportunities described in Section 3. Each of the following research strategies focuses on converting MSW feedstocks into three types of intermediates which could either be used directly as an energy source or converted to fuels and/or higher value chemicals.

4.1 Gasification and Utilization of Syngas

For some MSW fractions, particularly those lower in moisture contents, gasification is a viable strategy for the conversion to biofuels and co-produced bioproducts as it has the potential to create a more uniform intermediate from heterogeneous feedstocks. Gasification converts organic material into syngas, which is primarily comprised of carbon monoxide and hydrogen under high heat and oxygen limitation. While gasification has the advantage of converting hundreds of different species into a relatively uniform syngas intermediate, a major challenge associated with gasification of the MSW is the prevalence of nitrogen and sulfur species in the resulting syngas. The presence of these species requires cleanup and/or removal if the syngas is to be used in power generation units or catalytic processes to make fuels and co-products.

R&D opportunities exist to enable WTE strategies that produce a syngas intermediate. Biological conversion R&D opportunities include genetic engineering of more robust organisms to reduce separations costs and advanced reactor designs to enable continuous operation. Thermochemical conversion research opportunities include the development of advanced catalysts and high-temperature, high-pressure gas clean-up strategies. Fundamental research towards understanding the complexities and phenomena associated with real waste feeds and their impacts on conversion processes remains a considerable challenge and may merit additional attention.

4.1.1 Biological Conversion of Syngas

One strategy for overcoming the presence of these impurities is through the use of syngas fermenting organisms. In recent years, there has been a considerable amount of investment into genetic engineering of and optimizing fermentations for these organisms. An advantage of biologically converting syngas is the ability to genetically modify these microorganisms to produce a multitude of biofuels and co-produced bioproducts including alcohols, lubricants, polymers, and bioplastics. By leveraging significant technological improvements in synthetic biology such as advanced genetic transformation tools and high-throughput screening methods, the key objective is to reduce the time it takes to develop organisms that produce biofuels and co-produced bioproducts in industrially relevant quantities. While advances in biotechnology have been rapid, key R&D challenges still remain:

- **The ultimate product concentration that organisms can tolerate is a critical factor to optimize for process economic viability.** While high product concentrations reduce downstream purification and separation costs, many biofuels and bioproducts can become toxic at elevated concentrations and consequently impact organism viability.
- **Some biofuels and bioproducts accumulate inside the cell of the organism and are not naturally secreted.** Genetic engineering strategies to transport these molecules outside the cell can significantly reduce costs compared to lysing cells to recover the biofuel and bioproducts.
- **Many biochemical processes rely on batch processes, which are not compatible with gas feedstocks.** Research and development of continuous fermentation systems could overcome key challenges, including reactor designs to improve gas-liquid mass transfer and to achieve long-term (>1,000 hours) organism stability.

4.1.2 Thermochemical Conversion of Syngas

Syngas derived from MSW and other feedstocks can be converted to a variety of hydrocarbon biofuels and co-produced bioproducts through inorganic catalytic processes. Public and private R&D has explored this route for conversion of syngas extensively through approaches to improve clean-up technologies and novel catalytic backend pathways. Figure 6 illustrates some of these pathways suitable for exploration and their state of commercial development.

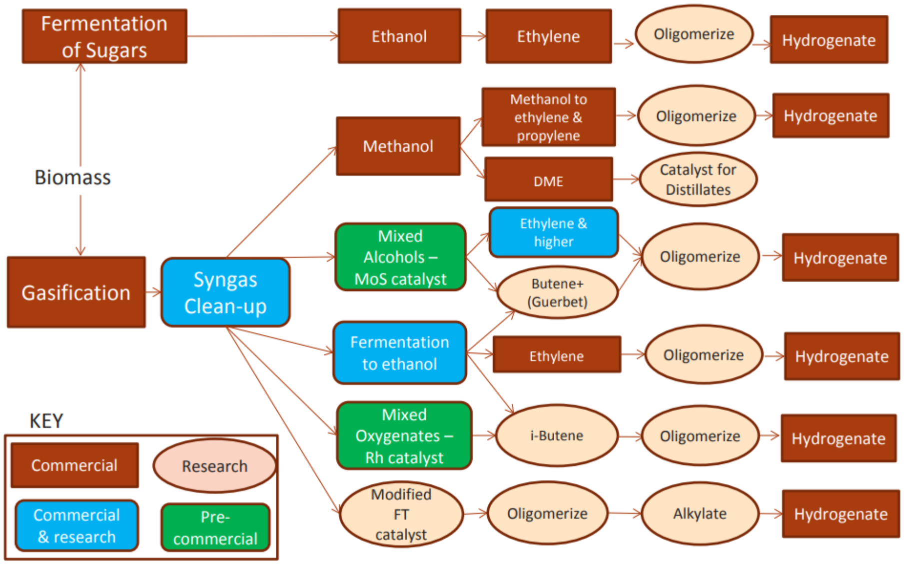


Figure 6. Technology pathways and R&D development status for producing fuel and co-products from syngas(66)

Irrespective of the pathway, there are key challenges that are ubiquitous to chemical catalysis representing areas where research can accelerate the development of technologies for the conversion of MSW:

- Catalyst performance evaluation encompasses many parameters, including but not limited to product yield, product selectivity, catalyst stability, and regenerability. Opportunities exist in the continued development of small-scale systems that can screen many permutations of catalyst support structures and catalyst concentrations while simultaneously being relevant to larger-scale systems.
- Given the increased prevalence of acid gases from MSW derived-syngas as well as increased overall feedstock heterogeneity compared to single lignocellulosic feedstocks, cleanup and conditioning is likely to be more intensive. In particular, syngas cleanup operations that can operate at temperatures and pressures similar to the gasifier can improve the energy efficiency of the system by obviating the need

for cooling and compression steps. This includes the need for novel separation media and processes tailored to MSW as a feedstock.

- When catalyst deactivation or performance drift does occur, opportunities exist for additional "post-mortem" analysis to investigate the method of catalyst degradation. This can help inform intelligent and more robust catalyst designs and protocols for catalyst regeneration to reduce catalyst replacement costs.

4.2 Next Generation Anaerobic Digestion Systems

Of the more than 2,200 anaerobic digesters that are in operation in the United States, more than 1,200 of these exist at wastewater treatment facilities for converting sludge to biogas.(12) Of these anaerobic digesters, many were constructed shortly after the passage of the Clean Water Act and are approaching the end of their system life. Thus, in the near term, there will be a need for replacement of these systems and an opportunity to employ new strategies for economic resource and energy recovery from municipal wastewater sludges. In addition, the proposed processes could also be employed at anaerobic digestion facilities that are targeting food and yard wastes or blends thereof.

Opportunities exist in the R&D of next generation anaerobic digestion systems that lower capital costs, such as anaerobic membrane bioreactors, or radically transforming the chemistry of anaerobic digestion to produce short-chain organic acid intermediates that can leverage existing chemical manufacturing infrastructure to make higher-value fuels and commodity chemicals like acetone and naphtha as well as chemicals derived from these intermediates.

4.2.1 Anaerobic Membrane Bioreactors

One of the major challenges facing traditional approaches to anaerobic digestion is that the capital investments required tend not to make economic sense at smaller scales. This frequently applies to food waste producers and for wastewater treatment plants that treat less than 5 million gallons per day.(19, 72) As Figure 3 shows, there are many communities with relatively small volumes of wastes, so processes that have low capital costs are necessary for breaking into these markets.

A key driver of capital costs for traditional anaerobic digestion is the need to retain water for extended periods of time, which requires large (and therefore expensive) processing vessels. Membrane-based technologies offer the opportunity to reduce the need to retain water by separating the water from the valuable solids which require processing time to derive value from their energy content. By passing the water through quickly, while holding the solids in a reaction area, membrane-based technologies have the potential to dramatically reduce capital costs and render anaerobic digestion economically viable at these smaller scales. However, several technical challenges remain in order for these strategies to attain commercial success:

- Fouling is always a key issue in any membrane-based technology, and thus represents a risk to this technical approach. Anaerobic membrane bioreactors systems rely on the formation of a biofilm on the upstream side of the membrane as a strategy to alleviate the problem.(73, 74) However, the formation, evolution, and sustainability of such biofilms is not fully understood, and additional investigation is required to bring such strategies to market readiness.

- Energy requirements and optimization of the required periodic cleaning of the membranes to maintain an optimal level of mass flux and biofilm concentration are key factors in determining overall energy balances and operating expenses.(75, 76)

- Industrial biotechnology challenges (e.g., culture stability, feed and substrate variability, and separations and purification of products) associated with anaerobic digestion must be overcome.(77)

- Anaerobic membrane bioreactors might also be useful in completely novel approaches to anaerobic digestion that redirect the final product from biogas to higher value biofuel and bioproduct precursors as described in the Transforming the Chemistry of Anaerobic Digestion section.(78, 79)

4.2.2 Transforming the Chemistry of Anaerobic Digestion

Through advances in microbiology and systems biology, potential exists to revamp traditional anaerobic digestion in radical new directions, namely to produce products other than biogas (methane and carbon dioxide) from anaerobic digestion systems.(80) In the breakdown of organic matter, the final stage is responsible for the production of methane. Through adjustment of pH, directed microbiological evolution, addition of inhibitors, and other strategies, methane production can be completely suppressed. Doing so results in the accumulation of short-chain organic acids (e.g., acetic acid, butyric acid) which provide building blocks for higher-value fuels and commodity chemicals such as acetone, jet fuel, naphtha, etc. This represents an opportunity for closed-digester systems such as food waste, municipal sludge, and co-digesters, but would not be compatible with existing landfills. While research into this approach is nascent, a few key challenge and opportunity areas are emerging(81-85):

- Developing stable microbial systems that can withstand methane-inhibition and high-acid environments of next generation anaerobic digester chemistry.
- Prospecting and research of organisms from industrial organic waste streams without an established history of microbial community development, such as stillage from ethanol production.
- Advanced separations for selective isolation of target compounds (e.g., acids) from a complex organic matrix through the use of novel solvents and separations processes including improved fundamental understanding of interfacial chemistry.

4.3 Conversion of MSW to Biocrude and Derivative Biofuels

Another group of research and development opportunities exist in the conversion of MSW directly into biofuels, bioproducts, or biocrude. Like petroleum derived crude oil, biocrude is a mixture of hundreds of molecules with different chemistries and functionalities. With proper catalytic treatment and fractionation into various fuel “cuts” (e.g., gasoline, jet, and diesel range molecules), this biocrude can mimic the key fuel properties required for these transportation applications. There are several processes that can in a single processing step convert diverse feedstocks such as MSW into biofuels, bioproducts, and biocrudes. However, it is important to recognize that biocrude often differs in composition from petroleum, so existing refining strategies may require adaptation to take advantage of the unique properties of bio-derived feedstocks.

Research and development opportunities exist in the development of enzyme treatments and genetic engineering for biological conversion of MSW to fuels, modular hydrothermal liquefaction reactor designs to simultaneously process multiple waste streams, and developing novel catalysis for MSW pyrolysis. Research opportunities also exist on the co-processing of biocrude from hydrothermal liquefaction and pyrolysis in existing petroleum refineries.

4.3.1 Direct Biological Conversion of MSW

Biochemical processes lend themselves well to MSW feedstocks in that they are compatible with high moisture and diverse feedstocks, as well as with small feedstock volumes. In terms of composition, MSW is high in carbohydrates (particularly cellulose), protein, and fats, yet low in lignin. As an additional advantage, fermentative processes can be feasible at scales that are orders of magnitude smaller than chemical catalysis processes. These conversion processes also operate at mild conditions (less than 50° Celsius and atmospheric pressure in this case) thereby requiring low energy inputs. Recent advances in genetic engineering and molecular biology afford an immense variety of potential biofuels and bioproducts that can be produced from these slurries. To date, industry has focused almost exclusively on developing organisms and processes for converting pure sugar streams to biofuels and bioproducts. Thus, the opportunity exists to further develop organisms to handle MSW that can leverage many of the advancements achieved elsewhere in industrial microbiology, including:

- Development of enzymatic treatment formulations to convert the cellulose fractions into sugars that are readily converted by microorganisms.(86)
- Targeted genetic engineering of microorganisms to improve their tolerance to (or even consumption of) toxic compounds found in MSW fractions, such as sulfur and nitrogen species. This would include introduction of new pathways for consuming additional species found in MSW (e.g., fats) and funneling those species as well as more readily convertible sugars into biofuels and bioproducts.

4.3.2 Hydrothermal Liquefaction and Related Strategies

Hydrothermal liquefaction (HTL) is a thermochemical method to convert organic feedstocks such as MSW into liquid biocrude. Under high temperature/pressure conditions (nearing the critical point), water becomes a much better solvent for the organic substances present in the organic fraction of MSW and other wet waste streams of interest.(87) HTL produces four phases: bio-crude, an aqueous phase that still contains organic materials, and both solid and gaseous streams.(88) The biocrude itself requires cleanup and hydrotreating to produce a drop-in biofuel. As an added benefit HTL biocrudes tend to be more stable, have better energy content, and have lower oxygen concentrations than fast pyrolysis oils.(89, 90)

Much of the R&D interest in HTL is because it can take advantage of some of the unique attributes of high moisture fractions of MSW, and experimental tests have been conducted on a variety of waste feedstocks. Examples include, and are not limited to, sewage sludge,(91-93) animal manure,(94) food waste, and mixed wet feedstocks.(95) Despite the fact that some manifestations of this technology are in the pilot-development stage, there remain opportunities for R&D, such as:

- Modular system designs that can maintain system performance and process efficiency with lower capital costs.
- Development of reactor systems that can process multiple waste feedstocks (e.g., food waste, yard waste, and municipal sludge simultaneously).
- Co-processing of the resulting biocrude with existing refining infrastructure, which could dramatically improve techno-economics by lessening the capital intensity of hydroprocessing. The presence of nitrogen and sulfur species in the HTL-derived biocrude represents a significant barrier and detailed characterization and R&D on economic intermediate separations are required.
- Managing and valorizing the remaining organics in the aqueous phase also remains a significant challenge that requires solutions that match the scale of operations.(96) Current processes such as catalytic hydrothermal gasification and ammonia stripping contribute significantly to the overall costs of operations.(96) Thus, improvements in both catalysis and other approaches could provide significant techno-economic improvements.

4.3.3 Pyrolysis Strategies

Pyrolysis is a strategy for converting waste to energy products in the absence of oxygen at high temperature and pressure before being refined into biofuels and bioproducts. Work is underway to process this biocrude simultaneously with fossil crude at existing petroleum refineries. While pyrolysis has been employed for processing of MSW in a limited number of installations overseas, it faces many of the same challenges as incineration.(15) DOE and others have done extensive work on pyrolysis of biomass feedstocks,(97, 98) wastes from cellulosic biorefineries,(91) and plastics, among various alternatives.(99) While there are possibilities for the production of liquid fuels from MSW via pyrolysis, the mixed composition of MSW creates technological challenges. As a consequence, the extensive biocrude cleanup, separations, and polishing required creates techno-economic hurdles. Opportunities for advancing the viability of pyrolysis exist in the follow areas:

- Evaluation of pyrolysis catalysis performance, including deactivation mechanisms and detailed compositional analysis of resulting biocrudes. These experiments can inform novel catalyst designs and strategies to improve process robustness.
- Co-processing of biocrudes derived from MSW fractions with compatible petroleum crude fractions such as vacuum gas oils (VGOs) to improve capital intensities of this process.

5 Conclusion

MSW has many unique and challenging characteristics and often presents a disposal problem to municipalities and other relevant entities. The assessment reported here finds that the technology for production of electricity from MSW needs to be more cost competitive with other power options in the market. Electricity production from MSW is cost competitive with other electricity generation options only in specific niche situations.

In order to improve the economic viability of existing facilities that process MSW, DOE has identified a number of areas where research and development could have a meaningful impact. These R&D opportunities are targeted at capital improvements that enhance the overall financial balance for these facilities by both decreasing operating costs and enhancing and/or supplementing revenue streams. These opportunities include development of advanced waste preprocessing techniques, methods for recovering valuable species from incineration ash, strategies to increase the yields of biogas from anaerobic digestion, separation processes, and processes for converting biogas into higher value biofuels and bioproducts. While the state of technological development varies significantly amongst these research areas, they represent opportunities to benefit a broad swath of existing WTE facilities across the United States.

R&D opportunities exist to further increase the resource recovery potential, and accompanying revenues, by targeting biofuel and bioproduct markets. These R&D opportunities represent technologies that could be implemented in next generation MSW processing facilities, but they require further development or risk reduction before being adopted by industry. These R&D opportunities include development of MSW gasification systems, approaches to decrease the capital intensity of anaerobic digesters, and processes for direct conversion of MSW to biofuels and bioproducts. Production of biofuels and bioproducts from these MSW feedstocks are both promising and at a much earlier stage of technological development than biopower. However, existing basic and applied research on producing biofuels and bioproducts from cellulosic materials, algae and other feedstocks can be leveraged to make MSW processes more cost effective.

Appendix A. Municipal Solid Waste in the Bioenergy Technologies Office Portfolio

In its vision for the Bioeconomy of the Future, the DOE's Bioenergy Technologies Office (BETO) identified technologies and processes that can create value from a wide variety of feedstocks. Under the Energy Policy Act of 2005 (Public Law 109-58) Section 932(a) (1-2), R&D for converting post-sorted MSW (where all recyclables and non-biomass components have been removed) is within BETO's authorization. In managing this portfolio, BETO recognizes that no singular feedstock or technology can achieve the domestic biofuel and bioproduct production goals. Further, developing strategies that can convert a variety of feedstocks could generate more economic opportunities nationwide and improve resiliency. In assessing attractiveness for future investment into strategies for constructive use of MSW, BETO is committed to the same standards used for the rest of its portfolio: a systematic assessment involving techno-economic analysis, resource/feedstock availability, and technical feasibility. BETO R&D investment in technologies to convert MSW and related waste streams has grown over the past several years (see Table A-1).

Table A-1. Selected Recent BETO Investments in MSW and Related Feedstocks/Conversion Technologies

Opportunity Type	Description	Relevant Number of Awards Selected	Relevant Project Description	Funding Total (Federal Funds)
Funding Opportunity Announcements	Fiscal Year (FY) 2018: Bioenergy Engineering for Products Synthesis	4	Reforming and catalytic biogas/landfill gas upgrading; Transforming AD; Paper sludge utilization; Biorefinery waste conversion	$7,350,000
	FY 2018: Process Development for Advanced Biofuels and Biopower	5	Hydrothermal liquefaction of food waste; Catalytic biogas/landfill gas upgrading; Syngas conversion to diesel; Biogas/landfill gas upgrading to renewable natural gas (RNG); Anaerobic membrane bioreactors	$10,480,000
	FY 2016: Project Development for Pilot and Demonstration Scale	2	Pyrolysis of waste to electricity; hydrothermal	~$4,000,000 for Phase 1. Down selection

Opportunity Type	Description	Relevant Number of Awards Selected	Relevant Project Description	Funding Total (Federal Funds)
	Manufacturing of Biofuels, Bioproducts, and Biopower		liquefaction (HTL) of waste to hydrocarbon fuels	for Phase 2 pending (Up to $15,000,000 available)
	FY 2014: Biological and Chemical Upgrading for Advanced Biofuels and Products	2	Conversion of biogas to high-value co-products	$5,000,000
Small Business Innovation Research Solicitations (SBIR)	FY 2018: Two topic areas on organic waste streams and small scale (five tons per day) systems	6 phase I		$900,000
	FY 2017: Three topic areas, including alternatives to anaerobic digestion and utilization of gaseous wastes	3 phase I and 6 phase II	Biodiesel from brown grease; high-value chemicals from paper wastes	$7,450,000
	FY 2016: Four topic areas, including HTL, biogas utilization, and hydrocarbon fuels and electricity from organic waste streams	11 phase I	Diesel fuel from biogas; isoprene from wet wastes; hydrocarbons from food waste	$1,645,000
National Lab Calls	FY 2018: Waste-to-Energy	13	Small-scale AD; HTL of waste; “rewiring” AD; biogas conversion; waste gas conversion	$5,450,000
	FY 2017: Biopower Lab Call: Three topic areas specifically targeting MSW and related waste streams	4	MSW torrefaction for biopower; small-scale AD; biogas cleanup	$4,700,000
	FY 2017: ChemCatBio Directed Funding Assistance Opportunity	2	Catalytic conversion of syngas to fuels and co-products	$800,000

Opportunity Type	Description	Relevant Number of Awards Selected	Relevant Project Description	Funding Total (Federal Funds)
	FY 2017: Agile BioFoundry Directed Funding Opportunity	3	Biological syngas upgrading to fuels and co-products	$1,900,000
	FY 2017: Feedstock-Conversion Interface Consortium Directed Funding Opportunity	2	MSW preprocessing	$2,018,000

DOE funds advanced WTE and biopower process research at DOE national laboratories, in particular at the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), and Argonne National Laboratory (ANL). BETO sees all three funding mechanisms (Funding Opportunity Announcements, Small Business Innovation Research solicitations, and a dedicated national lab portfolio) as complementary strategies to reduce the R&D times and costs for novel technologies in the WTE space, prior to handing them off to industry for demonstration and deployment.

Large-Scale MSW to Fuels Projects

Gasification processes and subsequent fuels and product synthesis work have been sustained areas of interest for BETO, and BETO has funded several large-scale projects to utilize MSW for biofuels. The first project, with Enerkem Inc., supported early-stage R&D to gasify and catalytically convert the dried and sorted biomass fraction of MSW into ethanol. Production of ethanol at one of their facilities began in September 2017, and the EPA certified their ethanol as an advanced biofuel in November 2017.(100) Similarly, INEOS Bio’s technology utilized gasification of presorted yard waste, converting the produced synthesis gas to ethanol via gas fermentation. Additionally, BETO has partnered with the U.S. Department of Defense and the U.S. Department of Agriculture under the Defense Production Act with the objective of co-developing biorefineries capable of producing cost-competitive, military biofuels. Fulcrum Bioenergy is located adjacent to Waste Management’s Lockwood Regional Landfill in Reno, Nevada, and is being designed to convert 175,000 tons of MSW to 10.5 million gallons of renewable fuel. The feedstock processing facility for this project is complete, and construction for the second phase—to gasify and convert MSW into Fischer-Tropsch fuels—broke ground in May 2018. This facility is expected to commence operations around 2020, and the resulting fuels will be transported to an Andeavor, Inc. refinery for fuel finishing, blending, and integration into the existing transportation infrastructure.

Additional Complementary R&D

Within BETO’s Conversion Technologies program, the Chemical Catalysis for Bioenergy (ChemCatBio) Consortium performs core research in collaboration with the Consortium for Computational Physics and Chemistry (CCPC) on the catalytic upgrading of synthesis gas, synthesis gas-derived intermediates, and pyrolysis streams into hydrocarbon fuels and bioproducts. R&D performed under ChemCatBio focuses on innovative catalyst synthesis and design, and the integration of catalytic reactions into overall reactor and process architecture, which can lead to improved catalyst lifetimes, product yields, and techno-economic viability. This research is directly applicable to many of the downstream catalytic processing challenges that a process doing pyrolysis or gasification of MSW would encounter. ChemCatBio also has a dedicated effort to upgrade biologically derived intermediate compounds into advanced biofuels. While the intermediate compounds are currently being produced from lignocellulosic materials such as corn stover, several of the priority technology areas for future MSW conversion could immediately leverage these advancements.

Elsewhere within the Conversion Technologies program, dedicated national lab efforts and funding opportunities have been issued to genetically modify organisms to produce biofuels and bioproducts from a variety of feedstocks. Most notably as it applies to MSW, organisms have been engineered and optimized to consume syngas as a sole carbon source. One industry awardee, LanzaTech, has begun pilot plant efforts converting MSW-derived syngas into ethanol at 100,000 gallons/year.(101)

Complementary to these specific technologies, the Agile BioFoundry (ABF) Consortium has a mission of reducing the time to genetically engineer microorganisms for the production of biofuels and bioproducts. ABF is currently developing advanced synthetic biology tools and processes (e.g., combinatorial DNA synthesis libraries, CRISPR-based genome editing tools, and high-throughput organism screening) that can enable technologies or processes that rely on biologic catalysis. BETO’s Agile BioFoundry is developing genetic transformation methods for a combination of organisms and novel biosynthesis pathways.(102) Recent work has taken place to include syngas fermenting organisms in this consortium.(103)

With regards to anaerobic digestion and approaches that can improve the economic viability in smaller scale digesters, BETO has begun early stage R&D to develop the chemistry necessary to selectively breakdown MSW to acids versus methane. Experimental results will inform some preliminary techno-economic analysis to assess the attractiveness and key economic leverage points for further investment into this process. Once these organic acids are isolated from the anaerobic digestion systems, current R&D under the ChemCatBio Consortium is investigating routes for the production of gasoline, diesel, and jet range hydrocarbon biofuels from these species. Thus, if the aforementioned challenges can be overcome, an existing body of R&D can be leveraged to accelerate this process to further development stages.

The aforementioned R&D and project efforts are not a comprehensive representation of BETO's work with MSW. Instead, they are intended to illustrate that BETO is committed to developing technologies and process building blocks that can be combined to provide the strongest market advantage to industry.

Appendix B. Examples of the Levelized Cost of Energy for Generating Power from MSW

This appendix provides examples of the levelized cost of energy (LCOE) for generating power from municipal solid waste (MSW) via anaerobic digestion (AD), landfill gas (LFG)-to-energy, and mass incineration. The compilation of these data was performed over a very short time-period and should be viewed as provisional. More work is needed to accurately represent the true costs of power generation via the pathways listed in Table B-1. A list of caveats below the table contextualize the estimates provided in Table B-1.

Table B-1. Example Estimates for the LCOE of Producing Electricity from AD of MSW, Capture and Conversion of LFG, and Mass Incineration of MSW(23)

	—— LCOE (U.S. cents per kWh) ——			
Technology	Low	High	Mean	Reference
LFG-1A	1.6	2.5	2.1	1
LFG-2A	5	6.8	5.9	1
MSW	12	17	14	1
AD	14	27	18	2,3

A = LFG-1A does not include the capital required to capture and convey the landfill gas; LFG-2A includes the capital required to capture and convey the landfill gas.

Caveats

- **LCOE** – The LCOE calculations in Table B-1 are based on the methodology outlined in NREL's Annual Technology Baseline (https://atb.nrel.gov/electricity/2018/equations-variables.html). The assumptions used for the financing parameters may not be appropriate for the types of projects listed in Table B-1. Also, the additional cost of fuel, tax incentives, and other policies are not included.

- **Sample size** – The LCOE calculations for landfill gas and mass incineration in Table B-1 were calculated from data provided in a recent study.(104) The LCOE estimate reported for anaerobic digestion is based on data from an NREL-supported costing tool and a 2013 technical report.(105) For a rigorous assessment of LCOE we recommend using a much larger sample size.

- **System size** – The LCOE calculations presented in Table B-1 represent specific technologies and system sizes. It is plausible that each system will have different economies of scale and optimal sizing. We did not account for this in our calculation of LCOE.

- **System boundary** – The LCOE calculations used in Table B-1 consider only the capital investment, operation and maintenance costs, capacity factor, and name-plate generation capacity of the project. It should be noted that the LCOE calculation for LFG-1 does not include the capital required to capture and convey the landfill gas. For LFG-1, we assume this to be a sunk cost as part of the landfill's compliance with Resource Conservation and Recovery Act of 1976(106) and the Clean Air Act.(107) LFG-2 is included to represent the capital required to capture and convey the landfill gas as well as the capital needed for conditioning and conversion to power.

- **Externalities** – We do not consider the costs associated with waste disposal. Both anaerobic digestion and mass incineration incur substantial waste burdens that must be handled, most likely through a combination of landfilling and/or land application, for anaerobic digestion, and landfilling and/or recycling for mass incineration.

- **Fuel costs** – Additional fuel costs are not considered in Table B-1.
- **Waste stream differentiation** – The pathways listed in Table B-1 do not necessarily accept the same feedstock. While they do all accept MSW, they each operate under different levels of sorting, preparation, and physical composition.

$$LCOE = \frac{FCR \times CAPEX + FOM}{CF \times 8760\,\mathrm{hr/yr}} + VOM + FUEL$$

where the variables are defined in Table B-2.

Table B-2. Definitions of Variables Used to Calculate the LCOE(23)

Variable	Definition
FCR	Fixed charge rate: Construction finance factor * project finance factor * capital recovery factor (real)
CAPEX	Capital expenditures: Total expenditure per kW of plant capacity.
FOM	Fixed operation and maintenance costs: Average annual fixed operations and maintenance costs over the life of the project.
VOM	Variable operation and maintenance costs: Average annual variable operations and maintenance costs over the life of the project.
CF	Capacity factor: Average annual energy production per kilowatt of plant capacity over the technical life of the project.
Fuel	Fuel costs are applied where appropriate.

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