U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Waste-To-Energy Workshop Summary

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Prepared by
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June 2015

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Note

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Workshop and report sponsored by the

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Preface

This report is based on the proceedings of the Waste-to-Energy (WTE) Workshop held by the U.S. Department of Energy's Bioenergy Technologies Office (BETO) on November 5, 2014, in Arlington, VA. The workshop gathered stakeholders from industry, academia, national laboratories, and government to discuss the issues and potential for research, development, and demonstration activities to pave the way for large-scale production of cost-competitive, renewable fuels from wet waste biomass resources. The ideas provided here represent a snapshot of the perspectives and ideas generated by the individual participants in attendance at the workshop.

Acknowledgements

Special thanks are extended to the workshop plenary speakers for helping to frame this workshop: Jonathan Male of BETO and Patricia Scanlan of Black and Veatch.

Special thanks also go to members of the WTE Workshop Steering Committee: Todd Campbell, USDA; Lauren Fillmore, WERF; Paul Grabowski, BETO (now U.S. Navy); Steve Jenkins, CH2M HILL Engineers; Chris Peot, DC Water; Mark Philbrick, ORISE Fellow with BETO; and Jim Spaeth, BETO.

BETO gratefully acknowledges the valuable ideas and insights contributed by all of the stakeholders who participated in the WTE Workshop. The willingness of these experts to share their time and knowledge has helped to identify and better define current and emerging opportunities to expedite the development and deployment of innovative technologies for sustainably producing a suite of advanced biofuels and bioproducts from wet waste feedstocks. These individuals are listed in Appendix A.

Following the workshop, on November 6, 2014, a number of workshop participants enjoyed a tour of DC Water's Blue Plains Advanced Wastewater Treatment Facility. We thank DC Water and Chris Peot for this informative and enriching experience.

Workshop planning and execution and the preparation of this report were conducted under the direction of BETO's Jim Spaeth and Daniel Fishman by Energetics staff members Aaron Fisher, Paget Donnelly, and Jonny Rogers, with significant contributions from others in BETO and Energetics Incorporated.

Executive Summary

To accelerate the commercial production of drop-in hydrocarbon fuels from wet waste biomass, the Bioenergy Technologies Office (BETO) in the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) held a workshop on November 5, 2014, in Arlington, VA. A broad spectrum of experts from industry, academia, national laboratories, and government participated in the workshop, contributing their ideas, insights, and perspectives. The wealth of information gathered at the workshop will enrich BETO's strategic planning and prioritization efforts.

As summarized and grouped thematically in Table ES.1, the participants discussed activities and technologies that could facilitate the commercial conversion of wet waste feedstocks into drop-in hydrocarbon fuels and products. Working in four parallel technical breakout sessions, the participants identified 17 advancement activities as high in priority. Some of these activities apply broadly to wet waste conversion, while others apply to specific technologies. Across these priority activities, four areas of focus emerge:

- **Pre-Processing:** Better understanding and modifying feedstocks to improve downstream processing efforts. Activities include limiting feedstock variability, optimizing pre-processing and conversion systems for use with available feedstocks, and enabling product flexibility.
- **Process Research:** Applying research concepts to conversion processes to achieve breakthroughs in operations. Focus areas include enhanced understanding of microbial and biological processes and of thermochemical reaction kinetics to improve process efficiency, product quality, product flexibility, and by-product utilization.
- **Process Engineering:** Applying engineering concepts to known processes to reduce operational or capital costs and make liquid fuels more cost-competitive. Activities focus on improving processes to accommodate highly variable feedstocks and contaminants, improving product quality and yield, and enabling the scale-up of technologies.
- **Analysis:** Conducting broad, computationally based efforts that will increase understanding of and help to improve WTE efforts. Analysis efforts focus largely on directing WTE research along promising pathways, validating the techno-economic feasibility of projects, and quantifying environmental impacts.

Activities identified by the workshop participants as having the potential to accelerate progress and help realize the commercial potential of drop-in hydrocarbon biofuels from wet waste feedstocks are summarized below in Table ES.1.

Table ES.1. Activities To Accelerate the Commercialization of WTE Technologies

Activity	Description	Group*
Pre-Processing		
Characterize feedstocks and co-digestion	Prepare guidance on the relationship of organic feedstock characteristics to digester performance and to biogas production	AD 1
Manage moisture by blending with dry biomass	Explore blending solutions to economically manage the variability and uncertainty of wet waste for hydrothermal liquefaction (HTL)	HTL
Demonstrate and deploy preprocessing and pretreatment technologies	Develop pretreatment to enhance methane production in anaerobic digestion; incorporate other waste streams into AD	Other
Process Research		
Improve understanding and real-time monitoring of microbial anaerobic processes	Increase the scientific understanding of microbial systems through the development of real-time biosensors for anaerobic processes	AD 1

Activity	Description	Group*
Enable direct conversion to high-value products including fuel intermediates	Control and modify microbial processes to improve profitability and flexibility of the products and product types	AD 2
Produce AD end products beyond methane, methanol, and ethanol	Develop technologies that are able to produce end products beyond CH_4, methanol, and ethanol through anaerobic digestion	AD 2
Develop economic usage of non-oil HTL effluent streams	Identify and develop an economically viable process/technology to utilize the nutrient-rich, non-HTL crude oil streams produced during the HTL process	HTL
Conduct R&D on biological and thermo-catalytic conversion technologies for pre-processed waste biomass	Develop higher-value, targeted profiles for storable/transportable products/intermediates that can be produced faster and under less severe conditions than anaerobic digestion (AD)	Other
Process Engineering		
Configure new bioreactor for enhanced AD and higher process efficiency	Improve environmental and technical performance via shorter retention times; improve gas quality, energy yield, and digestion rates to make AD cheaper, smaller, better, and faster	AD 1
Develop cheaper gas cleanup technology that works on smaller scale	Develop biogas cleanup technology that costs less than $2/MMBtu, produces 50-500 standard cubic feet per minute (SCFM), yields greater than 95% biomethane, and provides long-term reliability.	AD 2
Design robust digester to handle wide variability of feedstock	Design robust digester system to handle various feedstocks and high-solids waste streams	AD 2
Improve process monitoring and control to handle highly variable feed streams	Develop robust process controls to optimize novel waste-to-energy processes that use highly variable, non-homogeneous input streams	Other
Support scale-up of technologies	Demonstrate conversion of manure and organic substrates (waste) to middle distillate fuels (diesel); enable multiple value streams; prove beneficial use that avoids environmental runoff	Other
Analysis		
Design a lifecycle systems approach that includes feedstocks and biosolids, conversion technologies, and end use products	Quantify biogas production, energy balance, and carbon sequestration from wastewater sludge; reduce greenhouse gas (GHG) emissions from co-digestion diverted from landfills; calculate the economic, GHG, and resource conservation benefits of biosolids as fertilizers	AD 1
Optimize macro process improvements	Enable technology developers to co-optimize/optimize cost, environmental performance, and fuel yield ; Analyze HTL of wet-waste/biomass: integrated analysis of all HTL process unit operations (everything from sludge to fuel and resource recovery)	HTL
Conduct techno-economic analyses	Evolve conceptual process design and modeling to define process variables, technical barriers, and key drivers for economical technologies	Other
Other		
Identify and reduce regulatory barriers to improve technical acceptance by the marketplace	Clarify technical basis for regulatory concerns; examine and revise regulations in this field to facilitate technology implementation and early adoption	HTL

*** Breakout group suggesting the activity:**

AD 1- Anaerobic Digestion of Wastewater Residuals and Biosolids
AD 2- Anaerobic Digestion of Foodstuffs and Other Municipal Solid Waste
HTL- Hydrothermal Liquefaction of Wet Waste
Other- Other Conversion Processes of Wet Waste

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1. Introduction

As global energy demand continues to rise, the United States is strategically developing diverse renewable and other domestic energy resources as part of a robust energy portfolio for the long term. Pursuit of this national energy strategy has raised awareness that U.S. wet waste streams contain too much carbon and energy to simply discard. The 35.2 million wet tons of waste food scraps produced domestically in 2014 had the potential to provide approximately 71.4 TBtu,[1] and the 7.3 million dry tons of waste biosolids, about 101.5 TBtu—for a total energy output of 172.9 TBtu.[2] By 2030, population growth is projected to increase the energy in these two wet waste streams alone to 194.9 TBtu.[3] If that energy were converted to fuel, it would satisfy more than 1% of annual U.S. motor gasoline consumption[4]—meeting the criteria for worthwhile investment in energy technology research (see inset). Progress in pretreatment and conversion processes may extend the utility of wet waste feedstocks well beyond these two readily available and narrowly defined waste streams.

Investment Prioritization: Impact

EERE must focus its limited funds on clean energy challenges and solutions that, if successful, will have the highest possible impact on the energy sector. If successfully developed and fully deployed, the technologies and approaches supported by these investments should make material contributions toward national energy goals—such as petroleum import reductions, greenhouse gas emission reductions, total energy cost reductions, and increased economic growth.

Statement by David Danielson, Assistant Secretary for Energy Efficiency and Renewable Energy, U.S. Department of Energy, to the House Appropriations Subcommittee on Energy and Water Development

Although most U.S. wastewater treatment (WWT) plants view the provision of clean water as their primary responsibility, many also engage in energy recovery by producing and combusting biogas (see Figure 1). Biogas is a natural gas with low heating value that requires significant upgrading to meet pipeline-quality standards. Even if biogas is not destined for injection into a pipeline, it often requires cleaning to remove impurities and raise the heating value. After clean-up, biogas is often burned on site to generate heat and power, or it is used in specialized vehicle engines designed for this lower energy-content natural gas fuel. Significant opportunity exists to convert these and similar wet waste feedstocks into liquid transportation fuels. Technologies for performing this conversion are moving along the development curve and could deliver a wealth of benefits to the nation, including economic growth, competitive advantage, energy security, reduced greenhouse gas emissions, and positive impacts on sustainability and the environment.

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1 Scaled from 2012 population to 2014 population. Excludes 3.5 TBtu of energy that is captured www.epa.gov/waste/nonhaz/municipal/pubs/2012_msw_fs.pdf

2 14.5 billion dry lbs./yr., of which 50% is wasted @7000 Btu/ dry lb.
318 million people in the United States (June 2014, US Census Bureau) http://quickfacts.census.gov/qfd/states/00000.html
Each person makes 0.25 dry lbs./day =91.25 dry lbs./person/year (www.ohiowea.org/docs/802_biosolidstoenergy_rhodes.pdf)
50% is wasted/ not used productively (http://water.epa.gov/polwaste/wastewater/treatment/biosolids/genqa.cfm)
@ 7,000 Btu/dry lb. of biosolids (Biosolids: 6,250-8,100 Btu/ dry lb. www.ohiowea.org/docs/802_biosolidstoenergy_rhodes.pdf)

3 12.7% anticipated total population growth between 2014 and 2030 (www.census.gov/content/dam/Census/library/publications/2015/demo/p25-1143.pdf)

4 If the 172.9 TBtu were converted to gasoline (114,000 Btu/ gallon), this would be equivalent to 1.5 billion gallons.
In 2014, the United States consumed 136.7 billion gallons (3.26 billion barrels) of motor gasoline (www.eia.gov/tools/faqs/faq.cfm?id=23&t=10)

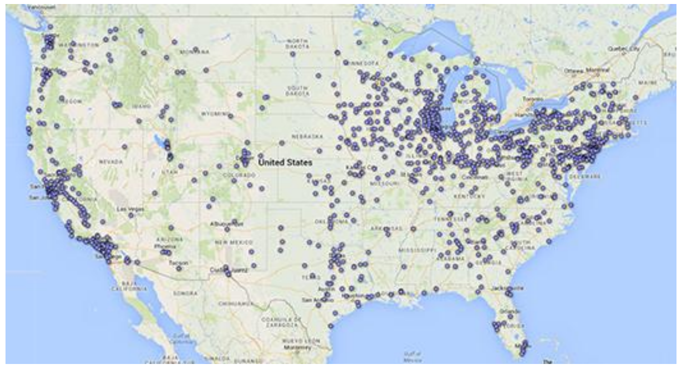

Figure 1. Operational U.S. Biogas Systems (www.americanbiogascouncil.org/biogas_maps.asp)

Having met the U.S. Department of Energy's (DOE's) modeled mature cost targets for cellulosic ethanol production in 2012, the Bioenergy Technologies Office (BETO) in DOE's Office of Energy Efficiency and Renewable Energy (EERE) continues to support cellulosic ethanol at the demonstration and market transformation level; however, BETO has shifted its research focus to the next generation of advanced bioenergy: drop-in hydrocarbon fuels from cellulosic feedstocks. This new research priority has stimulated keen interest in all available biomass feedstocks—including wastes—as a means to diversify carbon carriers and reduce feedstock supply risk.

BETO is now evaluating research approaches for accelerating progress and maximizing impacts in the waste-to energy (WTE) space. More specifically, the office is examining how novel and existing conversion technologies or pathways might best be applied to such underutilized yet readily available feedstocks as wet waste and biosolids. To better understand the barriers and challenges to converting these unique and highly variable feedstocks to hydrocarbon fuels, BETO convened a WTE Workshop in Arlington, VA, on November 5, 2014. At the workshop, stakeholders from industry, academia, national laboratories, and government gathered to discuss the issues and potential pathways to sustainably produce cost-competitive fuels, rather than stationary power, from wet waste and biosolids. These discussions are helping to define how BETO might simultaneously advance the sustainable utilization of wet waste streams, complement the work of other agencies, and maximize the value of its research investment.

The workshop and related activities align closely with direction provided by the U.S. Congress. In recent budget language, Congress expressed an interest in making productive use of wet waste feedstocks, specifically identifying biosolids as a feedstock of interest. Under the 2015 Appropriations Act, Congress directs the Department of Energy to expand its focus to do the following:

> include **biosolids derived from the municipal wastewater treatment and agricultural processes**, and other similar renewables, within the definition of noncellulosic. Furthermore, biosolids from wastewater treatment is encouraged as a feedstock for all research, development, and demonstration activities conducted within the available funding. Technologies utilizing biosolids must provide evidence of the potential to reduce the volume of waste materials and reduce greenhouse gas emissions over current uses of this feedstock. The Department is directed to host a stakeholder meeting to discuss the current state of technologies that utilize biosolids and determine the key barriers that need to be overcome to make substantial gains in reduction of greenhouse gases and cost of energy over full-scale operations already in existence globally [bold emphasis at top added].

This report summarizes the aforementioned stakeholder workshop results, which can provide useful input as BETO evaluates the research, development, demonstration, and market transformation efforts needed to achieve affordable, scalable, and sustainable production of hydrocarbon biofuels and renewable chemicals from wet waste feedstocks. This report is not designed to comprehensively cover all of the relevant issues but merely to summarize the innovative ideas generated by those in attendance at the workshop. These results are presented within four technical areas, each of which was the focus of one breakout group:

- **Anaerobic Digestion (AD) of Wastewater Residuals and Biosolids:** AD processes that operate on the types of wet waste feedstocks typically handled by wastewater treatment facilities
- **Anaerobic Digestion of Foodstuffs and Other Municipal Solid Waste (MSW):** AD processes that operate on types of wet waste feedstocks not typically handled by wastewater treatment facilities
- **Hydrothermal Liquefaction (HTL):** HTL or related processes that convert any wet waste feedstock into either fuels or products
- **Other Conversion Processes:** Processes *other than* AD or HTL that convert any wet waste feedstock into either fuels or products.

1.1 Workshop Presentations

Jonathan Male, BETO Director

Jonathan Male, Director of BETO, opened the workshop by providing context for DOE and EERE's interest in wet wastes and defining the target opportunities and scope for workshop discussions. BETO is tasked with developing and transforming renewable biomass resources into commercially viable, high-performance biofuels and bioproducts through targeted research, development, demonstration, and market transformation. DOE recently provided cost-shared support for three large cellulosic ethanol plants that commenced production within the past 18 months, and the Department is now partnering with the Department of Defense to build three new plants to produce *drop-in* biofuels. Of these six pioneer plants, three are designed to use waste feedstocks (other than agricultural): the INEOS plant in Vero Beach, FL (wood and vegetative waste, including palms fronds, for conversion into cellulosic ethanol), the Emerald Biofuels plant on the Gulf Coast (fats, oil, and greases for conversion into drop-in biofuels), and the Fulcrum Bioenergy plant in McCarran, NV (municipal solid waste for conversion into drop-in biofuels).

BETO seeks to build upon its experience in using agricultural and algal feedstocks by capturing the embedded carbon and energy in wet waste biomass feedstocks and returning those resources to the market as biofuels and bioproducts. Waste feedstocks are typically less expensive and have better established supply chains than non-food agricultural feedstocks, but wastes also tend to have a significantly greater level of variability. BETO is interested in supporting the development of technologies that can handle diverse wet waste streams as a complement to ongoing work by other agencies and teams focused on dry and single-source waste streams. Targeted work in the WTE space could address variability issues and bring additional biofuels to the market.

In the waste-to-energy space, the dominant output product to date has been biogas—a low-heating-value mixture of natural gas, carbon dioxide, and other impurities—which is usually used on site for transportation or stationary power. BETO views biogas production as a commercial technology and wants to evaluate the opportunity for research and development (R&D) to broaden the slate of potential products and intermediates that can be economically produced from wet waste streams. In BETO's view, the natural gas component of biogas is a key chemical intermediate that could be converted to more valuable hydrocarbon fuels and products. The office is also considering conversion routes that proceed through other processes (e.g., hydrothermal liquefaction).

Patricia Scanlan, Director of Residuals Treatment Technologies, Black and Veatch

Patricia Scanlan, Director of Residuals Treatment Technologies at Black & Veatch Corporation, delivered the keynote address to the workshop. Her team at Black & Veatch focuses on residuals management to help wastewater utilities overcome the challenge of treating and managing biosolids to meet increasingly stringent regulations and public pressures. She and her team implement technology not only to clean the wastewater but also to capture the energy embodied in the biosolids as a marketable product (e.g., as an alternative fuel in the transportation industry).

Scanlan stressed the need for innovative approaches to develop sustainable solutions to energy production from unconventional streams, such as wastewater. Energy production is not the core business of WWT plants, however, and there have been few incentives (economic or regulatory) to pursue energy-recovery WWT technologies. Mounting scientific and public pressure to develop alternative transportation fuels with reduced greenhouse gas (GHG) emissions is driving a new recognition of wastewater as a useful resource that could help meet U.S. fuel requirements.

Commercial WWT technology providers have largely focused on anaerobic digestion and hydrothermal liquefaction processes. AD is the more established of the two and is widely used in WWT facilities today. Biogas produced from existing municipal WWT anaerobic digesters could be used to produce fuel for 550,000 vehicles annually—instead of on-site heat and power, as is common practice today. Encouraging the use of biogas as a petroleum substitute will require improving the process economics of existing WTE AD conversion processes, developing the supporting infrastructure, and pursuing AD technology advancements for applications beyond on-site power generation. Alternatively, HTL offers a promising pathway to convert 70% or more of wet waste streams into useful bioproducts and biofuels, but this technology will require significant R&D to support future pilot and full-scale installations.

The economic and environmental costs of existing energy resources and regulations influence investment in technologies for utilizing alternate resource streams like wastewater. Continued efforts to increase energy recovery, reduce dependence on foreign petroleum, and lower greenhouse gas emissions will help the nation move toward a more sustainable future.

1.2 Non-Technical Barriers to Converting Wet Waste Feedstocks to Liquid Transportation Fuels

Conversion of wet waste feedstocks into liquid transportation fuels faces non-technical barriers in addition to technical challenges. While these issues fall outside the traditional scope of BETO activities, they constitute significant barriers and should be addressed in tandem with technical issues. This section is based upon discussions across the four breakout groups, as the issues are similar regardless of technology. These non-technical barriers broadly fit into three categories: regulatory, economic, and educational.

Regulatory

- **Unclear or inconsistent policies regarding waste from agriculture, municipalities, and other sources create uncertainty in feedstock supply and quality:** Jurisdictional disputes and differences in the commercial definition of "waste" and "biofuel" are common within and across departments and regulatory agencies. In addition, incentives vary by state and by the type of energy produced.

- **Lack of approved WTE pathways and standards:** Standards for the utilization of various waste streams and conversion pathways need to be qualified to comply with existing ASTM fuel standards, to enable EPA registration, and to obtain Renewable Identification Numbers (RINs). Benchmarks will facilitate objective comparisons between the life-cycle economic, environmental, and energy impacts of WTE technologies and other biomass or conventional fuels and will help shape effective regulation. Open data sharing among government offices, where data does not provide a competitive advantage, will advance WTE technology pathways and enable establishment of more consistent methods, standards, and regulations across agencies.

- **Uncertainty surrounding wet waste feedstock ownership:** To attract capital investment, producers must assure investors that appropriate quantities of waste are available, yet minimal case law exists to clarify ownership of public wastewater and MSW, and the assignment of associated liabilities is similarly unclear. If a waste authority wishes to build a facility to produce a commercial fuel, the unique ownership and potential liability issues, if unresolved, will create substantial barriers to the necessary commercial investments.

Economic

- **Difficulty attracting adequate capital investment for WTE projects:** WTE projects face significant hurdles to project financing, including the need for permits, approved operating sites, and long-term contracts for feedstocks and products. The economic viability of conversion processes is influenced by such factors as the feedstock processing model (local versus distributed), use of intensive fuel upgrading processes, and markets for co-products. A solid understanding of these issues is necessary to build a compelling case for investment.

- **Limited demand for WTE conversion technologies and products over alternatives:** WTE technologies must compete in a market with low-cost, petroleum-derived fuels and products. The current (and projected) low price of natural gas and other fossil fuels and the lack of consistent and enduring policy incentives (e.g., RINs for MSW and wastewater) have restrained the perceived profitability of these energy investments for key market players. The flexibility to utilize multiple feedstocks and products will help to improve the value proposition of WTE technologies. Free market access to WTE products and strong core messaging on the socio-environmental benefits of waste conversion processes will help to differentiate biomass from petroleum and increase demand.

Education

- **Challenge in shifting attitudes from wastewater treatment to resource recovery:** Education on waste conversion technologies is needed to garner public support and drive implementation. Positive messaging and successful demonstrations are needed to increase the perceived value of waste from both economic and sustainability perspectives. Using a bio-preferred label on waste conversion products is one way to increase public awareness and acceptance. A comprehensive public education campaign can also help to increase market demand, educate lawmakers, and drive additional investments in the productive use of new resource streams.

- **Need for validated processes and success stories to instill confidence in WTE technologies among the public, lawmakers, and utilities:** Wastewater treatment facilities are legally bound to clean the water to a specified level, and public confidence in their operations is imperative. Water treatment is the core mission of these facilities, and they cannot afford to shut down for any length of time, as the incoming waste will not subside. In this environment, even a proven technology needs a compelling business case to convince these facilities to deviate from existing processes. Reduced energy costs could build that compelling case. Successes related to anaerobic digestion are often defeated by a "not in my back yard" mentality or exaggerated concerns about odor.

- **Widen the concept of "profitability" from socio-economic to socio-environmental survival and viability:** Future development efforts must focus on the most sustainable and economically viable solutions. More mature technologies, such as anaerobic digestion, must be improved to maximize productivity and quality, whereas newer pathways, such as HTL, must address many uncertainties to demonstrate techno-economic viability. Clear, quantified sustainability benefits could increase demand for waste conversion technologies and strengthen investor confidence. A value proposition accounting for externalities would support continued deployment of WTE.

2. Anaerobic Digestion (AD) of Wastewater Residuals and Biosolids

The breakout group focusing on the Anaerobic Digestion of Wastewater Residuals and Biosolids discussed barriers and advancement activities related to the sustainable and economically viable production of liquid transportation fuels via this conversion pathway. AD is widely deployed in treating wastewater, but WWT facilities have had limited incentive to maximize energy recovery from the wastewater. Instead, these facilities have been primarily designed to treat wastewater streams for public health and safety. Only recently have some pioneering facilities begun to consider biogas production facilities as an energy-producing resource. Liquid transportation fuels from biogas face significant competition from petroleum and other biofuels. A greater understanding of the interplay among feedstocks, microbial systems, and digester process conditions could optimize anaerobic digester processes and yield high-quality products suitable for use as transportation fuels. Establishing a clear value proposition for this pathway over the alternatives will require a deeper scientific understanding of the anaerobic digestion process for wastewater, including its sustainability, economic viability, and associated GHG emissions.

2.1 Technical Barriers

Several technical barriers currently limit the production of liquid transportation fuels via the anaerobic digestion of wastewater solids. A critical need is to better understand the processes affecting this technology (e.g., the mechanisms of microbial processes or the impacts of feedstocks and co-digestion on production). Another important barrier is the wide variability in anaerobic digester performance due to variations in feedstocks, season, bacterial strain, and other factors. Feedstock variability presents unique challenges regarding contaminants and handling. While some existing technologies can preprocess the feedstocks or reduce impurities in the produced biogas or digester effluent streams, the associated costs pose significant barriers. Innovations are needed to remove contaminants from the input waste streams and products and to reduce the long residence times currently needed for processing. Several miscellaneous barriers to wastewater anaerobic digestion highlight the need for general process improvements and standards, enhanced safety, and better capacity design capabilities. Comprehensive life-cycle and techno-economic analyses (TEA) are needed to quantify the environmental and economic benefits from anaerobic digestion of wastewater solids. Future R&D must focus on advancing the most viable pathways, increasing productivity, developing innovative business models, and safeguarding the integrity of traditional WWT objectives.

Table 2.1. Technical Barriers to the AD of Wastewater Residuals and Biosolids in Producing Liquid Biofuels

Knowledge Barriers	• Need for better understanding and implementation of co-digestion to increase biogas production • Lack of understanding of microbial anaerobic processes • Need to better understand the attributes and synergies of animal waste for use a co-digestate feedstock in anaerobic digestion • Need to better assess feedstock resources and potentials
Feedstock	• Limited biodegradability of biomass • A low C:N ratio adversely impacts methane (biogas) production
Materials Handling	• Need for more cost-effective ways to decontaminate food waste for co-digestion • Need for mixed cultures – Challenge of managing multiple organisms in mixed cultures

Variability	• Unsatisfactory anaerobic digestion performance – Ineffective conversion – Lengthy retention times – Need for extensive post-conversion biogas cleanup • Inadequate robustness of anaerobic digestion operations to handle: – Variations in feedstock composition – Seasonal effects – Co-digestion • Wide variations in biogas production by day/season
Treatment	• Need for economical CO_2, H_2S, siloxane removal • Biogas cleanup needs lower-cost and more reliable technologies • Liquid stream complications • Handling and disposal of side-stream with high nitrogen and phosphorus loading
Lack of Technologies	• Lack of pretreatment technologies – Fractionation – Improved anaerobic digestion performance • Long residence time – Specifically, start-up times
Other/ Miscellaneous	• Anaerobic digestion is not the best technology for liquids and fuels • Lack of standards for feedstock (organic wastes) characteristics • Process stability issues with co-digestion • Safety risks to operators handling biogas • Limited efficiency for engines • Overdesigned and underutilized anaerobic digester capacity
GHG	• Accounting for radiative forcing of CH_4 and GHG emissions as part of renewable identification number (RIN) • Lack of understanding full lifecycle GHG emissions and water path of this technology
Techno-Economics	• Multiple competing digester objectives: – Clean water – Energy – Biosolids management – Odor control – Nutrients – Volume reduction • High cost of upgrading processes • Volumetric productivity and molecular kinetics (gram/liter/hour) • Inverse correlation between reactor size and capital expenditure (CAPEX)

2.2 Priorities for Advancement

High-priority topics, as determined by participant voting, are described below; further details may be found in Appendix D. The full list of activities receiving votes is provided in Table 2.2 (below).

Improve understanding and real-time monitoring of microbial anaerobic processes (15 votes). The highest priority activity is to increase scientific understanding of microbial systems through biological improvements and the development of real-time biosensors for anaerobic processes. Increased understanding of microbial capabilities will help to optimize design operations; produce multiple, value-added compounds; lower GHG emissions; improve sustainability; increase carbon and energy efficiency; and enhance the economic viability and robustness of anaerobic processes.

Configure new bioreactor for enhanced AD and higher process efficiency (12 votes). The second-highest priority is to improve the environmental and technical performance of anaerobic digestion via shorter retention times, improved digestion rates, and better gas quality and energy yield. Basic research and common performance metrics are needed to guide development of more efficient AD designs. Within 10 years, improved technology is expected to enable decentralized wastewater treatment and produce near-pipeline-quality biogas, water suitable for discharge or reuse, and solids suitable for fertilizer in land applications.

Design a lifecycle systems approach that includes feedstocks and biosolids, conversion technologies, and end use products (7 votes). Existing knowledge and resources from federal, state, local, industrial, and university efforts can be leveraged into harmonized models to define meaningful metrics for WWT facilities. A comprehensive lifecycle-based analytical approach will enhance understanding of the economic viability, energy efficiency, and sustainability of various anaerobic digestion technologies and processes for the production of liquid transportation fuels and value-added byproducts (i.e., enable comparisons of product end-use applications, including onsite power, compressed natural gas [CNG], liquid transportation fuels, land-applied biosolids, and nutrient recovery).

Characterization of feedstock and co-digestion (6 votes). Existing anaerobic digester equipment is overdesigned and underutilized, which presents an opportunity for the co-digestion of food and high solids waste with wastewater solids. Guidance on the relationship of organic feedstock characteristics and co-digestion process attributes will enable decision making to improve digester performance and enhance biogas production. The development of a relational database is considered attainable within five years at an initial cost of less than $1 million. This database would offer implementation tools (i.e., guidelines and software) for plant-specific applications.

Table 2.2. Identified Advancement Activities for the AD of Wastewater Residuals and Biosolids in Producing Liquid Fuels[5]

Biological Improvements	
High Priority	• Improve understanding and real-time monitoring of microbial anaerobic processes ●●●●●●●●●●●●●●● (15) – Develop advanced microbes or “Superbugs” – Need better understanding and real-time monitoring of microbial anaerobic processes – Better characterize and understand mixed microbial cultures in anaerobic digesters – Conduct R&D on microbial ecology of anaerobic digestion – Undertake metagenomic study to understand robustness of microbes and process upsets
Intensification	
High Priority	• Develop new bioreactor configuration to improve AD process efficiency ●●●●●● (6) • Integrate gas cleanup during digestion (CO_2, H_2S, siloxane) ●●● (3) • Apply process intensification principles to AD ●●● (3) – Shorter residence time – Better conversion of organics

[5] Those activities identified, but receiving no votes were excluded

	[All three combined as *Configure new bioreactor for enhanced AD and higher process efficiency - 12 votes]*
Analyses	
High Priority	• Develop whole-plant carbon-energy management model/paradigm ●●●● (4) • Develop common metrics to compare systems ●● (2) • Quantify GHG emission reductions via lifecycle analysis for converting biogas to fuel and for land application of bio-solids (including side stream impacts on H_2O quality) ● (1) [All three combined as *Design a lifecycle systems approach that includes feedstocks and biosolids, conversion technologies, and end-use products, 7 votes*]
Feedstocks and Co-Digestion	
High Priority	• Develop co-digestion AD design guidelines ●●●●●● (6) [Completed as a worksheet under the title *Characterization of feedstock and co-digestion*]
Medium Priority	• Improve biogas yield via co-digestion of food waste, organic waste ●●● (3) • Develop comprehensive relationships of waste organic feedstock characteristic to biogas potential, including operational side-effects (perhaps as database guidance) ●●● (3)
Equipment Design	
Medium Priority	• Improve start-up/recovery of anaerobic systems ●●●●● (5) • Research processing of diluted feedstocks ●●● (3)
Low Priority	• Research ways to improve the performance and reliability of fuel cells operating on biogas ● (1)
Pre-Treatment	
Medium Priority	• Compare pre-treatment systems and provide guidance on which to pursue in which settings ●●●●●● (6)
Post-Treatment	
Medium Priority	• Research side-stream nutrient treatment and fund best practices ●●● (3)
Low Priority	• Improve gas cleanup ● (1)

● = 1 priority vote

3. Anaerobic Digestion of Foodstuffs and Other MSW

Anaerobic digestion of foodstuffs and other organic municipal solid waste offers another route to the production of liquid transportation fuels and other end products. Participants were challenged by the moderator to think beyond the use of biogas for stationary power.

3.1 Technical Barriers

Efforts to make anaerobic digestion an economically viable means to convert municipal solid waste into liquid fuels and other products face technical barriers throughout the conversion process (Table 3.1). Other bioenergy technologies also face some of these challenges, such as the variability of feedstock quality and lack of large-scale feedstock handling infrastructure. More specific to AD technologies are the need for improved systems to collect and handle food waste; better systems for monitoring and controlling the AD process; and more reliable machinery, such as pumps and mixers, for use in harsh MSW environments. In the real-world operation of AD units, continuing hurdles include the lack of cost-efficient nutrient recovery technologies, the inability to quickly direct microbial community evolution, and slow process speeds. Finally, the most significant barriers to total process economics include the lack of high-value end products and cost-competitive conversion pathways to liquid fuels and other chemicals.

Table 3.1 Technical Barriers to the AD of Foodstuffs and Other MSW in Producing Liquid Fuels

Feedstocks	• Lack of understanding biogas yield as a function of crop type, harvesting practices, maturity • Variability of feedstocks; lack of process robustness • Difficulty in getting a clean feedstock at front end, e.g., de-packaging, collection, etc. • Diversity of feedstock chemistry • Supply and location of feedstock, i.e., wood pellets, woody biomass, crop residues − Could decrease production, increase cost
Feedstock Systems/ Equipment	• Lack of feedstock infrastructure (collection system) at large scale • Lack of coordinated collection systems for mixed food wastes • Inadequate receiving stations for food wastes/ slurry (feedstock)
Process	• Need for "pretreatment" of mixed solid MSW • Low efficiency of nutrient protein (amino acids, etc.) recovery • Lack of cost-effective nutrient recovery technology (digestive) • All molecules in waste are not equally good in CH_4 production. - Waste is made up of organic acids, alcohols, hydrogen etc., which all must be converted to CH_4 • Inability to direct microbial community evolution responsively/quickly • Lack of separation technology for intermediates • Lack of reliable on-line sensors and controls for process optimization • Inadequate system monitoring and controls to avoid shutdown of CH_4 production • Slow conversion speed and inability to accelerate conversion process from days to hours • Expensive catalyst (cost) • Low productivity in converting biogas to fuel

Pathways	• Lack of technologies for distributed methanol → energy – need additional dense fuel pathways and chemicals
	• Lack of economical upgrading pathways from CH_4 → conversion end product
	• Efficiency limited by thermodynamics (to convert methane one needs energy)
	• Poor understanding of mass transfer limitation of CH_4
	• Inhibitory effect of sulfur compounds in biogas upon downstream processing
	• Challenges of Fisher-Tropsch process and steam reforming
	  – Too complex
	  – Too costly
	  – Too large
	• Poor machine reliability (pumps, mixers)
	• Poor partial-load efficiency of mechanical equipment, e.g., for compressor and internal combustion engines

End Products	• Beyond tipping fees as a revenue stream – converting feedstocks into valuable products that can be sold

3.2 Priorities for Advancement

High-priority topics, as determined by participant voting, are described below; further details are found in Appendix D. The full list of activities receiving votes is provided in Table 3.2.

Producing AD end products beyond methane, methanol, and ethanol (24 votes). As a distributed technology, AD requires the downsizing of existing technologies for the production of higher-value liquid fuels compatible with the existing infrastructure (e.g., diesel). In the near term, identifying potential digester feedstocks, conversion technologies, and start-up companies could expedite progress. Research should focus on optimizing the most promising technologies and end products to enable the deployment of pilot and larger-scale demonstration facilities that could meet the ultimate cost performance target of $3 per gallon.

Robust digester design to handle wide variability of feedstocks (12 votes). Research efforts should focus on developing digester designs that can handle variable feedstocks and high solids. Researchers will need to first identify specific parameters for monitoring digester performance and stability and then develop the appropriate sensors. As data is collected on operational systems, modeling tools can be developed and validated. Successful R&D efforts will help to optimize yields, reduce costs, and decrease failure rates. Better understanding the processes and collecting relevant operational data will help to benchmark the different AD technologies.

Develop cheaper gas cleanup technology that works on a smaller scale (10 votes). The high cost of removing sulfur from biogas represents a major barrier, particularly for small-scale AD systems. Existing sulfur removal technologies should be evaluated and compared by unbiased third parties to assess their cost, performance, energy balance, and reliability. To avoid reinventing the wheel, previous technology ideas should be surveyed. The eventual goal should be to have an easily deployable, plug-and-play solution integrated with a low-cost gas liquefaction process.

Enable direct conversion to high-value products including fuel intermediates (10 votes). Developing the ability to better control and modify microbial processes will improve the flexibility and profitability of AD products. Research entities will need to investigate the use of different metabolic processes with varying feedstocks and assess the markets for potential new products. The most promising new products and processes should be deployed in pilot-scale plants and, if successful, scaled up to demonstration projects to prove technology viability. New end products will need to be cost competitive with petroleum-based products.

Table 3.2 Identified Advancement Activities for the AD Conversion of Foodstuffs and Other MSW in Producing Liquid Fuels[6]

Process Research	
High Priority	• Producing AD end products beyond methane, methanol, and ethanol ●●●●●●●●●●●●●●●●●●●●●●●● (24) – Conduct R&D to develop microbial consortia for product diversification – Develop new biogas-to-liquid system (simple, low-cost technology; low scale/sizing; ease of marketing product) – Research other fuel production process from AD intermediate gases/liquid • Develop new enzyme or microorganism to directly produce end product (not fuel) that is profitable to produce – high value ●●●●●●●●●● (10) [renamed to *Enable direct conversion to high-value products including fuel intermediates* on worksheet] – Enhance microbial, enzymatic applications (shorter HRT (hydraulic retention time) with greaterCH_4 yield, higher temperatures to facilitate consumption of cellulosic biomass) – Explore potential of microbial population and feedstocks for chemical production – Examine potential fuel intermediate
Medium Priority	• Conduct R&D on hybrid processes (catalytic/microbial) ●●●●●● (6)
Low Priority	• Solve NH_3 toxicity ● (1) • Conduct R&D to find better/cheaper catalyst ● (1)
Process Engineering	
High Priority	• Robust digester design to handle wide variability of feedstock ●●●●●●●●●●●● (12) – Shift to high-solids AD • Develop cheaper gas cleanup technology that works on smaller scale ●●●●●●●●●● (10)
Medium Priority	• Develop online sensors to monitor/control "global" health of bacterial population – holistic/global ●●●●●●● (7)
Low Priority	• Conduct R&D on reactor design to avoid fuel toxicity ● (1) • Provide specifications and SOPs (standard operating procedures) for equipment necessary at plants to receive food waste slurry ● (1)
Analysis	
Medium Priority	• Develop modeling tool for AD performance given different feedstocks/combos ●●●●●●● (7) • Conduct TEA and sustainability analysis; regional supply chain, seasonal ●●●●●●● (7) • Conduct metabolic flux analysis of complex and simple AD communities ●●●● (4) • Characterize potential bio-based products from digestate ●●●● (4)

● = 1 priority vote

[6] Activities that were identified but received no votes were excluded.

4. Hydrothermal Liquefaction (HTL)

HTL is a hydrous process in which temperature and pressure are applied to induce chemical changes and produce biofuels, bioproducts, and high-value intermediates. The breakout group focusing on HTL discussed the challenges and opportunities for accelerating the adoption of HTL technologies. These discussions covered the entire HTL process, including feedstock sources and logistics, slurry prep, HTL conversion, and process outputs.

4.1 Technical Barriers

The HTL group identified a number of technical barriers to the adoption of HTL (Table 4.1). In contrast to AD, HTL technology is not commercially mature, and many of the identified barriers follow from this status. Barriers related to scaling up the technology include the lack of opportunities to demonstrate technology feasibility (energy balance); challenges in pumping the slurried biomass; transport issues for downstream products; and problems with equipment stability, reliability, and dependability. The feedstock-related technical barriers are similar to those identified in other groups and are based upon a highly variable and geographically dispersed feedstock. These barriers include the logistical challenges of centralized collection, feedstock preprocessing, feedstock blending, feedstock storage, and expanding the flexibility of facilities to accept feedstock with different characteristics. As with any immature technology, access to capital is constrained by a number of factors. Participants specifically called out two barriers that if addressed would reduce risk and make investment in HTL systems more enticing: the limited understanding of conversion efficiencies and the lack of opportunities assessments for co-locating HTL infrastructure. Additionally a number of barriers identified related to the integration and dispersal of insufficiently characterized products into well-defined markets: including the transportation of end products, handling of wastewater and contaminants, leveraging of recovered metals and nutrients, and lack of understanding of output oil quality.

Table 4.1. Technical Barriers to HTL Technologies for Converting Wet Waste Feedstocks

Scale-Up	• Lack of demonstrations of energy balance
	  – Heat integration of HTL reaction
	  – Maintaining reactor at operational temperature not yet demonstrated
	  – Energy intensity of water cleanup processes
	• High-pressure pumping (of slurries) at large scale not demonstrated
	• Pumping slurried biomass in pipelines not demonstrated
	  – Water use/transport issue
	  – Relocating water from one location to another is water- and energy-intensive
	• Fabrication processes to achieve lifetime and cost at scale not demonstrated
	  – Scale, performance unknowns; odor, materials handling
	• Equipment reliability and dependability not demonstrated. Must be rock-solid based on operational data and records
	• Technical logistics of downstream product transportation have not been determined (e.g., pipelines)
	• Industry typically has more experience with feedstock preparation into slurry
	• Material stability of HTL equipment/long-term operations with high ash content not understood (e.g., biosolids, safety/maintenance schedules)
	• Front-end pre-processing/material handling systems do not exist
	  – Very different from wood and dairy, with which the industry has more experience handling their respective feedstocks
	• Long-term stability of the process equipment

Feedstock	• As-collected MSW has low organic content. Logistical challenges in centralized collection and sorting of recyclable streams (i.e., metals, glass, plastic) • Large-scale pilot and demonstration projects have not been accomplished • Feedstock preprocessing for active management of feedstock variability/uncertainty has not been proven • The more tightly HTL is coupled to the feedstock, the more specific HTL processes must be tuned to that feedstock, including tolerance to variability/uncertainty • Lack of understanding of HTL feedstock characteristic requirements and limitations so we can design multi-feedstock blends • Lack of flexibility of facilities to accept feedstock with different characteristics • Lack of feedstock storage and queuing of wet slurries • Blending of materials to balance co-products; creating feedstock blends – Blending feedstocks can help increase organic content to achieve constant product yield • Continuous separations of multiple feedstocks

Costs and Operating Expenses	• Lack of comparison of economies and potential uses of assets produced at WWT facilities
	  – Compare HTL end product to some similar end product
	• Low oil yield per gallon of total feed leads to high capital costs per barrel of oil
	  – Capital cost to process water
	• Metallurgy of HTL process
	  – Currently operating HTL in stainless steel. This may not be the best metal to use.
	• Systems integration in wastewater plants is not well understood
	• Lack of understanding of HTL conversion efficiencies and products that recycle residual nutrients for alternative feedstocks
	• Lack of detailed, national-scale assessment of opportunities for co-locating HTL to convert multiple/blended feedstocks (biomass spatial/temperature)
	• Model of HTL process for resource assessment

HTL Oil Products	• Biocrude upgrading to fuels • Making transportation quality fuels is challenging • Poor oil quality compared to traditional hydrocarbon feedstocks • Limited awareness and experience of refiners with oil and how to process • HTL oil is commonly grouped with pyrolysis oils, even though HTL oil is much higher quality – Bio-oil quality (C:N ratio; downstream catalyst stability of hydro-treatment)

Non-Oil Products	• Handling of effluent water has not been determined
	• Aqueous phase – N,P sink in WWT facilities (i.e., non-carbon)
	• Lack of understanding of opportunities for nutrient and metals recovery (e.g., anything interesting/significant)
	• Separation technologies targeted to concentrate convertible fraction
	• Aqueous/nutrient recycle-reuse
	  – Nutrient trading could provide additional revenue
	• Effect of contaminants and their fate in the process
	• Inorganic content in feed, removal during HTL process and handling inorganics
	  – Uncertainties in metals handling and disposition

4.2 Priorities for Advancement

High-priority topics, as determined by participant voting, are described below; further details may be found in Appendix D. The full list of activities receiving votes is provided in Table 4.2.

Identify and reduce regulatory barriers to improve technical acceptance by the marketplace (12 votes). The highest-priority HTL activity identified is to provide for a greater technical understanding of the HTL process by regulators, industry, and consumers. This activity should include developing an understanding of existing regulatory barriers and hurdles and working with agencies to update guidelines accordingly. If successful, this effort could reduce regulatory challenges for HTL scale-up and deployment.

Manage moisture by blending with dry biomass (8 votes). HTL is amenable to blending solutions, and blending may offer a viable way to actively manage feedstock variability and uncertainty to lower costs and attain a more consistent yield. However, additional research is needed to better understand the conversion performance of different feedstock blends as well as the quality and quantity impacts for enterprise-level scale-up. If successful, this effort could greatly improve the return on investment for this technology.

Optimize macro process improvements (8 votes). An integrated process analysis and optimization of HTL—including everything from sludge to fuel and resource recovery—should help to optimize cost, environmental considerations, yield, and equipment during scale up. These efforts should also expedite industry progress toward profitability and sustainability. The results of this analysis can help stakeholders at all levels to more readily accept and adopt the technology.

Develop economic usage of non-oil HTL effluent streams (7 votes). Identifying and validating viable solutions for nutrient recycling will enhance process economics. Validation should cover large-scale deployment, separation of toxic components, and measurement of the recovered nutrient value. If successful, this effort could prove the profitability of the nutrient recovery process.

Table 4.2. Identified HTL Process Advancement Activities

Process Operations	
High Priority	• Identify and reduce regulatory barriers to improve technical acceptance by the marketplace ●●●●●●●●●●●● (12) – Correct misperceptions (regulations and beyond) – Identify hurdles and work with other agencies; update guidelines • Manage moisture by blending with dry biomass ●●●●●●●● (8) – Identify alternative feedstock for blending with algae prior to HTL, as algae production varies seasonally in output (more in summer) – Develop methodology for determining design capacity of facilities (base on peak production or some percentage of peak?) • Optimize macro process improvements ●●●●●●●● (8) – Macro process improvement/total system optimization analysis – Optimization considering: ▪ Cost ▪ Environment ▪ Yield ▪ Large system models ▪ Understanding how components interact at multiple scales • Develop economic usage of non-oil HTL effluent streams ●●●●●●● (7) – Validate nutrient recycle – In aqueous phase, understand the fate of heteroatoms and inorganics
Medium Priority	• Enable small- / large-scale distributed upgrade ●●●●●● (6) – Optimize location of HTL systems relative to feedstock logistics • Reduce feedstock volumes by removing diluents in pretreatment (i.e., water) ●●●● (4) • Increase organic solids loading/throughput ●●● (3) • Integrate with cogeneration technology ●● (2) – Improve energy balance (power, heat, pressure)
Low Priority	• Improve extended storage method for wet biomass ● (1) • Champion people who are making progress/highlight accomplishments (0) • Demonstrate potential use of produced solids as soil amendments (0)

● = 1 priority vote

5. Other Conversion Technologies

The breakout group focusing on Other Conversion Technologies discussed waste-to-fuels conversion routes and product technologies *other than* anaerobic digestion and hydrothermal liquefaction. The identified technologies fell naturally into four broad categories: pre-processing, thermochemical conversion, biological conversion, and miscellaneous (Table 5.1). The pre-processing category includes better characterizing the feedstock, reducing moisture and impurities, and blending with other biomass streams—all in the interest of better defining and improving the feedstock stream. This focus was ultimately prioritized as a key area of research in the pathway to commercialization. The identified thermochemical processes include gasification, pyrolysis, and assorted other catalytic processes. Biological processes encompass all manner of organisms and pathways to make fuels or chemicals. The "Other" category includes hybrid biological and thermochemical processes as well as electrochemical systems.

Table 5.1 Other Conversion Technologies for WTE

Pre-Processing	Thermochemical Conversion	Biological Conversion	Miscellaneous
• Technologies for blending biomass feedstocks (MSW and other solid wastes blended with wet waste) to lower costs and increase efficiency during conversion to biofuels • Remediation of siloxanes • Improved sorting technologies (organic/non-organic) for MSW and other wastes • Separation/concentration of solids for thermochemical conversion processes - Moisture reduction	• Aqueous-phase reforming via catalytic transformations – Not hydrothermal catalysis (HTC) but still catalytic • Catalytic deploymeriza-tion (low-temperature, low-pressure, to separate remaining hydrocarbon material from the waste) • Pyrolysis • Gasification – Plasma gasification – Co-gasification of wet wastes with solid feedstocks (biomass, coal, pet coke, etc.) – Catalytic hydrothermal gasification (wet gasification)	• Biological CO_2 → C_xH_y (higher hydrocarbons) • Fermentation technologies - Syngas as feedstock - Fungi - Bacteria (non-AD) • Partial microbial digestion (stop AD early to get acids, H_2) • Algal fuel production	• Microbial electrochemical systems (MxCs) configured for chemical/fuel production (typically low energy requirement) • Novel combinations of technologies (e.g., anaerobic membrane bioreactors and microbial fuel cells [AnMBR+ MFC] or methanotrophs [prokaryotes that can metabolize methane]) • Bolt-ons to anaerobic digestion (post processing)

5.1 Technical Barriers

Some technical barriers currently preventing commercialization of WTE technologies are broadly applicable, while others are specific to a single technology. The first set of process barriers includes issues in identifying, sourcing, and transporting large quantities of wet waste feedstocks. The second set focuses on the need to better understand, anticipate, and limit variability in waste feedstocks. Some of the more extreme anecdotal variations in feedstock content include a dead coyote and an entire couch—highlighting some of the challenges to industrially processing these waste streams. Waste streams also present unique material challenges regarding storage, processing, and end use, all of which require further research. Downstream from the conversion processes, barriers include effluent management, market certification, and the inability to adjustably produce a suite of high-value products/fuels as market conditions change. Outside of these broad categories, other technical challenges include right-sizing of the equipment, scaling up processes, maintaining a positive energy balance regardless of high moisture, and integrating these technologies into an existing waste handling ecosystem.

Table 5.2. Technical Barriers to Other Conversion Technologies for Wet Waste Feedstocks

Wet Waste Resources	• Lack of cost competitiveness with other waste feedstocks for conversion—particularly MSW (need to justify to tax payers) • Time constraints on handling a resource (waste) that is liable to become putrid (logistics) • Unique transport challenges • Low organic content of the feedstock (quality) • Small scale – For gasification: Lack of fuels synthesis processes efficient enough to be cost effective at biomass/waste scales
Waste Stream Variability	• Variability in waste stream • Effects of impurities on process efficiency, catalysts, structural materials • Uncharacterized wastes and surprises • Challenge involved in sorting unknown substances – Need for sorting, processing, shredding, and drying to somewhat homogenize feedstock input • Lack of organism tolerance of impurities

Materials Issues	• Needs for materials of construction vary by process and composition of the feedstock (exacerbated by waste stream variability)
	• Need for more durable yet affordable materials, based on highly corrosive nature of waste liquid fuel and feedstocks
	  – Storage
	  – Processing
	  – End use (engines)
	• MxC; need supply of robust, cheap electrodes

Process Output Barriers	• Challenges in managing process effluent (post processing) • Challenges in producing intermediates and products at required levels of quality • Fuel/product certification • Deleterious effects of impurities • Finding uses or markets for output: process intermediate collection, separation, upgrading, and storage – Catalytic conversion

	– Pressurization – Utilization • Need for better separation of products into different process streams • Narrow product distribution and difficulties in marketing variety of products at small scale - Need to replace the whole barrel/look at fuel additives and nonfuels
Miscellaneous	• Lack of technology to enable use of the feedstock without dewatering • Need to right-size the scale (modularity) – Capital costs and economic scale of conversion processes versus scale of feedstock availability – Capital cost and required scale – Lack of scalable wet waste feed systems • Difficulty in scaling up some biological processes while maintaining lab-scale efficiency/yields (exception: gas fermentation) • High moisture works against a good energy balance (for thermal conversion technologies) • Need compositional experiments and analysis for blending waste/MSW and other feedstocks for low-cost formulation • Lack of process integration and intensification processes for better thermal efficiency – Utilization vs. treatment – New facilities or add-on – Gasification of MSW: warm gas cleanup and process intensification (e.g., S, Cl) – Lack of cross-sector sharing of expertise • Technology/application falls between traditional “stove pipes”/stakeholders (e.g., energy recovery vs. environmental engineering vs. wastewater treatment perspectives) • Need to develop catalysts for wet waste conversion processes – Organisms – Homogeneous & heterogeneous catalysts

5.2 Priorities for Advancement

High-priority topics, as determined by participant voting, are described below; further details may be found in Appendix D. The full list of activities receiving votes is provided in Table 5.3.

Conduct R&D on biological and thermo-catalytic conversion technologies for pre-processed waste biomass (10 votes). The highest priority pathway is to research and develop conversion technologies, either biological or thermos-catalytic, that could be applied to pre-processed waste. Applied research would address issues of organismal robustness, durability, yield, and selectivity. If successful, this thrust would yield higher-value, targeted product profiles more quickly than AD. Within 20 years, this technology is expected to be ready for widespread commercialization.

Conduct techno-economic analysis (7 votes). Analysis efforts to assess barriers and opportunities are next in priority. Chief among these efforts would be techno-economic analyses of the potential conversion pathways. A greater understanding of the economic and technical variables of a process would help strategically direct ongoing R&D and limit the need for large numbers of scale-up activities. In addition, these models would be refined as research progresses, leading to better agreement between the model and actual process outcomes in terms of emissions, costs, and revenues.

Demonstrate and deploy preprocessing and pretreatment technologies (6 votes). Late-stage development and deployment of preprocessing and pretreatment technologies would enhance methane conversion (AD). This activity would seek to integrate other waste streams and reduce facility size. The work targets biogas output concentrations as high as 75% methane. A key objective is to achieve broad domestic acceptance of proven technologies that were developed or are now in use elsewhere, predominantly Europe. Because of the near-commercial status of these technologies, this work is viewed as an activity that can be completed in the near term.

Support scale-up of technologies (6 votes). Scale-up activities are essential to the commercialization of wet waste-to-energy technologies. Participants at the workshop identified a number of technologies ready for scale-up. As an illustrative example, one technology considered ready for pilot-scale demonstration would process (cow) manure into diesel at a rate of 1 bone-dry ton per day. At a 300-cow farm, such a plant would produce 20,000-30,000 gallons per year; a tenfold scale-up is projected to cost $3.5 million. This plant would also create multiple value streams (fuel, fertilizer, and potable water) and avoid environmental runoff.

Improve process monitoring and control to handle highly variable feed streams (6 votes). Developing robust process controls that take advantage of novel WTE technologies would increase production from highly variable, non-homogeneous inputs. Much of this work will involve correlating operating parameters and sensors with real-world operations. Central to the development and scale-up of these novel technologies will be the establishment of long-term pilot runs, which enable factor analyses to assess the impacts of process conditions on yield and cost. Once developed, improved process monitoring and control technologies should increase yield by 10% and reduce costs by the same factor.

Table 5.3. Identified Advancement Activities for Other Wet Waste Conversion Technologies[7]

Process Operations	
High Priority	• Improve process monitoring and control to handle highly variable feed streams ●●●●●● – Better understand how feedstock variability affects process – Determine which parameters are most important – Develop effective on-line monitoring – Improve organism robustness • Support scale-up of technologies ●●●●●● – Validate manure- and food waste-to-diesel processes – Modeled on-farm system in California – Research: Scale and water content – Gasification makes syngas, which can potentially make aviation fuel – Define bottoms-up local case studies to focus on the feasibility/validation of “other” processes by forming success templates (~$100K activities) and/or pilots (~$1M activities) – Vermont has a project exploring manure as growth medium for oil-producing algae
Medium Priority	• Use process waste heat for dewatering ●●●

[7] Identified activities that received no votes were excluded.

Low Priority	• Identify and characterize sources of variation ●● • Identify and use existing, under-used facilities ●● • Conduct R&D on process intensification and integration ● • Collaborate with EERE's Advanced Manufacturing Office (AMO) to develop economies of scale for modular mass production ● • Modify reactor design ●
Feedstock Related	
High Priority	• Demonstrate and deploy preprocessing and pretreatment technologies ●●●●●●

Medium Priority	• Develop processes for the upgrading of preliminary products into drop-in fuels ●●●●●
	  – Self-contained, small scale
	• Conduct testing and demonstrations using actual feedstocks (e.g., onsite slipstreams) ●●●●●
	• Aggregation of waste feedstocks ●●●●
	  – Pump manure from within a seven-mile radius
	  – Community effort; integration of all nearby biomass

Biology and Materials Based R&D	
High Priority	• Conduct metabolic engineering/synthetic biology to improve biocatalysts ●●●●●● • Develop catalysts; screen and test model systems using real waste feedstocks ●●●● [combined with previous as *Conduct R&D on biological and thermo-catalytic conversion technologies for pre-processed waste biomass*]
Medium Priority	• Develop process for biological (or other) conversion of very high-moisture feedstocks (without dewatering) to common intermediate for conversion (sugar, acetate, H_2/CO_2, CH_4) ●●●●● - Aqueous phase reactions
Low Priority	• Develop novel sorbents for CO_2 removal, emphasizing ease of regeneration ● – Application of waste from fossil-based technologies • Identify novel electrode-electrolyte combinations for microbial electrochemical systems ●
Analysis Efforts	
High Priority	• Conduct techno-economic analysis /system integration analysis ●●●●●●●

Low Priority	• For materials issues, conduct studies to identify most suitable and low-cost material for each environment ●●
	• Identify high-resolution (e.g., 30 m.) geo-spatial and temporal (e.g., temperature, weather risk) tools to assess biorefinery sites, risks, and markets ●●
	• Analyze lessons learned in conversion technology development efforts of past decades and identify what is different today ●●
	  – Understanding the root causes of technology/commercialization failure
	• Conduct nationwide mapping of wastes/MSW, etc. (resource assessment, impacts and conversion pathways) ●
	• Study market geographies: See where customers, waste, and capabilities are co-located ●
	• Develop methodology to characterize variability ●
	  – Feedstock characterization

● = 1 priority vote

Appendix A: Workshop Attendees

Last Name	First Name	Organization	Breakout Group
Altman	Richard	Commercial Aviation Alternative Fuels Initiative	Other
Atwood	Matt	Algae Systems	HTL
Babson	David	U.S. Environmental Protection Agency	AD 2
Bingold	Jerry	Innovation Center for U.S. Dairy	AD 2
Biron	Remy	BCS Incorporated	HTL
Bohutskyi	Pavlo	Johns Hopkins University	AD 1
Campbell	Todd	USDA	HTL
Conrado	Robert	LanzaTech, Inc	Other
Costa	Allison	US EPA	AD 2
Craig	Kevin	US Department of Energy	HTL
Csonka	Steve	CAAFI (Commercial Aviation Alternative Fuels Initiative)	HTL
Davis	Wayne	Harvest Power, Inc.	AD 1
Dayton	David	RTI International	Other
Donnelly	Paget	Energetics Incorporated	Other
Drennan	Corinne	Pacific Northwest National Laboratory	Other
Drown	Peter	ALQIMI Technology Solutions, Inc.	Other
Duffield	James	USDA	HTL
Dunn	Jennifer	Argonne National Laboratory	HTL
Dvorak	Stephen	DVO, Inc.	AD 2
Elliott	Douglas	Pacific Northwest National Laboratory	HTL
Fillmore	Lauren	Water Environment Research Foundation	AD 1
Fisher	Aaron	Energetics, Inc	Other
Fitzgerald	Jay	Bioenergy Technologies Office	Other
Guerami	Behrouz	TANZICO	Other
Han	Jeongwoo	Argonne National Laboratory	Other
Haynes	Chad	Booz Allen Hamilton/DOE ARPA-E	AD 1
He	Qiang	University of Tennessee	AD 1
Heitkamp	Michael	Savannah River National Laboratory	AD 1
Herzfeld	Jenny	Energetics Incorporated	AD 2
Hess	J Richard	Idaho National Laboratory	HTL
Hornback	Chris	NACWA	AD 1
Justiniano	Mauricio	Energetics Incorporated	AD 1
Keiser	James	Oak Ridge National Laboratory	Other
Keleman	Michael	InSinkErator	AD 2
Kerester	Alison	Gasification Technologies Council	Other
Kester	Greg	California Association of Sanitation Agencies	AD 1
Levine	Elliott	US DOE	AD 1
Liang	Yanna	Southern Illinois University Carbondale	HTL
Liu	Yanjin	American Water	AD 1
Makila	Tommi	Energetics Incorporated	AD 2
Mantri	Vishakh	Energy Information Administration	AD 2
Marks	Howard	Energetics, Inc.	N/A
Massello	Rebecca	Energetics Incorporated	HTL
McAdams	Callie	Informa Economics	AD 2
McDonald	Norma	Organic Waste Systems, Inc.	AD 2
McElroy	Rob	Algae Systems	HTL

Last Name	First Name	Organization	Breakout Group
McFadden	Lisa	Water Environment Federation	AD 1
McKiernan	Christine	BIOFem Energy Systems	AD 2
Moriarty	Kristi	National Renewable Energy Laboratory (NREL)	AD 2
Oyler	James	Genifuel Corporation	HTL
Peot	Chris	District of Columbia Water and Sewer Authority	HTL
Perla	Donna	Office of Research and Development, US EPA	AD 1
Pezzullo	Leslie	DOE - BETO	AD 1
Philbrick	Mark	Department of Energy	Other
Pomerening	Joseph	US Department of Energy	N/A
Rice	Elizabeth	Gershman, Brickner & Bratton, Inc.	Other
Richardson	Grace	US EPA	HTL
Rogers	Jonathan	Energetics Incorporated	AD 1
Saydah	Benjamin	Sapphire Energy	HTL
Scanlan	Trish	Black and Veatch	HTL
Schleifer	Jackob	Plan It Green /Sustainable Energy Development LLC	AD 2
Schottel	Brandi	National Science Foundation-CBET Division	AD 2
Schuppenhauer	Michael	Farmatic Inc.	AD 2
Schwab	Amy	National Renewable Energy Laboratory (NREL)	Other
Searcy	Erin	Idaho National Lab	AD 2
Serfass	Patrick	American Biogas Council	AD 2
Shelton	Tim	Arcadis	Other
Singh	Seema	Joint BioEnergy Institute/Sandia National Laboratories	AD 2
Skaggs	Richard	PNNL	HTL
Snyder	Seth	Argonne National Laboratory	AD 1
Spaeth	James	U.S. Department of Energy	HTL
Stokes	Bryce	CNJV	N/A
Stolark	Jessie	Environmental and Energy Study Institute	AD 2
Studer	Sarah	ORISE Fellow at DOE	Other
Tagore	Sam	US Department of Energy	Other
Tamm	Yannick	Energetics Incorporated	HTL
Tao	Ling	National Bioenergy Center/National Renewable Energy Laboratory	AD 1
Thompson	Vicki	Idaho National Laboratory	Other
Turgeon	Jason	US EPA Region 1	AD 1
Turick	Charles	Savannah River National Laboratory	AD 2
Tyler	Cynthia	US Department of Energy	AD 2
Urgun-Demirtas	Meltem	Argonne National Laboratory	AD 1
Welch-White	Venus	USDA/ Energy Division	AD 2
Wilson	W. Patrick	The Babcock & Wilcox Company	Other
Wu	May	Argonne National Laboratory	AD 2

AD 1- Anaerobic Digestion of Wastewater Residuals and Biosolids
AD 2- Anaerobic Digestion of Foodstuffs and Other Municipal Solid Waste
HTL- Hydrothermal Liquefaction of Wet Waste
Other- Other Conversion Processes of Wet Waste

Appendix B: Acronyms

AD	Anaerobic digestion
AnMBR	Anaerobic membrane bioreactor
AMO	Advanced Manufacturing Office in EERE/DOE
BETO	Bioenergy Technologies Office
C	Carbon
CAPEX	Capital expenditure
CASA	California Association of Sanitation Agencies
CNG	Compressed natural gas
DOE	U.S. Department of Energy
EPA	Environmental Protection Agency
EROI	Energy return on investment
GTL	Gas-to-liquids conversion
H	Hydrogen
HRT	Hydraulic retention time
HSW	High-strength waste
HTC	Hydrothermal catalysis
HTL	Hydrothermal liquefaction
IRR	Internal rate of return
LCA	Life-cycle analysis
MMBtu	Million British thermal unit
MFC	Microbial fuel cell
MRF	Mixed refuse facility
MxC	Microbial electrochemical cell
MSW	Municipal solid waste
N	Nitrogen
NACWA	National Association of Clean Water Agencies
NPV	Net present value
ROI	Return on investment
SOP	Standard operating procedure
SWANA	Solid Waste Association of North America
TEA	Techno-economic analysis
USDA	U.S. Department of Agriculture
W3170	Working Group on the Beneficial Reuse of Residuals and Reclaimed Water
WEF	Water Environment Federation
WERF	Water Environment Research Foundation
WWT	Wastewater treatment

Appendix C: Meeting Agenda

Day 1: November 5th	
Time	**Activity**
7:30-8:30 am	Registration and Coffee
8:30 am	**Welcome and Opening Remarks**
8:45 am	**Bioenergy Technologies Office, Program Overview** ▪ Jonathan Male, BETO Director
9:15 am	**Technical Keynote** ▪ Patricia Scanlan, Black and Veatch, Director of Residuals Treatment Technologies
10:00 am	**Charge to Breakouts**
10:10 am	Break
10:30 am	**Breakout Session I** : **State of Technology and Major Technical Barriers** Four Breakout Groups: ▪ Anaerobic Digestion of Wastewater Residuals and Biosolids ▪ Anaerobic Digestion of Foodstuffs and Other Organic Municipal Solid Waste ▪ Hydrothermal Liquefaction of Wet Waste ▪ Other Conversion Processes of Wet Waste
12:00 pm	Lunch *(Deli Buffet)*
1:00 pm	**Breakout Session II: Technology Development Priorities and Metrics** *(same groups)*
2:25 pm	Break
2:40 pm	**Breakout Session III: Roadmap Worksheets** *(same groups)*
4:00 pm	Break and Transition to Main Room
4:25 pm	**Breakout Session Reports**
5:00 pm	Adjourn Day 1

Day 2: November 6th	
Time	**Activity**
8:30 am	Depart Hotel – Meet in Lower Lobby
9:00-11:00 am	Offsite Tour of Blue Plains Wastewater Treatment Facility
11:30 am	Arrive Back at Hotel

Appendix D: Advancement Activity Worksheets

Note: Numerical targets reflect the views of participants and not necessarily those of BETO.

Worksheet D-1.1: Improve Understanding/Real-Time Monitoring of Microbial Anaerobic Processes

High-Impact Technology Scenario

Increase the scientific understanding of microbial systems through the development of real-time biosensors for anaerobic processes

Value Proposition

Higher efficiency and more diversified products, lower GHGs, increased sustainability, and improved economics.

Barriers

	Cost Reduction	Performance Improvement
R&D	• Lack of scientific understanding • Lack of effective, real-time biosensors	• Inability to control and optimize process
Deployment and Scale-up	• Currently non-optimized system design and operation • Resistance to capital investment, low ROI	None reported

Technology Maturity Level

Basic/Fundamental, Applied R&D

Market Entry

None reported

	Advancement Activities	Interim Milestones	Overarching Targets
Immediate (<5 yrs)	• Increase scientific understanding of mixed microbial cultures • Identify key useful/desirable organisms • Identify microorganisms to avoid/control	• Understand key microbial components • Link microbes to process performance • Understand carbon and energy flow	None reported
Near-Term (5-20 yrs)	• Develop real-time bio-sensors to monitor microbial populations • Develop early warning system/controls • Optimize microbial consortia and performance	• Increase microbial resistance to fluctuations and process conditions • Increase process robustness for handling different feedstocks, pretreatment, etc. • Develop real-time process control for proactive response/preventive actions	
Long-Term (>20 yrs)	• Optimize engineering design and facility configuration • Develop ability to customize direction of carbon and energy flows • Expand technology for use of unconventional feedstocks (e.g., dilute organic waste)	• Make process more efficient, robust, and economical • Develop capability to produce multiple value-added compounds • Create paradigm shift for WWT plants beyond energy recovery toward valuable biorefineries	

Factor	Impact	Reasoning
Process yield	High	AD configuration not optimized; new technology will improve efficiency
Output quality	Medium	None reported
Reliability	High	None reported
Technology validation	High	None reported
Cost reduction	High	None reported
Ease of market adoption	5.5/10 Hard/Easy	None reported

Key Stakeholders

- **Technology Development:** Academia, national labs, and industry
- **Technology Deployment:** Industry and wastewater treatment (WWT) plant operators
- **Validation and Testing:** None reported
- **Regulatory:** None reported

Worksheet D-1.2: Configure New Bioreactor for Enhanced AD and Higher Process Efficiency

High-Impact Technology Scenario

Improve environmental and technical performance via shorter retention times; improve gas quality, energy yield, and digestion rates to make AD cheaper, smaller, better, and faster

Value Proposition

- More efficient AD design; less fugitive methane emissions
- Smaller and faster = cheaper
- Better gas yield of solids destruction = cheaper

Barriers

	Cost Reduction	Performance Improvement
R&D	• Hydraulic decoupling from solids • Addition of adsorbents/ divalents for gas cleanup	• Need to shrink digester size • Need to improve gas quality before separation • Need to improve total solids digestion
Deployment and Scale-up	• Lack of long-term feed-stock performance analysis • Quality of digestate • Digester stability over long term	• Lack of basic research • Lack of common performance metrics • Lack of understanding of ultimate performance related to substrate, cultures, and conditions

Technology Maturity Level

Applied R&D

Market Entry

Decentralized waste treatment

Advancement Activities / Interim Milestones / Overarching Targets

	Advancement Activities	Interim Milestones
Immediate (<5 yrs)	• Develop basic metrics to compare AD improvements • Benchmark materials-feedstocks, absorbents • Fully understand all HRT-SRT decoupling technologies	• Metrics developed and published • Gas from existing digesters is close to pipeline quality • Feedstocks are well understood; digesters can quickly be optimized for specific mixtures
Near-term (5-20 yrs)	• Develop AD as go-to method to handle all wet, heterogeneous carbon feedstocks economically with high-rate, high-quality end products	• Yield of substrate energy content 70-90% • Concentrated wastewater can rapidly be treated for discharge or reuse/system shrunk to size suitable for decentralized application • Solids suitable for land application as fertilizer
Long-term (>20 yrs)	None reported	None reported

Overarching Targets

Technology/ Performance:

- Small, fast, cheap, highly efficient, highly automated digesters suitable for decentralized treatment at a range of scales.

Installed Cost Targets:

Initial deployment cost:

- 30-50% of current costs

Cost at scale:

- 10-25% of current costs on an MMBtu basis

Factor	Impact	Reasoning
Process yield	High	To improve yield
Output quality	High	To improve quality
Reliability	High	To improve reliability
Technology validation	Medium	Some technology exists at bench scale
Cost reduction	High	To reduce capital, increase revenue; avoid post-treatment processing
Ease of market adoption	8.5/10 Hard ↔ Easy	Market is eager; this does not require reinventing the wheel.

Key Stakeholders

- **Technology Development:** DOE and national labs, EPA, NSF, USDA, private firms, academia
- **Technology Deployment:** USDA, EPA, private firms, existing WWT incumbents
- **Validation and Testing:** Federal agencies and utilities of national labs
- **Regulatory:** Minimal: regulations exist, just need to optimize processes. EPA is principal regulator

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Worksheet D-1.3: Design a Lifecycle Systems Approach That Includes Feedstocks and Biosolids, Conversion Technologies, and End Use Products

High-Impact Technology Scenario

Quantify biogas production, energy balance, and carbon sequestration from wastewater sludge; reduce greenhouse gas (GHG) emissions from co-digestion diverted from landfills; calculate the economic, GHG, and resource conservation benefits of biosolids as fertilizers

Value Proposition

Enhanced understanding of the economic viability, energy efficiency, and sustainability of various anaerobic digestion technologies and processes for the production of liquid transportation fuels and value-added byproducts.

Barriers

	Cost Reduction	Performance Improvement
R&D	• Need to quantify biogas production and carbon sequestration from biosolids applications • Lack of cost-effective conversions	None reported
Deployment and Scale-up	• Lack of economic models that enable pathway comparisons • Lack of LCAs that analyze GHGs, net energy, and water footprints	None reported

Technology Maturity Level

None reported

Market Entry

None reported

	Advancement Activities	Interim Milestones
Immediate (<5 yrs)	• Leverage existing knowledge and resources from federal, state, local, industry, university efforts – Including economic models, LCAs, technology assessments (e.g., BEAM-Canada, GREET, SimaPro), resiliency foods (e.g., wheat), sustainable community management tools	None reported
Near-Term (5-20 yrs)	• Define metrics meaningful to WWT plants (existing resources from other entities, e.g., WEF, WERF, EPA, DOE, CASA, USDA, etc.) • Identify data available and quality needed for metrics and LCAs	None Reported
Long-Term (>20 yrs)	• Frame economic analyses that demonstrate WWT plants as resource recovery facilities • Develop markets for recovered resources	None reported

Overarching Targets

Technology/ Performance:

- Quantify biogas production and carbon sequestration from biosolids applications
- ↓ GHG from co-digest diverted from landfills
- Assess nutrient recovery efficiencies in biosolids and side streams
- Calculate economics, GHG, and resource conservation benefits of land applied biosolids and recovery of nutrients
- Btu input/Btu output

Installed Cost Targets

Initial deployment cost:

- Expected return on investment based upon prevailing economic conditions

Cost at scale:

- Economic comparisons for onsite power vs. CNG and liquid transportation fuels
- GHG comparisons for onsite power vs. CNG and liquid transportation fuels

Factor	Impact	Reasoning
Process yield		Avoid GHG costs of fossil-based fertilizers
Output quality		Improve resiliency of facility
Reliability		Reduce capital cost for facility and create revenue
Technology validation		
Cost reduction		
Ease of market adoption		

Key Stakeholders

- **Technology Development:** CASA, WEF, WERF, EPA, NACWA, W3170, others
- **Deployment:** Fertilizer industry interested in nutrient recovery
- **Validation and Testing:** None reported
- **Regulatory:** None reported

WORKSHEET D-1.4: CHARACTERIZATION OF FEEDSTOCK AND CO-DIGESTION

HIGH-IMPACT TECHNOLOGY SCENARIO

Prepare guidance on the relationship of organic feedstock characteristics to digester performance and biogas production

VALUE PROPOSITION

Existing AD equipment is overdesigned and underutilized; therefore, co-digestion of food and high-strength waste (HSW) with wastewater solids produces anaerobic digester process synergy

BARRIERS

	Cost Reduction	Performance Improvement
R&D	• Synthesis of impacts of feedstock characteristics on AD performance – need standardized metrics, understanding of relationship to performance attributes – data library	• Understanding of C/N ratios, trace nutrients, energy content to enable operations decision making
Deployment and Scale-up	• Collection area size adequate to optimize feedstock characteristics • Implementation tools (guidelines, software) to enable plant-specific application	• Pilot-scale demonstration and validation of tool

TECHNOLOGY MATURITY LEVEL

Applied R&D

MARKET ENTRY

- Domestic wastewater sector and food waste sector.
- Ag sector and misc. organic wastes, ranging from biodiesel to airports (e.g., spent deicing fluid)

ADVANCEMENT ACTIVITIES / INTERIM MILESTONES / OVERARCHING TARGETS

	Advancement Activities	Interim Milestones
Immediate (<5 yrs)	• This can be done in five years • Aggregate literature on co-digestion • Fund development of relational database that utilizes these relationships to create decision tool/software • Conduct elective pilot studies to fill data gaps	• Improved digester performance and biogas yield • Reduced risk of AD operational upset or failure • Better utilization of energy imbedded in organic food waste
Near-term (5-20 yrs)	None reported	None reported
Long-term (>20yrs)	None reported	None reported

Overarching Targets

Technology/ Performance:

- Greater 1 m^3 biogas/1 m^3 AD capacity/day (Europe averages up to 2.3 m^3 /1 m^3 AD capacity/day)

Installed Cost Targets

Initial deployment cost:

- Nationwide product/program—initial cost less than $1 million

Cost at scale:

- Nationwide—not a site-specific cost

FACTOR	IMPACT	REASONING
Process yield	High	High biogas yield
Output quality	Medium	Dilutes effect of siloxanes in biosolids
Reliability	High	Improves reliability and minimizes uncertainty
Technology validation	NA	NA – a decision making tool
Cost reduction	High	Up to 250% increase in biogas yield
Ease of market adoption	9/10 Hard ↔ Easy	Easy to create, need to market its use

KEY STAKEHOLDERS

- **Technology Development:** Must be open source, can be any stakeholder group (e.g., industry, government, academia, etc.)
- **Technology Deployment:** Wastewater sector, consultants, government facility operations, food waste/HSW handlers operators
- **Validation and Testing:** Government labs, NGO, NF profit research organization, wastewater sector/industry
- **Regulatory:** Coordination with EPA, state regulations

Disclaimer: Numerical targets reflect the views of participants, and are not necessarily those of BETO

Worksheet D-2.1: Producing AD End Products Beyond Methane, Methanol, and Ethanol

High-Impact Technology Scenario

Develop technologies that are able to produce end products beyond CH4, methanol, and ethanol through anaerobic digestion

Value Proposition

Gas to liquid (diesel) offers greater compatibility with existing infrastructure and engines (higher value)

Barriers

	Cost Reduction	Performance Improvement
R&D	• Biological – productivity • Catalytic – selectivity	None reported
Deployment and Scale-up	• Downsizing existing technology, AD is distributed (need smaller efficient GTL)	None reported

Technology Maturity Level

None reported

Market Entry

- Diesel, jet fuel, gasoline
- Secondary market: Dimethyl ether (DME), or hydrogen

Advancement Activities / Interim Milestones / Overarching Targets

	Advancement Activities	Interim Milestones	Overarching Targets
Immediate (<5 yrs)	• Identify start-ups and technologies capable of performing small-scale GTL • Identify potential bio-based feedstocks from digestate and other process co-products • Select viable technology and products pursue/optimize • Pilot demonstration	• Identify catalytic biogas to liquid fuel pathways for diesel, jet fuel, gasoline feedstock • Identify biological routes to useful intermediates/fuels other than CH_4/CO_2 (think biodiesel, efficient fuel/gasoline feedstock)	*Installed Cost Targets* Cost at scale: • $3 per gallon
Near-term (5-20 yrs)	• Study supply chain/sustainability analysis relative to biomass waste distribution (regional analysis) and fuel demand • Technology development: testing to deployment	None reported	
Long-term (>20 yrs)	• Greater deployment, integration to optimization within fuel distribution system	None reported	

Factor	Impact	Reasoning
Process yield	None reported	
Output quality		
Reliability		
Technology validation		
Cost reduction		
Ease of market adoption		

Key Stakeholders

None reported

Disclaimer: Numerical targets reflect the views of participants, and are not necessarily those of BETO

WORKSHEET D-2.2: ROBUST DIGESTER DESIGN TO HANDLE WIDE VARIABILITY OF FEEDSTOCK

HIGH-IMPACT TECHNOLOGY SCENARIO

Design robust digester system to handle various feedstocks and high-solids waste streams

VALUE PROPOSITION

Increased capacity, more resiliency to upset, optimized for CH_4 production

BARRIERS

	Cost Reduction	Performance Improvement
R&D	• Lack of modeling of AD performance based on multiple feedstocks	• Lack of sensors to test for specific parameters; volatile acids, alkalinity
Deployment and Scale-up	• Issues in pumpability of high solids, higher energy costs	• What is the goal for "optimized" performance based on the feedstocks?

TECHNOLOGY MATURITY LEVEL

Basic/Fundamental, Applied R&D, or Prototype (Based on Various Feedstocks)

MARKET ENTRY

None reported

	ADVANCEMENT ACTIVITIES	INTERIM MILESTONES
IMMEDIATE (<5 YRS)	• Identify specific parameter to monitor performance for stability • Develop sensor systems • Data collection from operational systems • Determine optimized conditions for model	• Modeling tool • Deploy, test, and validate tool • Database of operational data
NEAR-TERM (5-20 YRS)	None reported	None reported
LONG-TERM (>20 YRS)	None reported	None reported

OVERARCHING TARGETS

Technology/ Performance:

- Benchmarking of various AD designs
- Yield optimization
- Cost reduction
- Decreased failure rate

Installed Cost Targets

Initial deployment cost:

- $500,000

Cost at scale:

- $50,000

FACTOR	RELATIVE IMPACT	REASONING
Process yield	High	None reported
Output quality	High	None reported
Reliability	High	None reported
Technology validation	High	None reported
Cost reduction	Medium	None reported
Ease of market adoption	8/10 Difficult ↔ Easy	None reported

KEY STAKEHOLDERS

- **Technology Development:** Equipment suppliers, process integrators, engineers, and operators
- **Technology Deployment:** System designers and operators
- **Validation and Testing:** Trade associations, 3rd party SWANA, WERF
- **Regulatory:** EPA (data collection)

Disclaimer: Numerical targets reflect the views of participants, and are not necessarily those of BETO

Worksheet D-2.3: Develop Cheaper Gas Cleanup Technology that Works on Smaller Scale

High-Impact Technology Scenario

Develop biogas cleanup technology that costs less than $2/MMBtu, produces 50-500 standard cubic feet per minute (SCFM), yields greater than 95% biomethane, and provides long-term reliability to enable self-reliance, larger market, without limits by "big oil," utilities

Value Proposition

Self-reliant, larger market, and not limited by "big-oil" or utilities

Barriers

	Cost Reduction	Performance Improvement
R&D	• High hydrogen sulfide (H_2S) removal expense • High cost compressor and coverage	• Limited research at small scale • Limited research into physics of fuel compression and cold temperatures for transportation
Deployment and Scale-up	• Needs on-site engineering • No process to liquefy cost effectively	• No plug and play • Few small fleets aid

Technology Maturity Level

Near-commercial

Market Entry

System yields >90% biomethane

Advancement Activities / Interim Milestones / Overarching Targets

	Advancement Activities	Interim Milestones
Immediate (< 5 yrs)	• Third-party, side-by-side comparison of existing technologies, cost and performance, energy balance, reliability • Survey previous ideas, approaches, "near misses" • Identify "best of class" from each and why	• Technology and cost targets are confirmed • Build on, integrate best ideas, avoid reinventing wheel • Helps articulate research, potential hybrid approach
Near-term (5-20 yrs)	• Invent new compressor • Invent plug and play "skid" robust enough to cover the market	• Cheaper compression, improve ROR, ↓ $/MMBtu • Wide-scale deployment at largest facilities
Long-term (>20 yrs)	• Invent low-cost liquefaction • Invent new biomethane or biogas → other liquid fuel	• High fuel density on board with lower -cost fuels, increasing market • Increased displacement of fossil fuels, national security, independence

Overarching Targets

Technology/ Performance:

- >95% methane
- >98% availability and lifecycle >10 years
- Wide inlet gas composition range
- Wide volume (50-500 cfm) range

Installed Cost Targets

Initial deployment cost:

- < $4/MMBtu (biogas to biomethane CNG)

Cost at scale:

- < $2/MMBtu

Factor	Impact	Reasoning
Process yield	Low	Current is > 95%
Output quality	Low	Current is > 95%
Reliability – (5 years)	High	Current is < 70%
Technology validation	Medium	Only a few exist now
Cost reduction	High	Less than 25% of current
Ease of market adoption	8.5/10 Difficult ↔ Easy	Market is ready, cost is issue

Key Stakeholders

- **Technology Development:** Government – funding; academia and industry - development
- **Technology Deployment:** Industry – installation; Government and trade group - awareness
- **Validation and Testing:** Industry and technology operators
- **Regulatory:** Government – DOT, OSHA, etc.

Disclaimer: Numerical targets reflect the views of participants, and are not necessarily those of BETO

WORKSHEET D-2.4: ENABLE DIRECT CONVERSION TO HIGH-VALUE PRODUCTS INCLUDING FUEL INTERMEDIATES

HIGH-IMPACT TECHNOLOGY SCENARIO

Control and modify microbial processes to improve profitability and flexibility of the products and product types

VALUE PROPOSITION

Improves profitability via increased high-value products

BARRIERS

	Cost Reduction	Performance Improvement
R&D	• Segregation of various microbes and their metabolic processes • Cost and availability	• Estimation of process kinetics and metabolite monitoring
Deployment and Scale-up	• Extraction of products. May not scale effectively. Distribution and contact time harder to control.	• Temperature distribution and flow dynamics. Manipulation is difficult

TECHNOLOGY MATURITY LEVEL

Applied R&D

MARKET ENTRY

Diversified intermediate products (or end products) matching market volatility/fluctuations

	Advancement Activities	Interim Milestones	Overarching Targets
Immediate (<5 yrs)	• Government and academic research labs to investigate different metabolic processes with varying feedstocks • Determine product yields and economic feasibility • Examine co-cultures metabolic activity – review multiple product potential	• Validate yields for different feedstocks • Configure process for the pilot plant scale • Estimate costs for pilot plant scale	*Technology/ Performance:* • Functional at lab scale • Products meet market specifications • Pilot design and financing completed
Near-term (5-20 yrs)	• Market assessment (size and volatility) • Develop pilot plant, finance it, front-end design, and modeling tools • Pilot plant location, procure components	• Operate pilot plant 2,000 hours • Validate flexibility of process/ monitoring and control implementation • Finalize microbes/enzymes to be used	*Installed Cost Targets* Initial deployment cost: • Producing 90,000 barrels/day; positive net present value (NPV); 30% pretax internal rate of return (IRR)
Long-term (>20 yrs)	• Review adaptability to existing digestion technology • Design commercial facility/process controls/permits • Continuous process improvement	• Open commercial plant • Demonstrate profitable operations and sustainability	Cost at scale: • Products competitive with petrol-based production, 90% utilization of feedstock

Factor	Impact	Reasoning
Process yield	High	Multiple and flexible products
Output quality	High	Product meets specs
Reliability	High	Multiple products, continuous operations, meet various markets
Technology validation	High	Lab-pilots, commercial adjustments
Cost reduction	High	Competitive with petrol-based
Ease of market adoption	8.5/10 Hard ↔ Easy	30% pre-tax IRR

KEY STAKEHOLDERS

- **Technology Development:** Academia, government, industry
- **Technology Deployment:** Industry, government, trade groups
- **Validation and Testing:** Industry, government
- **Regulatory:** Government

Disclaimer: Numerical targets reflect the views of participants, and are not necessarily those of BETO

WORKSHEET D-3.1: MANAGE MOISTURE BY BLENDING WITH DRY BIOMASS

HIGH-IMPACT TECHNOLOGY SCENARIO

Explore blending solutions to economically manage the variability and uncertainty of wet waste for hydrothermal liquefaction (HTL)

VALUE PROPOSITION

HTL robustness gives more options to cost-effectively manage variability/ uncertainty of feedstocks

BARRIERS

	Cost Reduction	Performance Improvement
R&D	• Managing feedstock variability and uncertainty (quality, availability, supply security) within or cost envelope	• Conversion performance of feedstock blends
Deployment and Scale-up	• Right sizing HTL processing equipment with feedstock supply scale • HTL is amenable to blending solutions rather than advanced pre-processing	• Need to understand impacts of feedstock supply variability/ uncertainty (i.e., quality and quantity) at enterprise scales

TECHNOLOGY MATURITY LEVEL

Applied R&D, Prototype

MARKET ENTRY

Waste to energy/fuel as an integral part of the biomass-to-energy/fuels system

	ADVANCEMENT ACTIVITIES	INTERIM MILESTONES	OVERARCHING TARGETS
IMMEDIATE (<5 YRS)	• Feedstock characterization and performance metrics relative to product(s) • Blending and formulation against performance • Pre-processing and slurry technologies for individual and blending feedstocks	None reported	None reported
NEAR-TERM (5-20 YRS)	• Correlate detailed feedstocks characteristics with detailed characteristics of outputs (e.g., products, aqueous phase, solid phase, etc.)	None reported	
LONG-TERM (>20 YRS)	None reported	None reported	

FACTOR	IMPACT	REASONING
Process yield	None reported	
Output quality		
Reliability		
Technology validation		
Cost reduction		
Ease of market adoption		

KEY STAKEHOLDERS

None reported

WORKSHEET D-3.2: IDENTIFY AND REDUCE REGULATORY BARRIERS TO IMPROVE TECHNICAL/MARKET ACCEPTANCE

HIGH-IMPACT TECHNOLOGY SCENARIO

Technology implementation and early adoption in this field would benefit from revised regulation; develop technical basis for regulatory concerns

VALUE PROPOSITION

None reported

BARRIERS

	Cost Reduction	Performance Improvement
R&D	None reported	None reported
Deployment and Scale-up	• Lack of industry and consumer knowledge • Lack of definition in existing regulations → e.g., must be permitted as an incinerator to receive MSW	None reported

TECHNOLOGY MATURITY LEVEL

Applied R&D, Prototype

MARKET ENTRY

None reported

	ADVANCEMENT ACTIVITIES[8]	INTERIM MILESTONES	OVERARCHING TARGETS
IMMEDIATE (1-2 YRS)	• Determine existing regulatory barriers. Produce a Request for Information and conduct a workshop • Evaluate responses from this RFI and workshop and confirm with industry that these are, in fact, barriers • Present these barriers and technical information to the regulatory agencies	• Produce a white paper document that sums up the concerns	None reported
NEAR-TERM (2-5 YRS)	• Work with regulatory agencies to begin addressing these issues and to begin rulemaking • Identify and confirm certification requirements for a technology validation program	None reported	
LONG-TERM (>5 YRS)	• Change the ways that state and federal government communicate to address and overcome regulatory barriers	• Pass regulation that shows a defined and approved process for this pathway	

FACTOR	IMPACT	REASONING
Process yield		
Output quality		
Reliability		
Technology validation	High	None reported
Cost reduction	High	None reported
Ease of market adoption	7.5/10 Hard ↔ Easy	Regulation mitigates risk and uncertainty for investors

KEY STAKEHOLDERS

None reported

[8] Participants adjusted the timescales to 1-2 years, 2-5 years, and >5 years for their relevant advancement activities and milestones.

Worksheet D-3.3: Optimize Macro Process Improvements

High-Impact Technology Scenario

Enable technology developers to co-optimize/optimize cost, environmental performance, and fuel yield; Analyze HTL of wet-waste/biomass: integrated analysis of all HTL process unit operations (everything from sludge to fuel and resource recovery)

Value Proposition

- Wet feedstock capability (enables use of wastes)
- Higher hydrocarbon yield vs. other technologies

Barriers

	Cost Reduction	Performance Improvement
R&D	• Lack of integrated demonstration of whole process • Metrics that might prevent process viability: cost, yield, sustainability	• Bench scale data for each of the individual process operations
Deployment and Scale-up	• Risks: – Issues of feedstock choice – Feedstock variability and availability – Technical execution – Logistics	• Lack of knowledge about the system and its process operations

Technology Maturity Level

None reported

Market Entry

- Sludge resource recovery
- Use of algal biomass

Advancement Activities / Interim Milestones

	Advancement Activities	Interim Milestones
Immediate (<5 yrs)	• Develop model framework • Identify resources for data (e.g., researchers, patents, publications) • Build model and establish optimization scenarios (cost, environment, yield)	• Model built and vetted • Data flows established (e.g., experimental results to model, model results guide R&D) • Preliminary results guide technical targets, R&D, communication strategy
Near-term (5-20 yrs)	• Revise model as more data become available • Communicate results to stakeholders (government, industry, broader biofuels community)	• Revised model, more accurate
Long-term (>20 yrs)	None reported	None reported

Overarching Targets

Technology/ Performance:

- Providing guidance to industry on system variations (in HTL process, upgrading, etc.) to guide technology development toward profitability and sustainability

Installed Cost Targets

Initial deployment cost:

- Costs meet needs of potential off takers

Cost at scale:

- Parity with petroleum-derived fuels

Factor	Impact	Reasoning
Process yield	High	Optimize for yield
Output quality	Medium	None reported
Reliability	Low	None reported
Technology validation	High	Model will show system performance
Cost reduction	High	Model identifies key steps to reduce cost
Ease of market adoption	None Reported	Industry understanding of system improved

Key Stakeholders

- **Technology Development:** Industry would want to see most representative data to validate against own processes
- **Technology Deployment:** Industry, government, academia to develop model
- **Validation and Testing:** Industry to test/validate model with real-world data and facilities
- **Regulatory:** Model output could have regulatory implications; government is key customer
- *Comment:* Need input from all stakeholders to develop model

WORKSHEET D-3.4: DEVELOP ECONOMIC USAGE OF NON-OIL HTL EFFLUENT STREAMS

HIGH-IMPACT TECHNOLOGY SCENARIO

Identify and develop an economically viable process/technology to utilize the nutrient-rich, non-HTL crude oil streams produced during the HTL process

VALUE PROPOSITION

Production of an economically viable method of nutrient recycle

BARRIERS

	Cost Reduction	Performance Improvement
R&D	• Need for algae growth means HTL processing and effluent feedback in cooperating facilities	• Concentration of effluent water which is too dilute for same uses and too strong for others
Deployment and Scale-up	• Same as above, but all facilities need to be co-located	• Validate both nutrient value at large scale and separation of toxic components

TECHNOLOGY MATURITY LEVEL

Applied R&D, Prototype, Pilot/Demo

MARKET ENTRY

Algae growing, agricultural waste recycling, and municipal secondary water

	ADVANCEMENT ACTIVITIES	INTERIM MILESTONES
IMMEDIATE (<5 YRS)	• Produce enough selected biomass to test • Perform HTL to obtain and analyze effluent streams • Analyze results of recycling effluents	• Demonstrate 90% recovery of nutrients in effluent • Demonstrate 90% bioavailability of recovered nutrients • Model economies of recycle to determine viability for go/no-go decision
NEAR-TERM (5-20 YRS)	• Modify/redesign as result of testing • Scale up	None reported
LONG-TERM (>20 YRS)	None reported	None reported

OVERARCHING TARGETS

Technology/ Performance:

- 90% recovery of nutrients
- 90% bioavailability
- Market profitability of nutrient recovery process

Installed Cost Targets

Initial deployment cost:

- CAPEX cost of less than $5/bbl of oil produced over 20 year life

Cost at scale:

- CAPEX cost of less than $2/bbl of oil produced over 20 year life

FACTOR	IMPACT	REASONING
Process yield	Low	Little impact on oil output
Output quality	High	Clean water and nutrient recovery
Reliability	Low	Some negative effect on complexity
Technology validation	High	Water and nutrients critical to LCA
Cost reduction	Medium	Reduction of external inputs
Ease of market adoption	9/10 Hard ↔ Easy	If economical, will be easily adapted

KEY STAKEHOLDERS

- **Technology Development:** Academia, government, industry
- **Technology Deployment:** Industry, technology operators, trade groups
- **Validation and Testing:** Technology operators, government labs, and trade groups
- **Regulatory:** Industry, government, and trade groups

Disclaimer: Numerical targets reflect the views of participants, and are not necessarily those of BETO

WORKSHEET D-4.1: CONDUCT R&D ON CONVERSION TECHNOLOGIES (BIOLOGICAL AND THERMO-CATALYTIC) FOR PRE-PROCESSED WASTE BIOMASS

HIGH-IMPACT TECHNOLOGY SCENARIO

Develop higher-value, targeted profiles for storable/transportable products/intermediates that can be produced faster and under less severe conditions than anaerobic digestion (AD)

VALUE PROPOSITION

Higher value, targeted product profiles, quicker than AD, less severe process conditions, storable/ transportable products/ intermediates

BARRIERS

	Cost Reduction	Performance Improvement
R&D	• Yield and selectivity to a stable end/intermediate product • Robustness and durability • Organism and materials identification (discovery)	• Proof of lifetime, performance without degradation • Easily separated product (e.g., low energy requirements) • Process intensification (e.g., pre-processing, stream processing)
Deployment and Scale-up	• Proof in a continuous process with real feedstocks • Integrated separations technologies	• Feedstock availability and variability

TECHNOLOGY MATURITY LEVEL

Basic/Fundamental, Applied R&D

MARKET ENTRY

Food processing and industrial waste streams, mixed refuse facility (MRF), any consistent stream

	ADVANCEMENT ACTIVITIES	INTERIM MILESTONES	OVERARCHING TARGETS
IMMEDIATE (<5 YRS)	• Pursue discovery of catalyst materials/organisms • Test at larger scales • Test in a continuous process configuration • Test in a continuous, engineering-relevant scale, with real feedstock	• Productivity greater than a digester • Carbon and/or thermal conversion efficiency greater than electricity production • Industrially relevant lifetimes and terms of service (TOS)	None reported
NEAR-TERM (5-20 YRS)	• Integrate processing steps • Pilot • Increase feedstock breadth	• Stable, continuous operation at industrially relevant scale and time on stream	
LONG-TERM (>20 YRS)	• Extend deployment of commercial technologies • Build de-centralized, modular facilities • Maximize feedstock breadth	• Requires minimally skilled, or no/limited operators (similar to AD)	

FACTOR	IMPACT	REASONING
Process yield		
Output quality		
Reliability	High	Feedstock variability
Technology validation		
Cost reduction	High	Capital expenditures, reduced scale
Ease of market adoption		

KEY STAKEHOLDERS

- **Technology Development:** Academia, industry, and government: Lab-scale development of novel technologies and materials. Testing improves understanding of process conditions, R&D needs, and opportunities. Grants to support research enable these developments.
- **Technology Deployment:** Loan guarantee; Government supports the deployment of technology through integration into existing municipal WWT systems at pilot scales, operated by industry.
- **Validation and Testing:** Government aligns incentives across municipalities, local, and central governments; Industry refines process conditions for optimal performance, high effluent quality, and maximum biogas recovery.
- **Regulatory:** Government sets standards for effluent quality, toxicity, end use of effluent, etc.; Trade groups spread public awareness, support WWT efforts, and facilitate discussions between Industry and Government to help shape effective regulations.

WORKSHEET D-4.2: CONDUCT TECHNO-ECONOMIC ANALYSES

HIGH-IMPACT TECHNOLOGY SCENARIO

Evolve conceptual process design and modeling to define process variables, technical barriers, and key drivers for economical technologies

VALUE PROPOSITION

- Save time and cost on full-scale R&D
- Make R&D more focused; make better use of resources

TECHNOLOGY MATURITY LEVEL

Applied R&D, Analysis

MARKET ENTRY

Target existing large-scale waste treatment facilities first

BARRIERS

	Cost Reduction	Performance Improvement
R&D	• Limited process-related data: most advanced technologies are developed by the private sector • Variability of feedstock characteristics: process-related kinetics are suitable only for a particular feedstock.	• Trade-offs between environmental and economic benefits
Deployment and Scale-up	• Use lab data to design commercial TEA model • Scaling up problems	• Gaps between models and commercialized technologies

ADVANCEMENT ACTIVITIES / INTERIM MILESTONES / OVERARCHING TARGETS

	Advancement Activities	Interim Milestones	Overarching Targets
IMMEDIATE (<5 YRS)	• Conduct TEA of conversion technologies, considering all potential technology pathways in terms of TEA ($) and LCA (GHG, water) • Communicate and network with industrial partners, federal and local partners • Conduct comparative analyses, considering sensitivities and uncertainties	• TEA and LCA reports on different pathways including $/GGE, CO2 emissions/GGE • Integrate industrial data to improve results from TEA and LCA • Publish TEA and LCA reports on the analysis	*Technology/ Performance:* • More consistent research opportunities/funding • Increased publicity and outreach on those pathways • Broader knowledge of pathways
NEAR-TERM (5-20 YRS)	• Continue TEA and LCA with emerging technologies • Conduct TEA of the whole waste-to-energy supply chain, including feedstock conversion technologies and fuel distribution • Integrate new technologies into an existing waste-to-energy facility; consider/analyze retrofitting existing plants (AD and combustion)	• Report cost and LCA results • Report supply chain analysis	
LONG-TERM (>20 YRS)	• Use analysis tools to plan path toward total national waste reduction, potentially to net-zero waste, so that all waste generated can be recycled, reused, or converted to energy.	• Provide plans and guidance to approach net-zero waste scenarios	

FACTOR	IMPACT	REASONING
Process yield	High	Provide guidance for technical barriers and key drivers
Output quality	High	High-resolution analysis is possible with better data
Reliability	High	Same as above
Technology validation	High	TEA quality improves with more iterations among industry, governmental stakeholders
Cost reduction	High	Good TEA can provide guidance to reduce cost and uncertainty
Ease of market adoption	10/10 Hard ↔ Easy	Very easy to transfer knowledge

KEY STAKEHOLDERS

- Technology Development: Academia, industry, government. Transparent data sharing and validation. Everyone will need to work together to develop models that reflect actual plant operation.
- Technology Deployment: None reported
- Validation and Testing: Industry and government demonstrate process concepts to get data for TEA and LCA
- Regulatory: Government (GHG reductions may support RFS standards, costs could influence policy)

WORKSHEET D-4.3: DEMONSTRATE AND DEPLOY PREPROCESSING AND PRETREATMENT TECHNOLOGIES

HIGH-IMPACT TECHNOLOGY SCENARIO

Develop pretreatment to enhance methane production in anaerobic digestion; incorporate other waste streams into AD

VALUE PROPOSITION

- Incorporate other water streams into AD
- Minimum 15-20% improvement in CH_4 yield

BARRIERS

	Cost Reduction	Performance Improvement
R&D	• Efficiency enhancements • Reduce scale requirements	• Break down cell walls without losing chemical energy
Deployment and Scale-up	• Not proven in U.S. • Breaking down packaging materials from MSW	• Contaminant (and toxins) removal • Adequate work volumes within economical transportation distances

TECHNOLOGY MATURITY LEVEL

Near-Commercial

MARKET ENTRY

- MSW, industrial food waste
- Large-scale wastewater treatment plants, integrated organic waste facilities

	ADVANCEMENT ACTIVITIES	INTERIM MILESTONES
IMMEDIATE (<5 YRS)	• Carefully monitor demonstration projects • Disseminate results • Investigate application to MSW, particularly re: packing	• Enhance methane production • Encourage additional adoption • Determine applicability to MSW
NEAR-TERM (5-20 YRS)	• Develop standards • Disseminate training materials • Develop capacity for more waste streams	• Deploy (commercial) in x% of wastewater treatment plants • Validate MSW applicability • Further increase efficiency (y%)
LONG-TERM (>20 YRS)	• Commercialize technology	• Technology will be commercial

OVERARCHING TARGETS

Technology/ Performance:

- 75% methane in biogas
- 65% methane with MSW streams included (lower quality)

Installed Cost Targets

Initial deployment cost:

- Ask commercial facility

Cost at scale:

- Added value of enhanced production must provide competitive return on pretreatment

FACTOR	IMPACT	REASONING
Process yield	High	This is the primary goal
Output quality	High	Necessary for AD operation
Reliability	High	Facilities must meet permits
Technology validation	High	European acceptance is not sufficient for acceptance by U.S. market
Cost reduction	Medium	
Ease of market adoption	7/10 Hard ↔ Easy	Is operating in EU. Uncertain about MSW as feedstock

KEY STAKEHOLDERS

- **Technology Development:** DOE, EPA, USDA: Wastewater treatment plants, dairies, municipalities, waste management firms, landfills
- **Technology Deployment:** DOE, EPA: Waste-to-biofuels conversion companies, waste-to-energy firms
- **Validation and Testing:** DOE, EPA: Waste-to-biofuels conversion companies, waste-to-energy firms
- **Regulatory:** EPA, states, regional water and air quality boards

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Worksheet D-4.4: Support Scale-up of Technologies

High-Impact Technology Scenario

Demonstrate conversion of manure and organic substrates (waste) to middle distillate fuels (diesel); enable multiple value streams; prove beneficial use that avoids environmental runoff

Value Proposition

- Multiple value streams (fuel, fertilizer, potable water for animals), cost avoidance
- Beneficial use avoiding environmental runoff

Barriers

	Cost Reduction	Performance Improvement
R&D	None reported	• TBD from pilot operation • Specific barriers not identified
Deployment and Scale-up	• Co-product (phosphorus and nitrogen fertilizer) • Effluent runoff mitigation • Validation scale up (algae and manure)	• Management of multiple waste streams • Quantifiable co-product • Energy return on investment (EROI) (energy balance)

Technology Maturity Level

Applied R&D, Prototype, Pilot/Demo

Market Entry

- Specific to dairy industry with their cow manure
- Farms in distressed watersheds
- Potential for other confined feeding operations

	Advancement Activities	Interim Milestones
Immediate (<5 yrs)	• Pilot plant: 1 bone dry ton/day manure • Integration of technology into 10x scale system • Expansion to other food waste types	• Technology performance and cost targets from rural business enterprise outcomes • Process confirmations optimized
Near-term (5-20 yrs)	• Addition of other food wastes	• Validation of CAPEX for commercial scale • Validation of product quality and process reliability • Two additional states and two additional nations adopting technology (export) • Expansion of concept to other states or countries
Long-term (>20 yrs)	None reported	• Nations adopting technology (export) • Two additional food waste types successfully adopted

Overarching Targets

Technology/ Performance:

- 300-cow farm, 20,000 to 30,000 gal/yr biocrude (based on mass and energy balance)
- Positive EROI
- Annual production of 100,000 lbs. of co-products
- Granular time release of phosphorous and nitrogen

Installed Cost Targets

Initial deployment cost:

- CAPEX of $1.5M, OPEX extra

Cost at scale:

- $3.5M for 3,000-cow farm (projection)

Factor	Impact	Reasoning
Process yield	High	Validate yield for fuels/ fertilizer
Output quality	High	Refined fuels produced by third party from biocrude
Reliability	Medium	Demonstrate operational long-term reliability
Technology validation	High	See above
Cost reduction		Demonstrate 5-6 year payback
Ease of market adoption	8.5/10 Hard ↔ Easy	

Key Stakeholders

- **Technology Development:** Industry, state governments, federal agencies
- **Technology Deployment:** Aviation industry, diesel transport, home heating, digester industry
- **Validation and Testing:** Industry refines the process
- **Regulatory:** Government benefits by reduced compliance cost and improved nutrient management

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Worksheet D-4.5: Improve Process Monitoring and Control for Highly Variable Feed Streams

High-Impact Technology Scenario

Develop robust process controls to optimize novel waste-to-energy processes that use highly variable, non-homogeneous input streams

Value Proposition

Supports novel technology development and scale-up

Barriers

	Cost Reduction	Performance Improvement
R&D	• Process optimization for variable inputs; correlation between input composition and process performance	• Effects of variable input streams on process efficiency, adaptability and robustness • Lack of on-line, real-time process monitors • Impact of variations on process
Deployment and Scale-up	• Lack of pilot-scale demonstration for performance metrics and reliability, availability and maintenance estimates • Process integration and intensification to reduce CAPEX	• Long-term pilot demonstration to collect commercially relevant process data

Technology Maturity Level

Pilot/Demo

Market Entry

- Municipal and industrial waste water treatment
- Solid waste-to-energy technologies

	Advancement Activities	Interim Milestones
Immediate (<5 yrs)	• Develop process monitors for variable waste-water streams • Develop process monitors for variable solid waste (MSW, bio-solids, food wastes, etc.) • Develop/apply existing or new technology to measure process streams	• Develop and apply measurement devices on model wastewater components • Develop and apply novel imaging technology for characterizing solid wastes
Near-term (5-20 yrs)	• Baseline and test process monitors and develop predictive correlations for on-line monitoring • Integrate process monitoring in pilot and demonstration-scale facilities	• Validate process monitoring technology • Use process data to optimize yields and efficiency
Long-term (>20 yrs)	• Deploy technology for process monitoring and optimization in commercial facilities	• Optimize process and control to maximize revenue in commercial systems • Reduce cost of process monitoring

Overarching Targets

Technology/ Performance:

- Demonstrate 10% yield improvement
- Demonstrate 10% cost reduction

Factor	Impact	Reasoning
Process yield	High	Yield of product has largest impact on economics
Output quality	High	Intimately tied to yield
Reliability	High	Process optimization requires robust and reliable monitoring
Technology validation	Medium	Same as above
Cost reduction	High	Process optimization and control
Ease of market adoption	9/10 Hard ↔ Easy	Analogous to linear program modeling in petroleum refineries

Key Stakeholders

- **Technology Development:** Academia, industry and government: Laboratory technology development, installation and testing
- **Technology Deployment:** Industry, government, and trade groups
- **Validation and Testing:** Industry
- **Regulatory:** Industry and government: Standards, performance metrics, emissions

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DOE/EE-1182 • June 2015