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Biofuels and Bioproducts from Wet and Gaseous Waste Streams: Challenges and Opportunities

Bioenergy Technologies Office

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Preface

This report draws together activities related to wet and gaseous waste feedstocks into a single document. It enables an amplified focus on feedstocks in the category, relevant technologies, and potential markets and helps to inform and support ongoing wet and gaseous resource recovery activities or efforts in the Bioenergy Technologies Office (BETO) and in the broader federal space. Historically, the office has identified wet and gaseous waste feedstocks as potentially advantageous, but has not pursued them with a sustained focus. This document seeks to position these waste streams appropriately alongside more traditional feedstocks in BETO efforts.

This document is intended as one step in a longer journey, in which BETO can enhance the economic and environmental sustainability of utilizing wet and gaseous wastes. Without prescribing any particular course of action, this report identifies areas of opportunity. It is intended as a useful resource for reference in selecting targets for more rigorous analyses or areas for future RD&D investment.

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The review meeting was planned and executed by the aforementioned authors. Meeting facilitation was conducted by Jonathan Rogers, Paget Donnelly, and Shawna McQueen, all of Energetics Inc. Special thanks to Jill Coughlin of the National Renewable Energy Laboratory, for her help coordinating the event. Note taking was provided by Brandon Hoffman, Allegheny Science & Technology; Brendan Scott, Allegheny Science & Technology; Cindy Gerk, National Renewable Energy Laboratory; Jeremiah Wilson, Office of Energy Policy and Systems Analysis, Department of Energy; and Zachary Peterson, BCS Incorporated.

List of Acronyms

AD	Anaerobic Digestion
AFO	Animal Feeding Operation
AnMBR	Anaerobic Membrane Bioreactor
ARPA-E	Advanced Research Projects Agency – Energy
bcf	Billion Cubic Feet
BETO	Bioenergy Technologies Office
BOD	Biochemical Oxygen Demand
bpd	Barrels per Day
Btu	British Thermal Units
CAFO	Concentrated Animal Feeding Operation
cf	Cubic Feet
CH_4	Methane
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COD	Chemical Oxygen Demand
CONUS	Conterminous U.S.
CWC	Cellulosic Waiver Credit
CWNS	US EPA's Clean Watersheds Needs Survey
DDGS	Dried Distillers Grains with Solubles
DOE	U.S. Department of Energy
DRM	Dry Methane Reforming
EERE	Office of Energy Efficiency and Renewable Energy
EIS	Electrochemical Impedance Spectroscopy
EOR	Enhanced Oil Recovery Operations
EPA	U.S. Environmental Protection Agency
FE	DOE Office of Fossil Energy
FOGs	Fats, Oils, and Greases
GGE	Gallons Gasoline Equivalent
GHG	Greenhouse Gas
GHGRP	EPA's Greenhouse Gas Reporting Program
GTL	Gas to Liquids
GWh	Gigawatt-Hour
H_2	Hydrogen

H_2S	Hydrogen Sulfide
HEFA	Hydrogenated Esters and Fatty Acids
HHV	High Heating Value
HRT	Hydraulic Retention Time
HTC	Hydrothermal Carbonization
HTL	Hydrothermal Liquefaction
kg	Kilogram
kWh	Kilowatt-Hour
LCA	Life Cycle Analyses
LCFS	Low Carbon Fuel Standard
LNG	Liquefied Natural Gas
m	Meter
mgd	Millions of Gallons per Day
MJ	Mega Joule
MM	Million
MM GGE	Million Gallons of Gasoline Equivalent
MMBtu	Million British Thermal Units
MMO	Methane Monooxygenase
MMt	Million Metric Ton
MSW	Municipal Solid Waste
Mt	Metric Ton
MW	Megawatt
MxCs	Microbial Electrochemical Cells
MYPP	Multi-Year Program Plan
N	Nitrogen
NGO	Non-governmental organization
NH_3	Ammonia
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
P	Phosphorus
PNG	Pipeline Natural Gas
PNNL	Pacific Northwest National Laboratory
POTW	Publicly Owned Treatment Works
PTC	Production Tax Credit
R&D	Research and Development
RD&D	Research, Development, and Demonstration
REC	Renewable Electricity Credit or Renewable Energy Certificate

RFS	Renewable Fuel Standard
RIN	Renewable Identification Number
RNG	Renewable Natural Gas
SBIR	Small Business Innovation Research
scfd	Standard Cubic Feet per Day
SMR	Steam Methane Reforming
SRT	Solids Retention Time
TBtu	Trillion British Thermal Units
tcf	Trillion Cubic Feet
TEA	Techno-Economic Analyses
USDA	U. S. Department of Agriculture
VSS	Volatile Suspended Solids
WE&RF	Water Environment and Reuse Foundation
WEF	Water Environment Federation
WESyS	Waste-to-Energy System Simulation
WRRF	Water Resource Recovery Facility
WTE	Waste to Energy
WWTP	Waste Water Treatment Plant

Executive Summary

Will be completed last

Contents

Figures

Tables

1. Introduction

The Bioenergy Technologies Office (BETO) invests in technology research, development, and demonstration (RD&D) projects to accelerate the cost-effective production of clean fuels and products from domestic biomass. BETO, as part of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), has already helped to significantly advance the technologies and systems for converting woody and herbaceous wastes, purpose-grown energy crops, agricultural residues, and algae (DOE 2016a) into affordable biofuels.

There are other resources that have not been the primary focus of BETO RD&D efforts in recent years. Wet and gaseous feedstocks, many of which are either organic or produced from biogenic sources (see Table 1.2), represent another potential area of opportunity. BETO commissioned this report to better explore the techno-economic potential of these sources. Table 1-1 summarizes some of the drivers behind this choice.

BETO Mission

Develop and transform domestic renewable biomass resources into commercially viable, high-performance biofuels, bioproducts, and biopower through targeted RD&D supported by public and private partnerships.

Goals: Develop commercially viable technologies to

- Enable sustainable, nationwide production of biofuels that
  - are compatible with today's transportation infrastructure
  - reduce greenhouse gas emissions relative to petroleum-derived fuels
  - displace a share of petroleum-derived fuels to reduce U.S. dependence on foreign oil
- Support creation of a new domestic bioenergy and bioproducts industry.

(DOE 2015)

Table 1-1. Wet and Gaseous Waste Streams: Key Drivers

Wet and Gaseous Waste Streams: Key Factors		
Feedstock Characteristics	Energy Rich	U.S. waste streams hold considerable energy potential (USDA 2014; WERF 2014; Willis et al. 2015).
	Biogenic	Organic waste streams are considered renewable and are starting to be recognized under the Renewable Fuels Standard (EPA 2014).
Wet and Gaseous Waste Stream Considerations	Feedstock Production	These feedstocks already exist, are produced continuously, and must be addressed in some manner. In many cases, collection systems for these feedstocks are already in place.
	Economic Availability	Many waste feedstocks are currently available at negligible or even negative prices (tipping fees). Given the significance of feedstock pricing in determining biofuel competitiveness, the economics are promising—yet conditions may change as demand for waste streams increases. (DOE 2015)
	Added Value to Existing Processes	Byproducts (e.g., combined heat and power, nutrients like nitrogen and phosphorus, and even biofuels) can enhance the value proposition for wastewater treatment facilities (WERF 2011; WEF 2012; NACWA 2013).
	Existing Infrastructures	Conversion systems may be able to leverage existing infrastructure and operational investments (e.g., wastewater treatment facilities have begun to recognize that their systems represent a variant of integrated biorefineries).
	Aging Infrastructures	Aging infrastructures in need of replacement present diverse opportunities for improvement. Most anaerobic digesters at wastewater treatment plants are approaching their 50th year of service.

Non-technical Drivers	Avoid Disposal Costs	Wastes often bear a disposal cost—particularly in the case of biosolids from municipal wastewater treatment facilities or manure from some concentrated animal feeding operations.
	Landfill Diversion Efforts	Some states are moving toward restricting the use of landfills for the deposition of organic wastes, including both biosolids and food wastes of various kinds (CalRecycle 2015; Yepsen 2015).
	Shifts in Social Perception	Organic wastes are increasingly perceived as a problem to be solved, and the need for solutions has gained social traction around our country (and world).
	Economic Incentives	Recent techno-economic developments suggest that making biofuels from wet and gaseous feedstocks may be economically feasible, particularly with incentives like the EPA's Renewable Fuel Standard and California's Low Carbon Energy Standard (Elliott et al. 2015; He et al. 2015; Gaeta-Bernardi and Parente 2016).
Technical Drivers	Improved Process Efficiencies	By using water as a processing medium, some maturing technologies avoid the need to dry and chemically separate specific feed components (e.g., lipids) prior to processing and thus eliminate the high associated costs.
	Greater Biogas Utilization	Some emerging technologies utilize both the carbon dioxide and methane from biogas to produce precursors of biofuels and bioproducts (Fei et al. 2014; Haynes and Gonzalez 2014; Gopaul and Dutta 2015; Jafarbegloo et al. 2015).
	Emerging Technology Innovation	The DOE's Advanced Research Projects Agency – Energy (ARPA-E) has also developed relevant programs that could contribute valuable inputs to future BETO research and development (R&D) efforts (ARPA-E 2010; ARPA-E 2014).

1.1. Targeted Feedstocks

BETO has produced a substantial body of work on the projected availability and pricing of agricultural, woody, and other herbaceous biomass resources in the United States—most notably a series known as the *Billion-Ton* studies (DOE 2011). DOE has also made significant investments in algal biomass as a feedstock (Biddy 2013; Davis et al. 2014; Jones 2014; DOE 2015) and the non-recyclable portion of municipal solid waste (MSW) (Valkenburg et al. 2008). Those streams are covered by existing BETO documents and programs and are not included in this report.

This particular report focuses on wet and gaseous feedstocks, mostly biogenic in origin. This is a contrast with the traditional BETO focus on solid resources, with the notable exception of algae. All of the feedstocks addressed in *this* document have been subjected to some kind of processing intentionally directed by humans. Additionally, they also have either much higher moisture content than solid materials, or are actually gaseous. The precise boundaries between more traditional BETO feedstocks and those included in waste-to-energy RD&D are still evolving. Table 1-2 describes the resources identified in this report, several of which are also included in BETO's *2016 Multi-Year Program Plan* (MYPP) (DOE 2016b).

Table 1-2: Targeted Wet and Gaseous Feedstocks

Targeted Wet and Gaseous Feedstocks	
Wet and Aqueous Streams	
Sludge and Biosolids	Biosolids, organic-rich aqueous streams, and sludges derived from municipal wastewater treatment
Animal Waste	Manure slurries from concentrated livestock operations
Food Waste	Commercial, institutional, industrial, and residential food wastes, including fats, oils, and greases, particularly those currently disposed of in landfills
Industrial Organic Waste[1] (non-food operations)	Organic wastes from non-food industrial operations, including but not limited to ethanol manufacturing, biodiesel production, and biorefineries

Feedstock Blends	Blends of any of the above with drier feedstocks, such as corn stover or the organic fraction of municipal solid waste (MSW)
Gaseous Streams	
Biogas[2]	Biogas derived from any of the above feedstock streams, including but not limited to landfill gas
Biogenic CO_2[3]	CO_2 from ethanol plants, food and beverage operations, power plants, and other industrial processes
Industrial CO_2 and Flue Gases[4]	Based on DOE interpretation of relevant authorizing legislation, BETO is allowed to apply biological conversion processes to these streams, even though they are not biogenic in origin.
Stranded Natural Gas[5]	Under the same rationale as above (non-biogenic sources of CO_2), BETO is authorized to apply biological conversion processes to stranded natural gas streams.

[1] Other industries that generate streams potentially suitable for incorporation include pulp and paper, forest products, and pharmaceuticals.

[2] This report includes two other gaseous streams (CO_2 and Stranded Natural Gas) that have not yet been incorporated in the MYPP and require collaboration with the DOE Office of Fossil Energy (FE). While constructive discussions between BETO and FE are well under way, nothing has yet been formalized, so the inclusion of these feedstocks should be viewed as tentative.

[3] CO_2 from ethanol plants is considered biogenic and is highly concentrated (as much as 90% CO_2)(GCCSI 2016); it should thus be viewed as a highly attractive target feedstock for BETO. Similar logic applies to gaseous streams from the food & beverage and pulp & paper industries, which also tend to produce concentrated streams.

[4] In practice, collaboration with FE would provide clearer collective authority for both Offices, enabling the use of thermochemical, electrochemical, and hybrid conversion strategies.

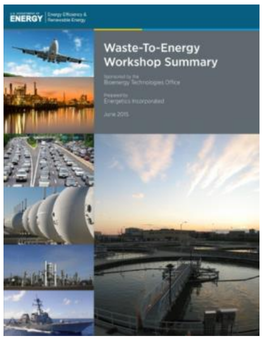
[5] Thermochemical or electrochemical routes might be economically or energetically superior under certain circumstances. In such instances, BETO would need to collaborate with FE Oil and Gas to provide a clear basis for issuing Funding Opportunity Announcements and related documents.

Part of the purpose of this roadmap is to clarify R&D boundaries, and to identify potential synergies and opportunities for collaboration. To what degree does an explicit focus on these wet and gaseous anthropogenic waste streams carve out a new investigative space for BETO? To what degree does it complement and build on existing efforts? More broadly, how might these particular feedstocks provide an analytical foundation for additional collaboration within EERE, across DOE, and among sister agencies and external stakeholders? Stakeholder feedback and internal research on these feedstocks, markets, and technologies provide insights that will help BETO to prioritize activities, identify potential opportunities for collaboration, and continue to shape its role in enabling sustainable wet and gaseous resource recovery.

1.2. Intersection with Relevant Stakeholder Movements

A paradigm shift is underway in the municipal wastewater treatment community. Faced with the exorbitant cost of replacing a large portion of its water treatment infrastructure, now close to 100 years old in some cases, the wastewater industry has begun to view its treatment facilities as a form of integrated biorefineries. In this new paradigm, wastewater is seen as a resource for producing clean drinking water, combined heat and power, and nutrient streams—as well as biofuels and bioproducts. This movement started small (WERF 2011) and has grown rapidly in recent years (WEF 2012; NACWA 2013; WERF 2014). The basic notion is that wastewaters should be viewed as resources available for conversion into clean water, combined heat & power applications, nutrient streams, and potentially biofuels and bioproducts. There is also increasing recognition of the potential for co-digestion of food and other organic wastes as a strategy for enhanced energy recovery. While Chapter two rightly notes that these feedstocks are relatively small in terms of dry tonnage, Chapter three points out that they are very significant in terms of market and political forces. So, municipal wastewaters and biosolids may provide an example of an organic feedstock that is poised in the right place at the right time.

This paradigm shift is nicely captured by the idea of "Energy-Positive Water Resource Recovery Facilities," which reflects the emerging conception of waste streams as valuable resources. This notion is particularly salient in a world in which clean water will be an increasingly valuable resource (DOE 2014), and also dovetails nicely with BETO's strategy to promote "Integrated Biorefineries." A coalition of DOE offices, other federal agencies (EPA, NSF, and USDA), and external stakeholders has recognized this opportunity and collaborated in convening a series of workshops over the last 22 months, the results of which directly inform this document.



Waste-to-Energy Workshop: November 5–6, 2014

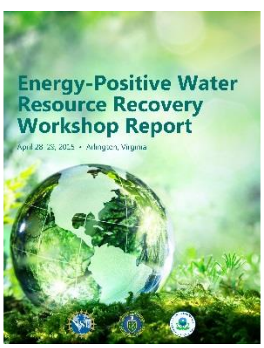
Hosted by BETO, this workshop focused on anaerobic digestion (AD), hydrothermal liquefaction, and other technologies for the production of energy products beyond biogas. Approximately 85 attendees identified 17 key ideas, including alternative reactor designs—which prompted further discussions and, ultimately, the follow-on workshop below.

The Waste-to-Energy Workshop Summary is available at: energy.gov/eere/bioenergy/waste-energy-workshop.

Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters Workshop: March 18–19, 2015

Hosted by BETO and the Fuel Cell Technologies Office, this workshop focused on anaerobic membrane bioreactors and microbial electrochemical fuel cells. Approximately 40 attendees discussed the topics over two days, identifying ways to advance the sustainable utilization of wet waste streams, complement the work of other agencies, and maximize the value of research investment.

The Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters Workshop Summary is available at: energy.gov/eere/fuelcells/hydrogen-hydrocarbons-and-bioproduct-precursors-wastewaters-workshop.



Energy-Positive Water Resource Recovery Workshop: April 28–29, 2015

NSF, DOE, and the EPA jointly hosted this workshop to better define the industry's long-term vision (20+ years) for water resource recovery facilities (WRRFs) and the actions needed to make that vision a reality.

The Energy-Positive Water Resource Recovery Workshop Report is available at: energy.gov/eere/bioenergy/energy-positive-water-resource-recovery-workshop-report/.

Biogas Opportunities Roadmap Progress Report: December, 2015

The USDA, EPA, and DOE collaborated to update the Biogas Opportunities Roadmap (USDA 2014). This effort extends the scope beyond the municipal wastewater community to include other relevant feedstocks, such as animal husbandry wastes. A key theme is that early opportunities may lie in feedstocks that currently pose disposal costs and challenges.

The progress report is available at: energy.gov/sites/prod/files/2015/12/f27/biogas_opportunites_roadmap_progress_report_0.pdf

EPA Nutrient Recycling Challenge: Launched 2015 (Ongoing)

In collaboration with the USDA, private stakeholders, and DOE, the EPA launched a Nutrient Recycling Challenge, focused initially on recovering nutrients from dairy and swine manure. Phase I awarded four primary and six secondary prizes and encouraged multiple additional applicants to move on to subsequent phases.

Additional details are available at the challenge web site: challenge.gov/challenge/nutrient-recycling-challenge/

These workshops seek to integrate the activities of federal agencies within larger market and regulatory contexts. As a federal agency, the DOE's efforts in these areas need to be informed by and partake in larger stakeholder contexts. This is part and parcel of the effort to integrate the productive use of these wet and gaseous feedstocks into the Bioeconomy of the Future.

Producing biofuels and bioproducts from these feedstocks represents an opportunity to displace virgin petroleum. At the same time, BETO's efforts to increase the availability of renewable energy must be carried out in a manner that simultaneously enhances economic and environmental sustainability. As Congress has directed in appropriations language, DOE-funded technologies converting waste streams into energy must demonstrate the potential to reduce greenhouse gas (GHG) emissions relative to current practice for treating these feedstocks. Comprehensive life-cycle analyses (LCA), including examination of counterfactual scenarios in which the waste stream is not utilized as an energy feedstock, are needed to measure progress in meeting the national social, environmental, and economic goals articulated in the Bioeconomy of the Future (see inset).

This document is intended to inform and support ongoing activities or efforts in BETO and in the broader federal space. This document and other sources of information will help to shape portions of future planning documents including the *Multi-Year Program Plan,* the *DOE Strategic Plan,* and *The 2021 Billion-Ton*

The Bioeconomy of the Future

The U.S. Department of Energy is working with other federal agencies to achieve the benefits of a thriving bioeconomy:

- Expanded U.S. energy options
- Reduced GHG emissions from the transportation sector
- Decreased dependence on imported oil
- More domestic jobs—especially in rural America.

The future bioeconomy includes the use of algae and traditional biomass as well as:

- Animal waste to produce biogas, fuel, heat, biopower, and income for farms
- Wet and gaseous waste streams to generate energy and alleviate pressure on wastewater treatment plants

Federal Activities Report on the Bioeconomy, February 2016

Update. Historically, the office has identified wet and gaseous waste feedstocks as potentially advantageous, but has not pursued them with a sustained focus in recent years. This project seeks to position these waste streams appropriately alongside more traditional feedstocks in BETO efforts.

1.3. Report Objectives and Organization

Wet and gaseous waste streams may represent an undervalued set of feedstocks. The fundamental question that this document and its underlying research seeks to answer is as follows:

> "Under what sets of conditions does it make techno-economic, social, and environmental sense to convert wet and gaseous waste feedstocks into biofuels and bioproducts?"

Further, since the primary focus is on defining the RD&D, analysis, and outreach areas in which DOE could provide the greatest value, a corollary to the fundamental question might be the following:

> "Under what conditions might DOE investment in the production of biofuels and bioproducts from wet and gaseous feedstocks generate the greatest benefit to U.S. energy independence, economic prosperity, and environmental and human health"?

At a high level, the purpose of this effort is to provide guidance for BETO's R&D activities in these areas for the next 5-10 years. Without attempting to be inappropriately prescriptive, the goal is to develop a rich understanding of the context within which BETO will need to make specific prioritization decisions. In order to make such choices under dynamic conditions, BETO must understand both the current state of play and probable future dynamics in at least three areas:

1. Novel Wet and Gaseous Feedstocks
2. Emerging and Evolving Markets for Biofuels and Bioproducts
3. Promising Conversion Technologies for Wet and Gaseous Feedstocks

Recognizing that all of these areas affect one another in complex ways, this document explores each topic individually and collectively—with an eye toward the future bioeconomy:

Feedstocks (Chapter 2)

- Type and composition of resources
- Quantity/location of resources
- Key considerations related to collecting and processing each feedstock

Markets (Chapter 3)

- Competing markets for relevant feedstocks
- Geographical and regulatory constraints
- Other market-related questions (e.g., Who owns waste feedstocks?)

Technologies (Chapter 4)

- The most promising current and emerging technologies for converting wet and gaseous feedstocks into biofuels and bioproducts
- Anticipated technological changes over the next 10-20 years
- Key challenges and opportunities for BETO to make the most impact

Future Bioeconomy (Chapter 5)

- Interdependence of feedstocks, technologies, and markets
- Triple-bottom-line (social, environmental, and economic) benefits that could be realized from wet and gaseous waste streams
- Waste feedstocks as a leading edge for the Bioeconomy of the Future

One thing that is clear at this juncture is that modeling and analysis will likely have a strong role to play in shaping future efforts. The core of this document, Chapters 2 through 4, is divided as described above for purposes of tractability. The real value, though, is likely to come from an integrated understanding of feedstocks, markets, and technologies as dynamic systems over time. Accordingly, this report seeks to elucidate not just technology development opportunities, but also needs for techno-economic analysis, market modeling, and policy investigations. The two core questions (see beginning of this subsection) are inherently multidimensional and dynamic; useful answers will share those characteristics. The final chapter attempts to tie the earlier chapters together in light of stakeholder feedback and the need to incorporate wet and gaseous waste streams into the Bioeconomy of the Future.

By drawing potential activities related to wet and gaseous waste feedstocks into a single document, this report enables an amplified focus on feedstocks in the category, relevant technologies, and potential markets. Without prescribing any particular course of action, this report identifies areas of opportunity. It gives BETO a useful resource for reference in selecting targets for more rigorous analyses or areas for future RD&D investment. The detailed discussion begins with an assessment of the relevant feedstocks.

1.4. Chapter 1 References:

ARPA-E (2010). "Microorganisms for Liquid Transportation Fuel." ARPA-E. Accessed November 28, 2014, http://arpa-e.energy.gov/?q=arpa-e-programs/electrofuels.

ARPA-E (2014). "Reducing Emissions using Methanotrophic Organisms for Transportation Energy." ARPA-E. Accessed November 28, 2014, http://arpa-e.energy.gov/?q=arpa-e-programs/remote.

Biddy, M. J., Ryan Davis, Susanne Jones, Yunhua Zhu (2013). Whole Algae Hydrothermal Liquefaction Technology Pathway. Golden, CO, NREL**:** 10.

CalRecycle (2015). "California’s 75 Percent Initiative: Defining the Future." CalRecycle. Accessed June 26, 2015, http://www.calrecycle.ca.gov/75Percent/.

Davis, R. E., D. B. Fishman, et al. (2014). "Integrated Evaluation of Cost, Emissions, and Resource Potential for Algal Biofuels at the National Scale." Environmental Science & Technology **48**(10): 6035-6042.

DOE (2011). Billion Ton Update. Oak Ridge, TN, Oak Ridge National Laboratory**:** 227.

DOE (2015). Bioenergy Technologies Office Multi-Year Program Plan. Washington, DC, Department of Energy**:** 244.

DOE (2016a). 2016 Billon-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. Washington, DC, Department of Energy**:** 448.

DOE (2016b). Bioenergy Technologies Office Multi-Year Program Plan Washington, DC, DOE**:** 258.

Elliott, D. C., P. Biller, et al. (2015). "Hydrothermal liquefaction of biomass: Developments from batch to continuous process." Bioresource Technology **178**: 147-156.

EPA (2014). "Regulation of Fuels and Fuel Additives: RFS Pathways II, and Technical Amendments to the RFS Standards and E15 Misfueling Mitigation Requirements " Federal Register **79**(138): 42128-42167.

Fei, Q., M. T. Guarnieri, et al. (2014). "Bioconversion of natural gas to liquid fuel: Opportunities and challenges." Biotechnology Advances **32**(3): 596-614.

Gaeta-Bernardi, A. and V. Parente (2016). "Organic municipal solid waste (MSW) as feedstock for biodiesel production: A financial feasibility analysis." Renewable Energy **86**: 1422-1432.

GCCSI (2016). "CO2 Streams from Industrial Processes." Global CCS Institute. Accessed June 13, 2016, https://hub.globalccsinstitute.com/publications/hazard-analysis-offshore-carbon-capture-platforms-and-offshore-pipelines/e5-co2-streams-industrial-processes.

Gopaul, S. G. and A. Dutta (2015). "Dry reforming of multiple biogas types for syngas production simulated using Aspen Plus: The use of partial oxidation and hydrogen combustion to achieve thermo-neutrality." International Journal of Hydrogen Energy **40**(19): 6307-6318.

Haynes, C. A. and R. Gonzalez (2014). "Rethinking biologocal activation of methane and conversion to liquid fuels." Nature Chemical Biology **10**(5): 331-339.

He, C., K. Wang, et al. (2015). "Products evolution during hydrothermal conversion of dewatered sewage sludge in sub- and near-critical water: Effects of reaction conditions and calcium oxide additive." International Journal of Hydrogen Energy **40**(17): 5776-5787.

Jafarbegloo, M., A. Tarlani, et al. (2015). "Thermodynamic analysis of carbon dioxide reforming of methane and its practical relevance." International Journal of Hydrogen Energy **40**(6): 2445-2451.

Jones, S. R. D. Y. Z. C. K. D. A. R. H. D. E. A. S. K. A. T. H. M. (2014). Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading Richland, WA, PNNL**:** 69.

NACWA (2013). The Water Resources Utility of the Future: A Blueprint for Action. Washington, DC**:** 48.

USDA (2014). Biogas Opportunities Roadmap: Voluntary Actions to Reduce Methane Emissions and Increase Energy Independence Washington, DC, USDA**:** 28.

Valkenburg, C., C. Walton, et al. (2008). Municipal Solid Waste (MSW) to Liquid Fuels Synthesis, Volume 1: Availability of Feedstock and Technology. Richland, WA, Pacific Northwest National Laboratory**:** 43.

WEF (2012). Driving Water and Wastewater Utilities to More Sustainable Energy Management. Alexandria, VA, Water Environment Federation**:** 16.

WERF (2011). Energy Production and Efficiency Research - The Roadmap to Net-Zero Energy. Alexandria, VA, Water Environment Reserch Foundation**:** 8.

WERF (2014). Utilities of the Future Energy Findings. Alexandria, VA, Water Environment Research Federation**:** 86.

Willis, J., N. Andrews, et al. (2015). Assessment of Technology Advancements for Future Energy Reduction. London, WERF**:** 200.

Yepsen, R. (2015). "BioCycle Nationwide Survey: Residential Food Waste Collection In The U.S." JG Press. Accessed June 13, 2016, https://www.biocycle.net/2015/01/15/residential-food-waste-collection-in-the-u-s-2/.

2. Feedstock Descriptions

The wet and gaseous feedstocks identified in this document each present opportunities and challenges for resource recovery. Fundamental collection and treatment systems already exist to handle many of these resources traditionally considered "wastes." Despite the energy-dense nature of many of these resources, their compositional variability and distributed nature have limited their utilization to date. This chapter addresses each resource in terms of availability and utilization, collection and processing issues, and characteristics. Table 2-1 summarizes the availability and inherent energy value (in trillion British thermal units (TBtu) and million gallons of gasoline equivalent (MM GGE)) of the identified resources. The table does not consider conversion efficiencies, impurities, or other processing issues.

Table 2-1. Summary of Annual Wet and Gaseous Resource Availability

	Annual Resource Availability		
Feedstocks	Estimated Annual Resource Availability	Inherent Energy Content (Trillion Btu)	Fuel Potential (MM GGE)[1]
Wet Feedstocks	76.18 MM Dry Tons	1,306.6	11,255.3
Wastewater Residuals	13.70	220.0	1,895.4
Animal Waste	41.00	547.1	4,713.0
Food Waste[2]	15.10	313.0	2,696.5
Fats, Oils, and Greases	6.38	226.4	1,950.4
Gaseous Feedstocks		733.7	6,319.8
Biogas[3]	420 Billion CF	430.5	3,708.6
CO_2 Streams	2,850 MM Dry Tons	-	-
Associated Natural Gas	289 Billion CF	303.1	2,611.2
Other Waste Feedstocks		526.1	4,531.6
Glycerol	0.6 MM Tons	8.7	75.1
Black Liquor	44 MM Tons	517.4	4,456.5
DDGS	44 MM Tons	n/a	n/a
Total		**1,832.7**	**22,106.8**

[1] 116,090 Btu/gal, does not account for conversion efficiency

[2] The moisture content of food waste varies seasonally, ranging from 76% in the summer to 72% in the winter.

[3] Methane potential. Does not include currently operational landfill digesters (>1,000 Bcf annually). May double count potential from wastewater residuals and livestock digesters.

In some cases, favorable resource distribution and mature conversion technologies have led to established markets and applications for these resources. Table 2-2 compares current utilization to the annual recoverable quantities of excess wet resources. Examples of current uses of wet resources include digestion (biogas production), esterification to biodiesel, land application (soil enrichment), composting, animal feed, export, and other products. In cases where these resources are digested, the biogas can also be converted to energy, fuels, or products. Potential excess resources include those that are currently untreated, incinerated, landfilled, or are otherwise unknown.

Table 2-2. Wet Resource Comparison – Annual Utilization and Excess

Wet Resources	Annual Beneficial Utilization (Current) Estimated Resource Availability (MM Dry Tons)	Inherent Energy Content (Trillion Btu)	Fuel Potential (MM GGE)[2]	Annual Potential Excess[1] Estimated Resource Availability (MM Dry Tons)	Inherent Energy Content (Trillion Btu)	Fuel Potential (MM GGE)[2]
Wastewater Residuals	4.26	61.5	530.1	9.44	158.5	1,365.3
Animal Waste	15.00	200.2	1,724.3	26.00	347.0	2,988.8
Food Waste	1.30	27.0	232.9	13.80	286.0	2,463.6
Fats, Oils, and Greases	4.42	159.2	1,371.0	1.96	67.3	579.4
Total	**24.98**	**447.9**	**3,858.3**	**51.20**	**858.7**	**7,397.1**

[1] Unused excess in this definition includes landfilled biosolids and other wet resources.

[2] 116,090 Btu/gal, does not account for conversion efficiency

The availability of wet resources is best understood in the context of collection and distribution differences, chemical compositions, and energy content. Collection challenges directly affect the eventual price and scale of operations that can be achieved for various end uses. The characteristics of each resource will influence the potential for conversion technologies and markets in the near and long term. Ultimately, any opportunity to convert waste into energy, fuels, or products will face competition with other uses for these waste streams. Furthermore, source separation capabilities are likely to steer deployment toward either localized solutions (small in scale) or supply chains that aggregate the waste in a single, large-scale facility.

2.1. Municipal Wastewater Treatment-Derived Sludge and Biosolids

Residential, commercial, and industrial facilities all use water and subsequently produce wastewater. This water is then collected and treated at a WRRF to meet permitted standards. In treatment operations, water is first filtered and settled to generate primary sludge. Subsequently, the water is treated with microbes that further digest the organic matter, resulting in secondary sludge. After passing through polishing operations, the clean water can then be discharged or reused. Some advanced facilities are able to further treat the water to reduce nitrogen and phosphorous concentrations. Upon collection and treatment, wastewater residuals (e.g., primary and secondary sludge) is anaerobically digested to produce biogas, and the solids can then be applied to agricultural land as fertilizer. This report is concerned with valorizing these raw sludge streams without negatively impacting the treatment of wastewater.

2.1.1. Resource Assessment

The US EPA's *Clean Watershed Needs Survey* (CWNS) *2012*, documented data from 14,581 of 14,748 publicly owned treatment works (POTW). These POTWs provide the majority of wastewater treatment in the United States, treating 32.8 billion gallons of wastewater produced each day by 238.2 million Americans, or 76% of the US population. The remainder of the population is served by decentralized or private septic systems (EPA-CWNS 2016). South Carolina and the Northern Mariana Islands did not participate in CWNS 2012. National summaries of technical data include data from CWNS 2008 for South Carolina and Northern Mariana Islands.

Additional insights can be gained by placing the 14,581 facilities documented in CWNS 2012 into size categories based on total existing flow in millions of gallons per day (mgd). 1 mgd serves approximately 10,000 people.

- Large > 10 mgd
- Medium: 1 to 10 mgd
- Small: 0.1 to 1 mgd
- Very Small: <= 0.1 mgd

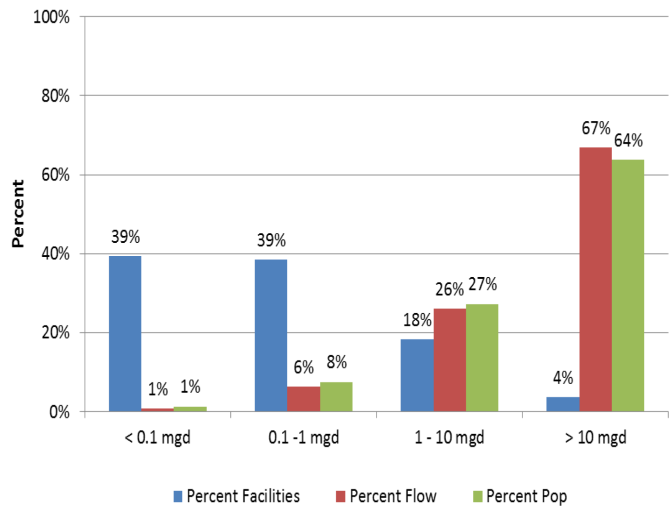


Figure 2-1 Comparison of Publically-Owned Wastewater Treatment Works by Size and U.S.

Figure 2-1 reveals that the majority of the U.S. population (91%) is served by large and medium sized POTWs (>1 mgd), which account for 22% of all systems. The remaining 9% of the population is served by small and very small systems (<1 mgd), which make up 78% of all systems.

Figure 2-2 depicts the spatial distribution of the contiguous US portion of the 14,581 CWNS 2012 catalogued treatment plants, classified by size. The quantity, composition, and quality of sludge within a facility will vary annually, seasonally, and even daily—depending on the composition of the incoming wastewater (i.e., municipal waste stream, combined stormwater runoff, industrial waste stream, etc.) and variations in treatment processes. Generally, increased levels of treatment will yield higher volumes of sludge. However, in the case of combined treatment with stormwater, the stormwater added to normal wastewater influent dilutes the solids concentration per gallon of combined influent.

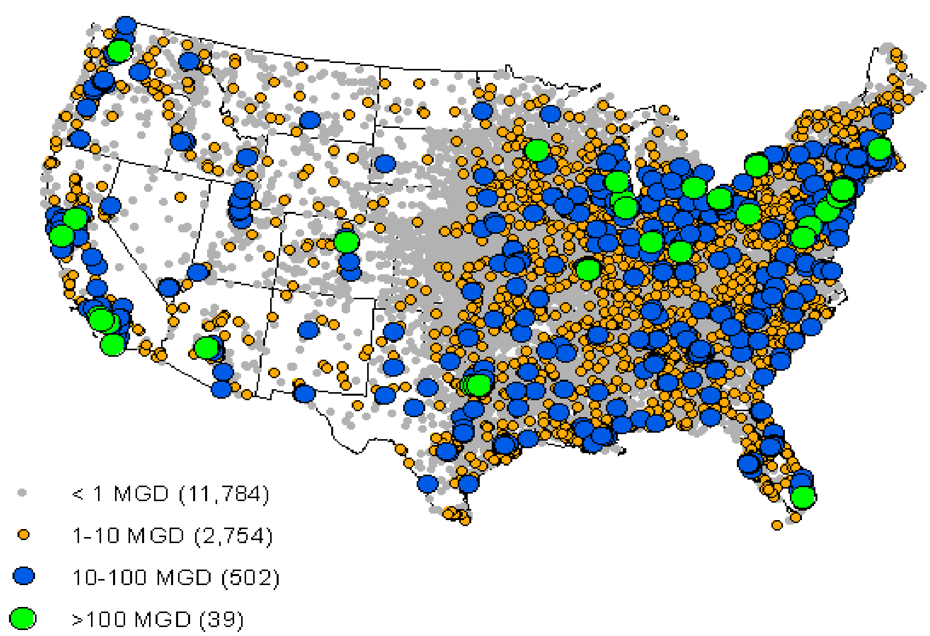


Figure 2-2 Spatial distribution and influent range of 14,581 US EPA 2012 Clean Water Needs Survey (CWNS) catalogued treatment plants

The sludge from the primary and secondary settling stages is composed of mostly organics with some inorganic solids. Preliminary work by the Pacific Northwest National Laboratory (PNNL) estimates that wastewater residuals represents a small fraction of the total annual influent flow at a majority of POTWs. Based on the calculated production of primary, secondary, and total sludges at the 14,581 documented POTWs in CWNS 2012, the country produced approximately 13.7 million dry tons of wastewater residuals in 2012.

Wastewater residuals that have been treated for use are thereafter referred to as biosolids. According to the Water Environment Federation's (WEF's) 2015 fact sheet on biosolids (based on 2004 US EPA data), the United States generates 7.1 million dry tons of biosolids each year (counting only reused sludge, not total sludge). About 60% of these biosolids are applied to land to replenish the soil, and the remaining 40% are landfilled. Table 2-3 summarizes the current annual utilization of wastewater residuals. In addition to the 2.84 MM dry tons of biosolids landfilled annually, 6.60 MM dry tons of wastewater residuals and sludge are untreated or unused. Combined, the landfilled biosolids and untreated wastewater residuals contain an inherent energy content of 158.5 TBtu (1,365 MM GGE).

Table 2-3. Wastewater Residuals – Current Annual Resource Utilization

Wastewater Residuals	Annual Resource Utilization (Current)		
	Estimated Resource Availability (MM Dry Tons)	Inherent Energy Content (Trillion Btu)	Fuel Potential (MM GGE)[1]
Biosolids [2]	7.10	102.6 [3]	883.5
Land Applied	4.26	61.5	530.1
Landfilled	2.84	41.0	353.4
Unused Wastewater Residuals and Sludge	6.60	117.5 [4]	1,011.9
Untreated/Unused	6.60	117.5	1,011.9
Total	**13.70**	**220.0**	**1,895.4**

[1] 116,090 Btu/gal, does not account for conversion efficiency
[2] Biosolids have been treated for use (e.g., AD/incineration for energy production, compost/soil amendments)
[3] Post digester sludge: 14.45 MMBtu/Ton (WERF 2016)
[4] Primary sludge (unused): 17.80 MMBtu/Ton (WERF 2016)

2.1.2. Collection and Processing

Pipes handle the majority of wastewater transport. Existing networks of sewer pipes collect wastewater so that it can be processed at a central facility—enabling WRRFs to operate at large scales. Numerous smaller facilities around the country are connected to smaller pipe networks. Some sewer pipe systems also collect stormwater, which impacts the biochemical oxygen demand (BOD) and flow volumes at a facility. Sludge is also transported through pipes onsite within a WRRF, whereas biosolids are primarily moved by truck for transport offsite.

Once settled out of the wastewater, sludge still contains a significant amount of water that must be removed (dewatering). Sludge may also contain organisms with high pathogenicity, heavy metals, pollutants of emerging concern, or odor-causing compounds that must be reduced, depending on the intended application.

In a high-level view, a typical municipal POTW performs a series of major processing steps on the wastewater, yielding sludge as the major waste product (see Figure 2-3).

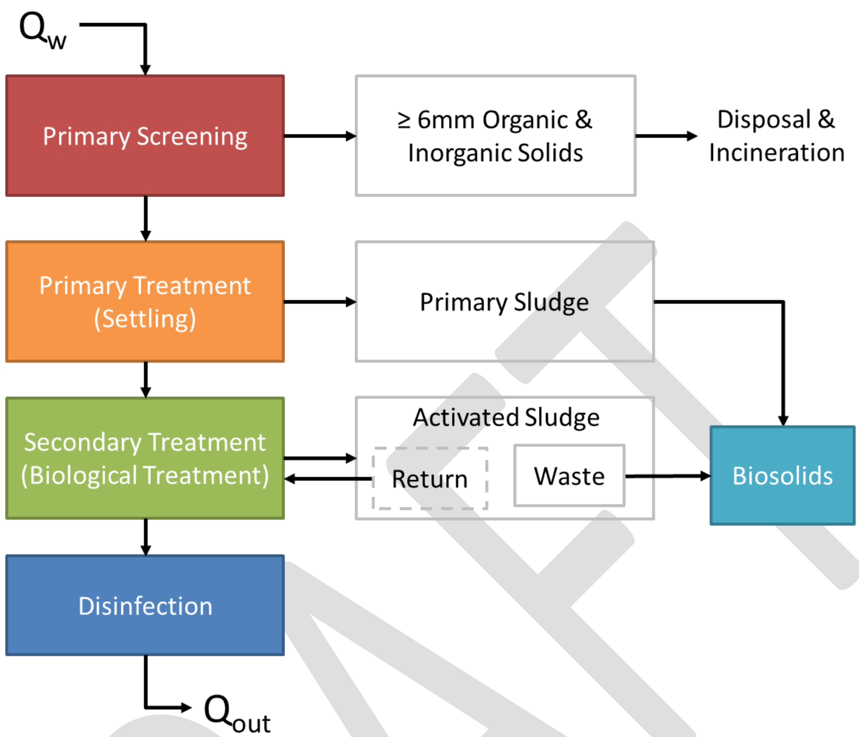


Figure 2-3. High-level process schematic for treatment phases of a POTW

2.1.2.1. Primary Screening

Primary POTW screening of raw incoming wastewater will filter out large debris. This step protects downstream processing equipment, prevents the discharge of large solids to waterways, and improves the efficiency of the entire treatment process. The debris screened out at this point is typically landfilled or incinerated; it typically includes a wide variety of organic and non-organic materials, especially in waste systems that incorporate stormwater. For typical municipal POTWs, a coarse bar screen is generally used to filter out materials larger than or equal to about 6mm. In a system such as this, grit (i.e., sand, gravel, coffee grounds, eggshells, etc.) can be settled into a grit chamber to eliminate these materials from further processing. In the future, materials collected in the primary screens might be evaluated for potential use as feedstocks for hydrothermal liquefaction (HTL). In general, the fraction of debris removed at this stage represents 5–10% of total influent solids (Turovskiy and Mathai 2006; Tchobanoglous et al., 2014). This primary screening process is not addressed further in this analysis as the resulting solids are not considered a “clean” source of organics.

2.1.2.2. Primary Treatment

The primary treatment stage involves the initial clarification or settling of suspended solids (i.e., primary sedimentation). Chemical flocculants can be used to increase the efficiency of solids settling (time to settle and total solids). This treatment produces a primary sludge, which consists of organic solids and inorganic fines. Solids concentrations are reduced to approximately 4–6%, of which 60–80% are volatile suspended solids (VSS). In general, 50–60% of the solids are captured at this stage.

2.1.2.3. Secondary Treatment

Secondary treatment involves a combination of aeration, exposure to microbes, and secondary clarification through additional solids settling (i.e., secondary sedimentation). This treatment focuses on the dissolved organic matter not captured during primary treatment. Secondary treatment produces activated sludge, which is divided into two fractions. Waste activated sludge is removed from the process for further treatment. Return activated sludge is returned to the aeration and clarification stage to support the secondary treatment process. At this phase, solids concentrations are reduced to 0.5–1.5%, with VSS at 70–80%.

2.1.3. Feedstock Characteristics

The usable energy in wastewater is determined by the organic fraction, which is measured by chemical oxygen demand (COD). For typical wastewater, the COD is approximately 1.9 kWh/m^3 (McCarty et al. 2011). Specifically, the potential energy contained in wastewater sludge is on the order of 12–16 kJ/g dry-weight, with approximately 66% of the available energy captured in the primary sludge and about 42% captured in the secondary sludge—making the potentially available energy 8–10 times the amount required to operate the average wastewater plant (Zanoni and Mueller 1982; Vesilind and Ramsey 1996; Shizas and Bagley 2004).

Sludge characteristics and content relevant to use of the sludge as a feedstock vary according to the particular source, process, and unit process. Table 2-4 shows some key feedstock characteristics and the nutrient composition of sludges from various sources. Trends in the individual process units (including primary sludge, secondary sludge and post-digester sludge) include decreasing amounts of carbon, oxygen, and high heating values (HHVs). These sludges also show an increase in sulfur and ash content.

Table 2-4 Feedstock and nutrient characteristics of various sludges shown on a dry weight basis

	Weight %						Moisture Content (%)	Volatile Matter (%)	HHV (MJ/kg)	Citation
Feedstock	C	H	N	O	S	Ash				
Primary Sludge	47.8	6.5	3.64	33.6	0.48	7.5	95.5	82.17	20.7	*WERF, 2016*
Secondary Sludge	43.6	6.55	7.9	29	0.72	16.2	96.1	76.25	19.6	*WERF, 2016*
Post-digester Sludge	38.7	5.68	4.48	27.9	1.63	28.1	~72[1]	N/A	16.8	*WERF, 2016*
Sludge	51.4	7.34	6.87	32.43	2.08	39.35	23.97	86.65	N/A	*ECN Phyllis2*
AD Sewage Sludge	39.88	6.2	6.04	20.5	5.62	21.8	82.5	69	17.97	*He et al 2015*
Sewage Sludge	51.98	7.61	7.49	30.35	2.57	36.68	N/A	56.78	N/A	*Malins et al 2015*

Note: 72% moisture for the post-digester sludge is after normal dewatering at the wastewater treatment plant where collected, not directly out of the digesters.

Application of raw or treated sewage sludge (i.e., derived from an AD process) to cropland can provide a large part of the nitrogen and phosphorus required for many crops while significantly reducing the sludge disposal costs of sewage treatment. Sludge from wastewater streams is comparable to animal waste; however, the presence of impurities (including metals, pathogens, or pharmaceuticals) is significantly more likely, as it is collected from a broader set of sources. These sludges often require remediation prior to any further processing. From this point forward, however, processing options are nearly identical.

2.2. Animal Waste

Animals like pigs and cows excrete manure that contains digested and undigested organic matter, bacteria, and other microorganisms from the gut. This manure, like urine, is rich in organic matter that is available for transformation into a saleable product. In most instances, animal manure is applied to fields as fertilizer or, in certain cases, used in anaerobic digesters. Animal manure is particularly useful as a fertilizer because, once applied to the soil, mineralization makes a portion of the nitrogen and phosphorous available for use as plant nutrients each year. Odors from field applications are a continuing concern, however, especially where fields border residential areas. This discussion of animal waste is limited to swine, dairy, and fattened cattle operations.

Although poultry manure is excluded from this report, it may also play a moderate role in energy production. In some parts of the United States and other countries, broiler or turkey litter is being combusted to thermally convert it into electricity or syngas. A few gasification and combustion projects using dry poultry litter have been developed in the Chesapeake region over the past few years (Sustainable Chesapeake 2016), and a $30 million centralized facility is now being constructed to produce electricity and steam in North Carolina. Poultry manure is also utilized as fertilizer, but the available spatial data is inadequate to accurately characterize these operations.

2.2.1. Resource Assessment

Animal manure has historically been used as an inexpensive fertilizer or additive to improve soil quality. Approximately 5% of all U.S. cropland is fertilized with manure. The use of manure is driven by both the agronomic needs of crops and the transport costs that limit haul distances, creating close links between certain types of livestock and crops. Corn is planted on about 25% of U.S. cropland and accounts for over half of the land using manure. The bulk of the manure applied to corn is generated from nearby dairy and swine operations. Manure from poultry and cattle feedlot operations are drier and thus less costly to transport, so they are often shipped to other operations (USDA 2009).

AFOs and CAFOs

According to the EPA, animal feeding operations (AFOs) are agricultural enterprises that raise and keep animals in confined situations. AFOs congregate animals, feed, manure, urine, dead animals, and production operations on a small land area, and feed is brought to the animals. The United States has approximately 450,000 AFOs.

A Concentrated Animal Feeding Operation (CAFO) is an AFO with more than 1,000 animal units (equates to 1,000 beef cattle, 700 dairy cows, or 2,500 swine weighing more than 55 lbs.) confined on site for more than 45 days per year. Any size AFO that discharges manure or wastewater into a natural or man-made ditch, stream, or other waterway is defined as a CAFO, regardless of size.

In the past few decades, livestock production has shifted to fewer, much larger operations, categorized as concentrated animal feeding operations (CAFOs) and animal feeding operations (AFOs), with the key distinction being the size of the operation (see inset). As a consequence of this increasing intensification of livestock practices, large quantities of manure are consolidated over limited geographic areas, exceeding the demand from nearby farms. The resultant excess of manure can pose environmental risks when stored or applied in heavier quantities (Yin, Dolan et al. 2010). Potential risks include fish kills, dissolved oxygen problems, algal blooms in surface water, increased nitrates and bacteria contamination in groundwater, and health problems for recreational water bodies. Certain constituents can cause health problems for grazing animals as well (NRCS 2012).

In response to these risks, Federal, State, and local governments have expanded regulations and conservation programs. In some cases, State and local governments have claimed damages to water resources from over application, runoff, and storage of manure, leading to lawsuits against livestock operations. Programs to comply with new regulations increase the cost of livestock operations. Many operations are now required to develop and comply with manure and/or nutrient management plans to limit the potential for catastrophic spills and to avoid exceeding the agronomic needs of nearby crops. Alternative approaches are to expand agreements with farmers to accept manure, acquire additional land for manure application, reduce manure nutrient content, reduce the production of manure, or find other uses for the manure.

Assessing the quantity of animal waste that is potentially available for waste-to-energy requires estimating the total manure generated, estimating the recoverable fraction of the manure generated, and then determining the excess manure that is available after subtracting the manure used for land applications. Noteworthy work by Kellogg et al. (2000) estimates annual US manure production for confined livestock at 452 million tons (wet). A recent update to this analysis is based on a current state-based inventory of confined livestock and typical manure production coefficients; manure recoverability factors to account for losses during collection, transfer, and storage; and assumed manure nutrient content to determine quantities needed to satisfy on-farm fertilization needs. This analysis estimates total annual manure production of 43.5 million dry tons, of which 41 million are the recoverable fraction, and 26 million excess after subtracting manure used for land applications. Table 2-5 summarizes the current annual resource utilization for animal waste. The 26 million dry tons of excess animal waste represent a significant inherent energy content: 347 TBtu (2988.8 MM GGE).

Table 2-5. Animal Waste – Current Annual Resource Utilization

Recoverable Animal Waste	Annual Resource Utilization (Current)		
	Estimated Resource Availability (MM Dry Tons)	Inherent Energy Content (TBtu)	Fuel Potential (MM GGE)[1]
Beneficial Uses	15.00	200.2	1,724.3
Digested and/or Land Applied	15.00	200.2	1,724.3
Excess	26.00	347.0	2,988.8
Other/Unknown	26.00	347.0	2,988.8
Total	**41.00**	**547.1**	**4,713.0**

[1] 116,090 Btu/gal, does not account for conversion efficiency

Land applied manure may be digested to produce biogas first.
13.34 MMBtu/dry ton based on Table 2-6. Nutrients and other characteristics for animal waste

2.2.2. Collection and Processing

As shown in Figure 2-4, the primary functions associated with manure handling are production, collection, transfer for storage and/or treatment, and utilization (SCS, 1992). Production addresses the amount and nature of manure generated. This resource assessment explores the type, volume, location, and potential timing of manure produced. Collection and storage refer to the “harvesting” of manure from the production locations and its temporary containment prior to either treatment and/or use. The optimal distance for transporting manure for energy projects is less than half a mile.

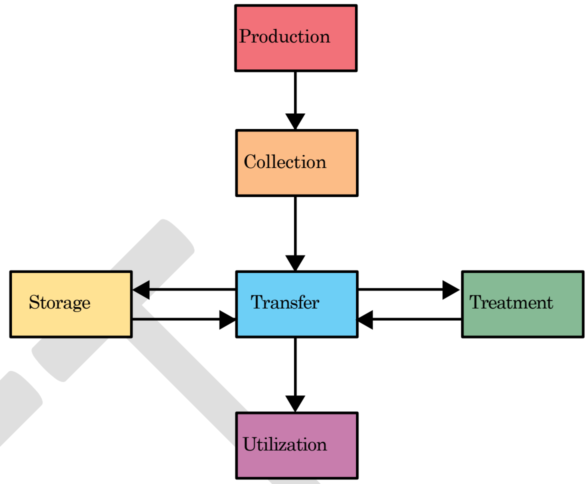


Figure 2-4 Typical animal manure handling functions (SCS 1992)

Manure treatment refers to the physical, chemical, or biological modification of the manure to reduce its pollution potential. Transfer refers to any movement of the manure, as a solid, liquid or slurry, throughout the management system. The point in this system at which it would be most advantageous to intercept the manure for delivery and processing has yet to be determined.

CAFOs hold large quantities of livestock and produce larger quantities of animal waste than AFOs. Collecting this waste can be accomplished using either manual labor (e.g., shovels) or engineered solutions (e.g., slanted floors). The majority of U.S. CAFO facilities specialize in beef cattle, dairy cows, swine, or poultry. Once collected, the manure is ready for processing. If needed, storage set ups must pay special attention to odor control.

2.2.2.1. Collection

Collection methods for manure are determined by the moisture content/solids content of the manure in question. Different species of livestock excrete manure with different percentages of solids. Manure collection practices also affect the final solids content of the manure. The type of equipment and the procedures used to collect and handle manure depend primarily upon the manure’s consistency. Figure 2-5 shows the total percentages of solids in manure, as

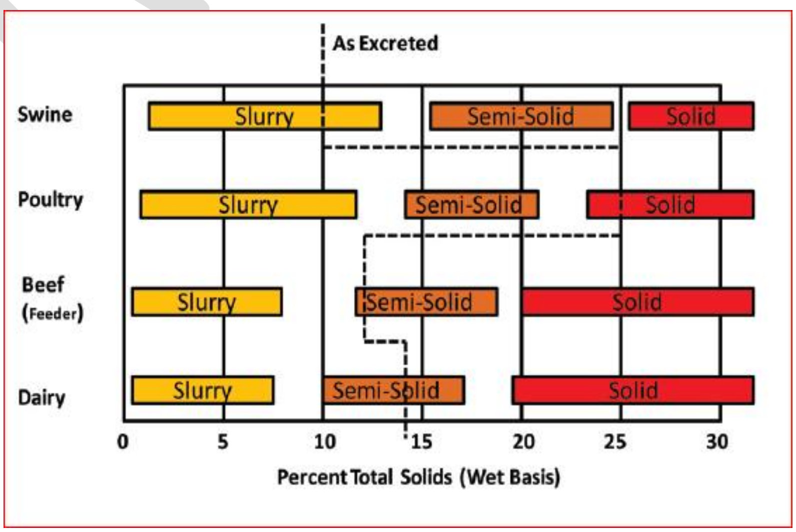


Figure 2-5 Solids content of manure as excreted (Ogejo 2015)

excreted by different types of CAFO animals in United States. (Ogejo 2015).

2.2.2.2. Solid manure

Solid manure is typically generated in systems that add bedding to the manure to absorb moisture and enhance environmental conditions in the production area. Solid manure can also result from drying conditions, which may occur on the surface of a beef feedlot. Solid manure storage and handling is typically more forthright than liquid or slurry manure systems. Solid manure is usually collected using scrapers, box scrapers, blades, front-end or skid-steer loaders, or similar devices. Equipment sizes range from small blades suitable for tractors of 50 horsepower or less to large bucket loaders mounted on dedicated power units for operations generating large volumes of manure.

Figure 2-6 Slotted floors

2.2.2.3. Slurry manure

Slurry manure is typically generated in systems that add little or no bedding to the excreted manure/urine. Slurry manure is typically between 5% and 15% solids. It is "thicker" than liquid manure but cannot be stacked or handled in the same way as solid manure. Slurry manure is collected using slotted floors, scrapers, vacuums, or slurry pumps.

Figure 2-7 Manure Scraper

<u>Liquid manure</u>

Liquid manure is characterized by very low solids content (less than 5%) and, generally, low nutrient content. In some cases, liquid manure is applied to crop fields through irrigation systems. However, liquid manure is generally stored in ponds or lagoons until it is applied to crop fields.

Figure 2-8 Slurry pump

2.2.2.4. Manure Processing and Management

Manure management is required of all dairy, beef cattle, and swine operations to control nutrient runoff and optimize the nutrient benefits of manure. Whether animals are in an open environment or in confined spaces, manure management is required to meet many State-level environmental laws and requirements.

Through manure management, animal waste operations establish a nutrient plan and carefully monitor soil conditions to determine the best times of the year for nutrient application. Solid manure is usually applied by manure spreaders, while tank wagons or drag hoses are often used to apply liquid manure and milking center wastes (Figure 2-9 to Figure 2-).

Figure 2-9 Manure spreader

Figure 2-9 Tank wagon used for liquid manure application

Figure 2-11 Drag hose used for manure slurry application

2.2.2.5. Anaerobic Digestion

According to the EPA's AgStar data, the United States had 264 AD projects using animal waste as of March 2015. As shown in Figure 2-10, the majority of these projects use waste from dairy operations (202), with the remainder using waste from operations focused on for hogs (39), mixed animals (8), beef (8), and poultry (7) (AgSTAR). AD projects can benefit from manure management and processing wherever substantial amounts of centralized manure can be collected and transported locally. The manure in these projects is collected and trucked or piped to the AD facility, where it is stored in large containers until it can be fed into the reactor.

In some cases, the manure must be processed upfront to assure that entrenched solids or other contaminants do not interfere with reactor operations. AD projects adjust these upfront processes as needed to address the resource. One operation, for example, is designed to wash away up to 99% of the entrenched sand that is used as bedding in dairies—yielding a clean manure stream for downstream digestion (Lee 2013). To increase biogas output, some operations add food waste (if available) to the manure before it enters the reactor.

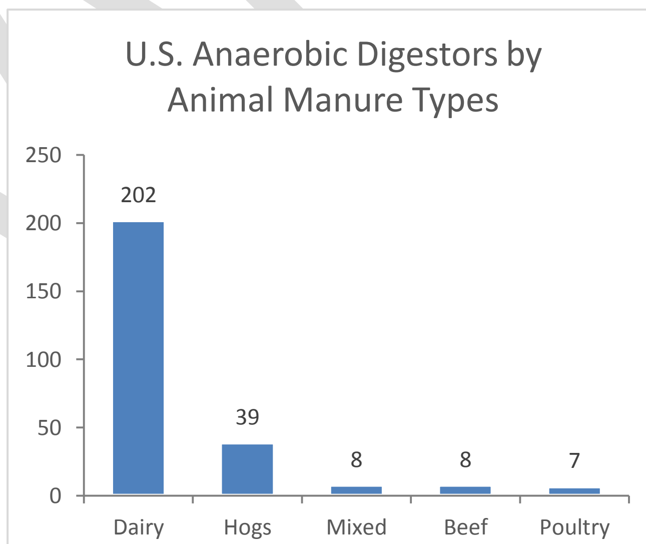


Figure 2-10 Manure AD projects in the United States
Note: Total 264 US AD projects

2.2.3. Feedstock Characteristics

Animal manure is an excellent source of nutrients when applied appropriately to the land. Manure contains macro- and micro-nutrients that supply organic matter for plants and improve soil quality. Table 2-6 lists some feedstock characteristics and the nutrient composition in various sources of manure generated by U.S. CAFOs. As shown, the different manure types contain varying amounts of carbon, nitrogen, oxygen, and ash.

Table 2-6. Nutrients and other characteristics for animal waste

	Weight % (dry basis)						Moisture Content	Volatile Matter	HHV (MJ/kg)	Citation
Feedstock	C	H	N	O	S	Ash	(%)	(%)	(dry basis)	
Swine Manure	41.1	5.42	3.36	50.1	N/A	16.3	N/A	83.7	N/A	*Chen et al, 2014*
Swine Manure	47.3	5.9	4.58	20.1	0.93	18.5	N/A	60.6	19.5	*Ro. et al. 2010*
Swine Manure	33.52	6.16	2.81	57.5	N/A	22.3	20	N/A	7.9	*Xiu et al 2011*
Cattle Manure (wet basis)	35.38	4.73	2.38	57.51	N/A	7.16	76.37	16.21	15.16	*Yin et al 2010*
Dairy Manure	38.8	5.1	1.3	54.7	N/A	N/A	N/A	83.2	11.9	*Midgett et al, 2012*

2.3. Food Waste

Food waste is generated in the preparation, cooking, and serving of food in a residential, commercial, or institutional setting—including homes, restaurants, grocery stores, catering outfits, hospitals, etc.—and dispatched for disposal. This report acknowledges that a portion of what might be considered food waste is still edible, and food that is still edible is excluded from this effort. This edible category includes foodstuffs that might not be saleable but can still be eaten (e.g., food at or just past its "sell by" date, but not yet rotten). Any food that can be used for its intended purpose, donated, or consumed by people or animals is not part of this effort. Please refer to EPA's Food Recovery Hierarchy for details.

This effort does include raw or prepared food that must be discarded in the interest of public health. The inefficiencies of food supply generate waste and increase cost, causing prices to reflect anticipated waste. Identifying and valorizing these waste streams can directly reduce the cost of food, particularly fresh produce that is liable to spoil—directly increasing market access. It is hoped that this valorization will also provide more beneficial use of off-spec foods that would otherwise not be harvested. Recognizing and eliminating waste in the food supply will directly benefit the United States.

Table 2-7 presents the key terms and definitions used to describe food waste and food waste sources in this report.

Table 2-7. Key Terms and Definitions Pertaining to Food Waste and Food Waste Sources

Key Terms and Definitions Pertaining to Food Waste and Food Waste Sources	
Key Terms	
Food Waste	Food not used for its intended purpose, no longer fit for human or animal consumption, and sent for disposal. By-products from food and beverage processing that cannot be recycled or reused are also in this category.

Food Loss	Food that gets spilled or spoilt before it reaches its final product or retail stage. These losses may be due to problems in harvesting (or other farm losses), storage, packing, transport, infrastructure or market mechanisms, as well as institutional and legal frameworks. Food loss is not included in the resource assessment.
Food Waste Disposal	Food waste discarded in landfills or incinerated
Food Waste Diversion	Food waste diverted from landfills/incinerators and re-used for other purposes (e.g., biogas, compost, food donation, animal feed)
Food Waste Sources	
Industrial	Includes off-spec or unsellable food at the food-processing stage, e.g., fruit and vegetable canneries, fresh/frozen fruit and vegetable processors, creameries, wineries, meat packing and processing plants, grain mills, soft drink bottling plants, byproducts, wash water, etc.
Commercial	Includes expired or unconsumed food at the point of sale, e.g., supermarkets or restaurants. Food waste from airports is also considered under this category.
Institutional	Includes food waste generated by educational entities, hospitals, correctional facilities, and hotels
Residential	Waste generated by residential entities and military bases

[1] US Census tracks military bases as residences to avoid double-counting

2.3.1. Resource Assessment

Food waste assessments estimate that the sources listed in Table 2-7 generate between 37 and 66 million wet tons of food waste annually (EPA 2015a and USDA 2013). The most common methodology used in these assessments is to calculate per-capita waste generation estimates based on sampling at a variety of waste aggregation sites. Depending on the location, season, and other factors, per capita estimates can vary from 0.03 tons per person per year to 0.24 tons per person per year. The National Renewable Energy Laboratory (NREL) recently analyzed a series of these food waste assessments and identified a clustering around 0.13 tons of food waste generation per person per year. This rate corresponds to a total estimate of 60.2 million wet tons per year (2012 estimate) (Milbrandt et al. 2016).

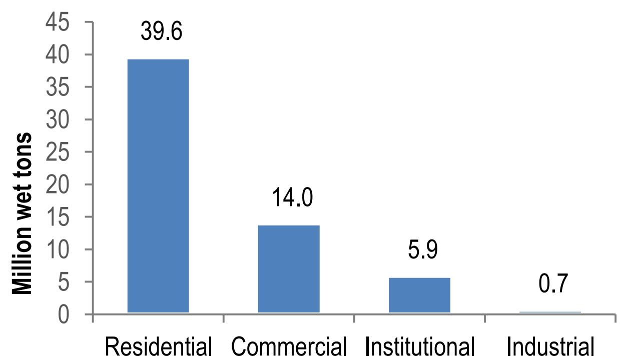


Figure 2-11 Food waste (million wet tons) generated by entity type

Figure 2-11 and Table 2-8 break down of the estimated 60.2 million wet tons of total food waste by entity type. Residential food waste comprises two-thirds of all food waste at 39.6 million tons (Milbrandt et al. 2016). Commercial food waste, institutional waste, and industrial waste contribute 23%, 10%, and 1% of total food waste, respectively. After residentially derived food waste, the next three largest single sources of food waste are restaurants (commercial), educational facilities (institutional), and supermarkets (commercial). Respectively, restaurants, educational facilities, and supermarkets contribute 10.8 million tons (18%), 4.2 million tons (7%) and 3.6 million tons (6%) toward the 60.2 million-ton total (Milbrandt et al. 2016).

Table 2-8. Food Waste – Sources and Energy Content

Food Waste Sources	Annual Resource Utilization (Current)			
	Estimated Resource Availability (MM Wet Tons)	Estimated Resource Availability (MM Dry Tons)	Inherent Energy Content (TBtu)	Fuel Potential (MM GGE)[1]
Residential	39.60	9.90	205.9	1,773.8
Commercial	14.00	3.50	72.8	627.1
Institutional	5.90	1.48	30.7	264.3
Industrial	0.70	0.18	3.6	31.4
Total	**60.20**	**15.05**	**313.0**	**2,696.5**

[1] 116,090 Btu/gal, does not account for conversion efficiency

Assumes 75% moisture content (the moisture content of food waste varies seasonally, ranging from 76% in the summer (8.6 MM dry tons equivalent) to 72% in the winter (9.7 MM dry tons equivalent)).

5.2 MMBtu/Ton - Average Heat Content of Selected Waste Fuels from http://cta.ornl.gov/bedb/appendix_a/Average_Heat_Content_of_Selected_Waste_Fuels.pdf

Because the methodology is based on per capita generation by entity type, the availability of the food waste is proportional to population, as shown in Figure 2-12.

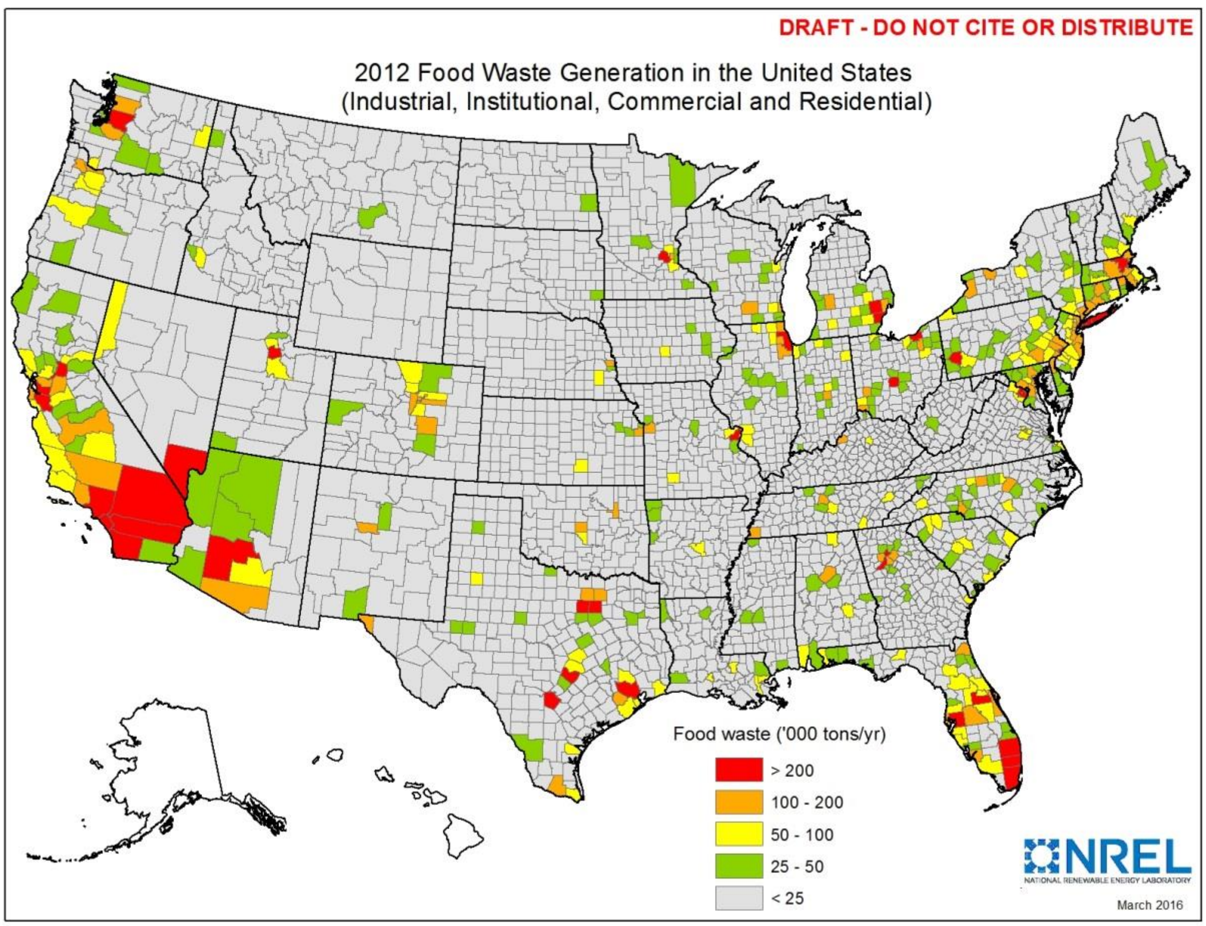


Figure 2-12 2012 Food Waste Generation in the US (wet tons)

2.3.2. Collection and Processing

Large volumes of food waste are generated by larger facilities, particularly supermarkets and banquet halls. Commingling of waste, particularly in the home (where food is not the only waste), creates a challenge for aggregating and transporting food waste. Food waste is often collected and commingled in trash bags and dumpsters, which are transported to waste transfer stations. It is at these stations that waste stream separation currently occurs, as items are removed for recycling, composting, and landfilling. However, waste separation at transfer stations is costly and could present feedstock quality issues. Source separated waste streams (e.g., restaurants, homes, communities) can help to cost-effectively limit contaminants and produce more consistent feedstocks than commingled trash.

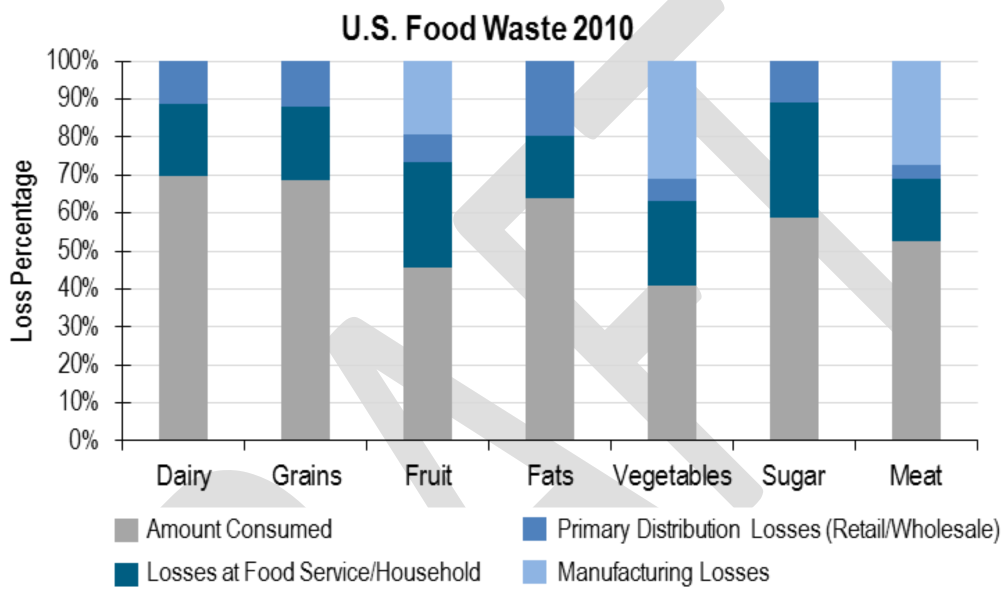


Figure 2-13 Food Waste from Harvested Food, 2010 (Buzby 2014)

Figure 2-13 shows the outcomes for various food types. Estimates for annual composting of food waste range from 1.7 to 4 million tons per year; however, this number is increasing as cities such as San Francisco and Seattle now require point source separation (EPA 2012; BSR 2012). Of all food waste generated, disposal in landfills is the most prevalent outcome, with an estimated 35.2 million tons discarded to landfills in 2013 (EPA 2015b). However, these disposal practices may be shifting as several States in the northeast have now banned the disposal of food waste in landfills. Donations to food banks total an estimated 0.6 to 1 million tons (EPA 2015b; Feeding America 2016). Finally, food waste used for animal feed is estimated at 0.1 to 0.2 million tons (EPA 2015; Westendorf et al. 1996). Co-digestion with other waste streams (such as waste water treatment plant (WWTP) sludge or manure) is a significant use for postconsumer food waste; however, limited estimates exist. At least 109 facilities currently co-digest food waste for waste-to-energy purposes (EPA 2015b). EPA is pursuing an information collection request pertaining to AD facilities that process food waste, and the results are expected to increase this number.

Table 2-9 summarizes the nation's current annual utilization of food waste. The 55 million wet tons (~13.8 MM dry tons) of excess food waste have an estimated inherent energy content of 286 TBtu, or more than 2.4 billion GGE. Although some of the landfilled food waste is captured as biogas in landfill digesters, alternative conversion approaches would help capture a larger portion of the inherent energy in food waste and avoid the associated fugitive methane (CH_4) emissions.

Table 2-9. Food Waste – Current Annual Resource Utilization

Food Waste	Annual Resource Utilization (Current)			
	Estimated Resource Availability (MM Wet Tons)	Estimated Resource Availability (MM Dry Tons)	Inherent Energy Content (Trillion Btu)	Fuel Potential (MM GGE)[1]
Beneficial Uses	5.20	1.30	27.0	232.9
Compositing	4.00	1.00	20.8	179.2
Food Banks	1.00	0.25	5.2	44.8
Animal Feed	0.20	0.05	1.0	9.0
Excess	55.00	13.80	286.0	2,463.6
Landfill	34.70	8.68	180.4	1,554.3
Other/Unknown	20.30	5.08	105.6	909.3
Total	**60.20**	**15.10**	**313.0**	**2,696.5**

[1] 116,090 Btu/gal, does not account for conversion efficiency

Assumes 75% moisture content (the moisture content of food waste varies seasonally, ranging from 76% in the summer (8.6 MM dry tons equivalent) to 72% in the winter (9.7 MM dry tons equivalent)).

5.2 MMBtu/Ton - Average Heat Content of Selected Waste Fuels from http://cta.ornl.gov/bedb/appendix_a/Average_Heat_Content_of_Selected_Waste_Fuels.pdf

Ultimately, any opportunity to convert food waste into energy will face access issues and competition with other uses of food waste. Furthermore, source separation capabilities will be key in determining the feasibility of deploying a localized solution or enabling a supply chain to aggregate the waste in a single, large-scale facility.

2.3.3. Feedstock Characteristics

The composition of food waste can vary significantly both geographically and temporally. Food waste is primarily comprised of carbohydrates, lipids, and proteins. The relative ratio of these three main constituents significantly affects the presence of carbon, nitrogen, and oxygen, which has implications for the potential conversion and upgrading technologies. As an example, biocrude produced from hydrothermal liquefaction can require more severe hydrotreating if the concentrations of oxygen and nitrogen are elevated.

Table 2-10 Seasonal average of elemental analyses of food waste samples, adapted from (WRAP 2010)

Season	Total Solids (%)	Elemental Analysis (% of Total Solids)				
		Carbon	Nitrogen	Sulfur	Hydrogen	Oxygen
Summer	24.2	45.75	3.36	0.71	6.26	35.06
Winter	27.7	49.32	3.17	0.35	6.53	37.14

In contrast to summer samples, winter samples contain higher carbohydrate and lipid concentrations and lower protein concentrations. Figure 2-14 and Table 2-10 show how food composition varies seasonally and geographically across Wales.

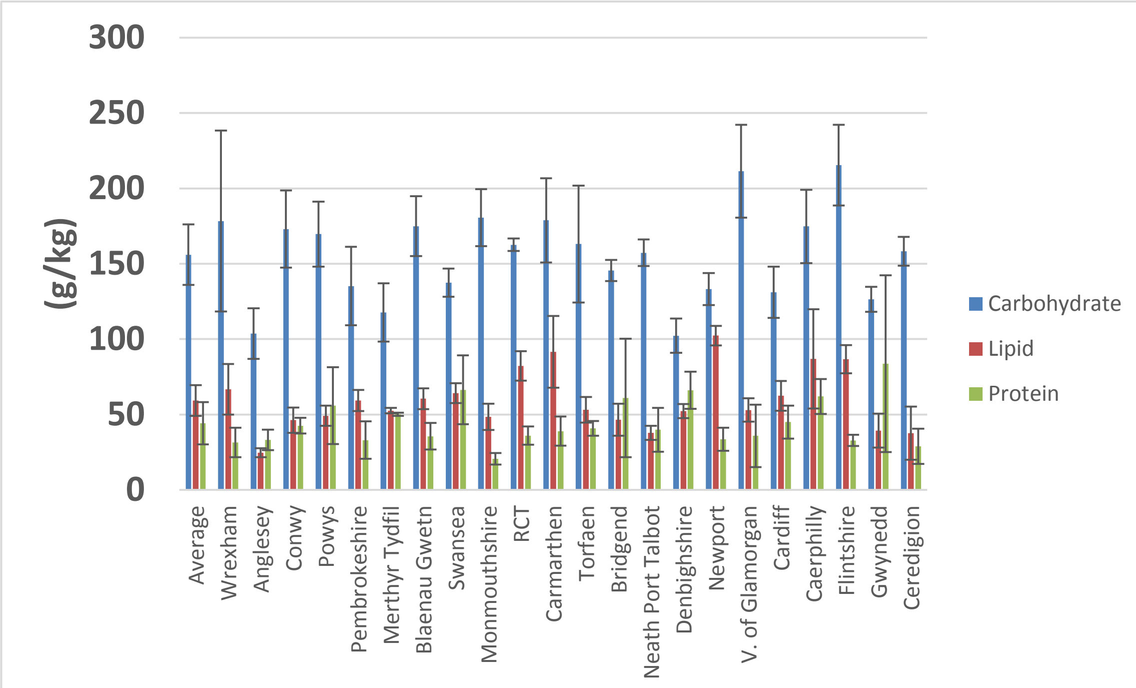


Figure 2-14 Winter food composition across Wales, adapted from (WRAP 2010).
Note: Error bars designate 1 standard deviation.

Food waste characterization studies in the United States have produced similar findings, with total solids between 20% and 32% (Zhang et al. 2007; Liao et al. 2007). Compared to previously described streams, the solids content is substantially higher—yet still very low relative to conventional cellulosic feedstocks.

2.4. Fats, Oils, and Greases

Fats, oils, and greases (FOGs) collectively refer to several resources. All edible FOGs, including those used for animal feed, are excluded from this technology report. Table 2-11 describes the three types of fats, oils, and greases that are included in this effort.

Table 2-11. Key Terms and Descriptions Pertaining to Fats, Oils, and Greases

Key Terms and Descriptions Pertaining to Fats, Oils, and Greases		
Type	**Description**	**Processing Considerations**
Yellow Grease	Yellow grease contains spent cooking oils derived from industrial- or commercial-scale cooking operations.	Renderers commonly filter out solids and remove moisture to meet desired specifications, e.g., keeping free fatty acid levels below 15% to assure compatibility with existing biodiesel operations
Brown Grease	Brown grease (or trap grease) is collected from grease traps that have been engineered to separate insoluble and gelatinous greases from commercial kitchen wastewater streams. These traps allow water to continue flowing to the main sewer or through the water treatment operations.	Brown grease possesses significant contamination and variability in free fatty acid and triglyceride content. Brown grease must be collected, treated, and properly discarded through a variety of methods: landfills, incineration, AD etc.

Animal Fats	Animal fats are composed of byproducts derived from meat processing facilities during rendering, wherein edible fats are removed and purified.	The primary fats of interest include inedible tallow, choice white grease from swine, and poultry fat.

The high density of triglycerides and fatty acids makes each of these streams attractive for transformation into biodiesel by mature esterification technologies. A subset of FOGs is currently processed into biodiesel through these technologies. This report explores these and other FOG resources that are *unsuitable* for biodiesel production (i.e., too high in free fatty acids) and would otherwise require disposal.

2.4.1. Resource Assessment

2.4.1.1. Yellow Grease

Based on available resource assessments, the availability of Yellow Grease ranges between 0.9 and 1.1 million tons per year (Swisher 2015; Milbrandt et al 2016). This range corresponds to an energy potential of 265 million to 324 million GGE, based on an assumption of 39,000 kJ/kg (Joseph 2004).

Domestic production of yellow grease increased by 1.3% annually from 2009 to 2014 (Swisher 2015). NREL estimates have been based on per-capita grease generation at a county level, resulting in a

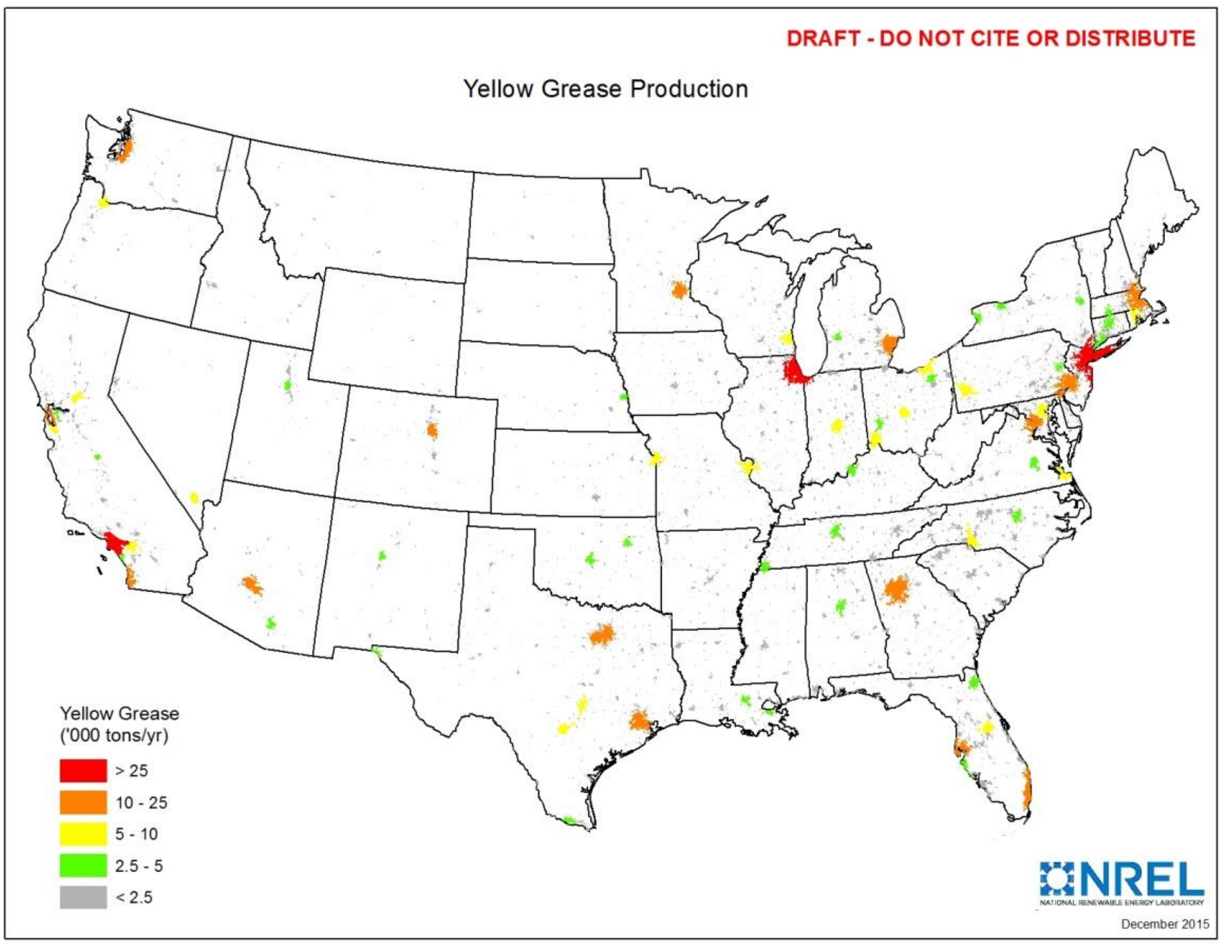


Figure 2-15 Yellow grease production in the United States

resource that is naturally higher in densely populated regions. The distribution of yellow grease production in the United States is shown in Figure 2-15.

2.4.1.2. Brown Grease

Resource analysis performed by NREL estimates 1.7 million tons of brown grease is produced each year in the United States, corresponding to 501 million GGE (Milbrandt et al 2016). As with yellow grease, the estimates for brown grease are based on per-capita extrapolations, concentrating the resource close to urban areas.

The brown grease resource is almost completely untapped at this point, as it is usually incinerated, landfilled, or sent to anaerobic digesters for co-digestion. In rare instances, renderers will process brown grease, suggesting significant potential to valorize brown grease. The distribution of brown grease production in the United States is shown in Figure 2-16.

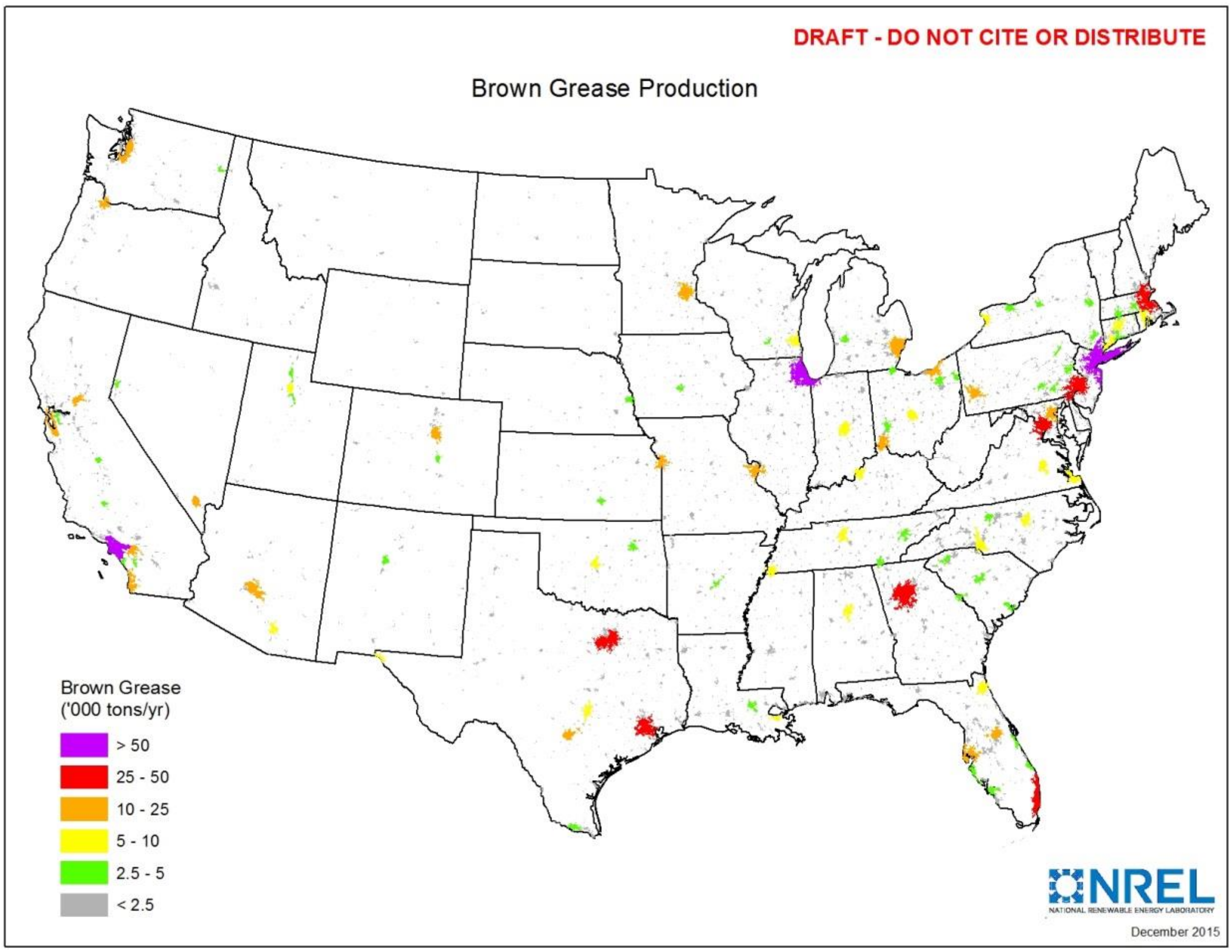


Figure 2-16 Brown grease production in the United States

2.4.1.3. Animal Fats

The National Renderers Association and the USDA have separately estimated the availability of animal fats nationwide at 3.5 million tons and 4.5 million tons, respectively; however, both of these numbers include edible fractions. A more recent NREL analysis of cattle, swine, and poultry slaughtering data yielded an estimate of 4 million tons or 1.18 billion GGE. Animal fats are most abundant in the Midwest, where the concentration of rendering facilities is highest, as illustrated in Figure 2-17.

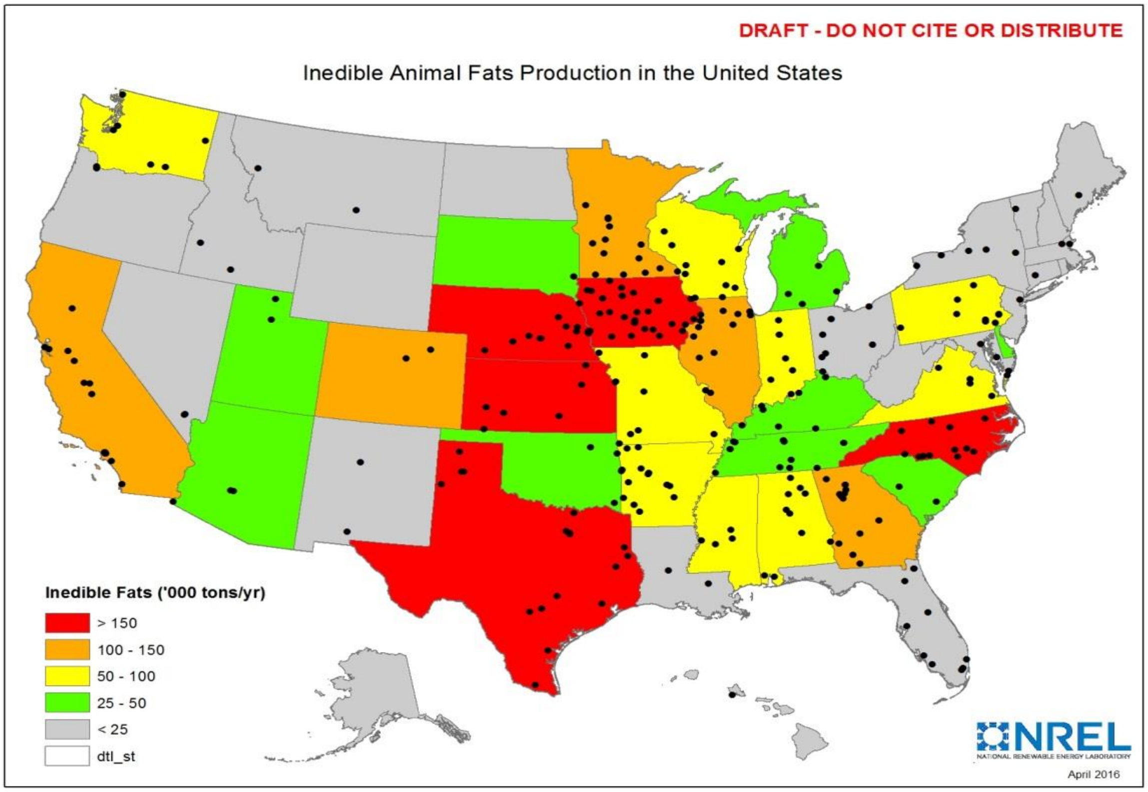


Figure 2-17. Inedible Animal Fats Production in the United States.

Note: Black dots represent livestock rendering plants and select poultry plants.

Inedible animal fats are dominated by inedible tallow, choice white grease, and poultry fat. Figure 2-18 shows the 2014 trends for animal fat consumption. Tallow is commonly commingled for feed purposes and for domestic biodiesel production, while a large fraction of inedible tallow is exported, primarily to Mexico. Choice white grease is used extensively for domestic biodiesel production. Finally, poultry fat is used primarily as animal feed, however, processes to develop renewable diesel from poultry fat have emerged in recent years (not reflected in the figure). U.S. capacity for renewable diesel using hydroprocessing currently exceeds 210 million gallons per year (NREL 2016).

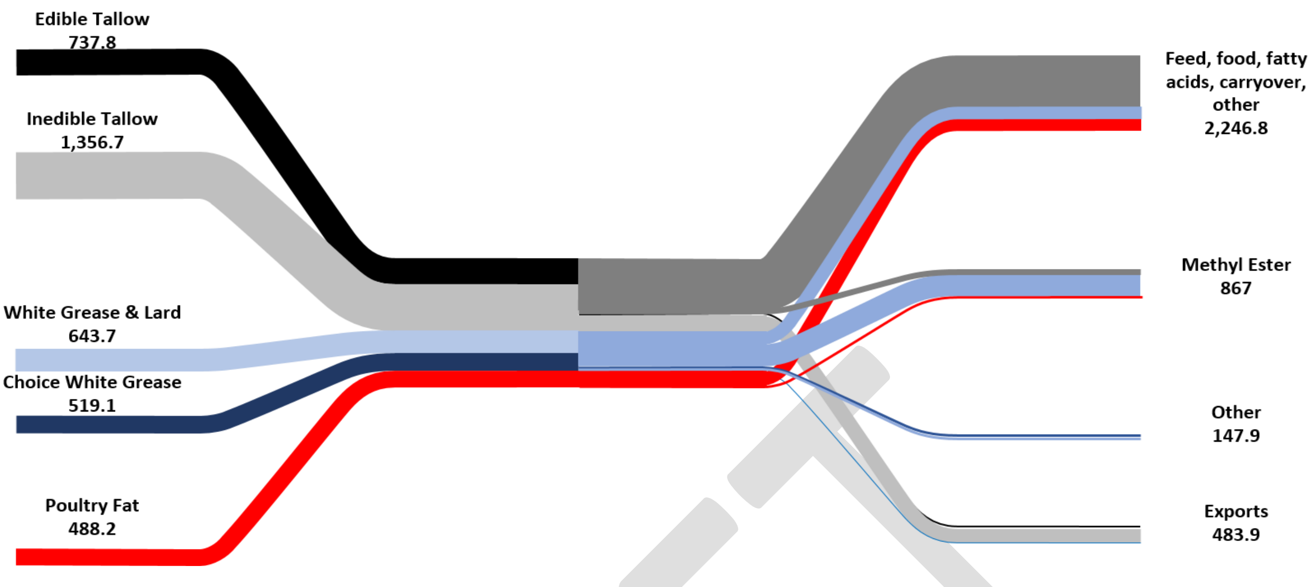


Figure 2-18 Sankey Diagram showing the 2014 mass flows for various animal fats, adapted from (EIA 2016; Swisher 2015)

Note: On the consumption end, tallows are commingled and are shown in an intermediate gray; choice white grease and lard are also commingled and shown in an intermediate blue.

Table 2-12 summarizes the current annual utilization of yellow grease, brown grease, and animal fat. Despite the comparatively small availability of these resources, their high energy density makes them attractive for energy applications.

Table 2-12. Fats, Oils, and Greases – Current Annual Resource Utilization

Fats, Oils, and Greases	Annual Resource Utilization (Current) Estimated Resource Availability (MM Tons)	Inherent Energy Content (TBtu)	Fuel Potential (MM GGE)[1]
Yellow Grease[2]	0.93	31.2	269.2
Biodiesel	0.49	16.4	141.0
Export	0.33	11.2	96.3
Other	0.11	3.7	31.8
Brown Grease	1.70	58.2	501.0
Incinerated, landfilled, or digested	1.70	58.2	501.0
Animal Fat	3.75	137.0	1,180.2
Biodiesel	0.87	31.7	273.2
Feed, food, fatty acids, carryover, other	2.25	82.2	708.0
Export	0.48	17.7	152.5
Other	0.15	5.4	46.6
Total	**6.38**	**226.4**	**1,950.4**

[1] 116,090 Btu/gal, does not account for conversion efficiency

[2] Current US Production, consumption and export of yellow grease adapted from (Swisher 2015; EIA-MBR 2016)

Yellow Grease: 33.53 MMBtu/ton (Joseph 2004)

Brown Grease: 36.54 MMBtu/ton and Animal Fat: 36.58 MMBtu/ton (Milbrandt et al 2016)

2.4.2. Collection and Processing

Nationwide, a relatively small number of rendering operations produce a significant portion of fats, oils, and greases, frequently in close proximity to major population centers. In most areas, specialized waste processing or waste disposal licenses are required to accept FOGs.

The infrastructure for collecting and distributing animal fats and yellow grease is well established, and the processing of these byproducts is localized to rendering facilities. For restaurants and other smaller-scale yellow-grease producing operations, grease collection and processing is highly competitive—with many service providers vying for restaurant off-take agreements. This well-developed collection system makes both animal fat and yellow grease waste streams attractive for biodiesel production.

Brown grease handling is significantly more varied than it is for animal fat and yellow grease. It is collected by service companies, which regularly empty the grease traps and dispose of the aggregated waste in a variety of ways. Brown grease is primarily disposed of at wastewater treatment plants and landfills. Some municipalities require delivery directly to wastewater treatment operations, where volumes can be closely monitored, whereas others allow service providers to inject it into main sewage lines, if plugging is not a concern.

2.4.3. Feedstock Characteristics and Composition

Table 2-13 provides composition information of FOGs and vegetable oils to show the dramatic compositional differences between these feedstocks. The higher concentrations of saturated compounds in FOGs (C14:0, C16:0, and C18:0) imbue them with cold flow properties inferior to those of plant-derived biodiesel. Despite similar fatty acid profiles, trap grease poses challenges for biodiesel production in the form of high water content, solid impurities, and free fatty acids, which can cause the accumulation of soap. Moisture content and insoluble impurities of unprocessed restaurant grease have been measured at up to 18% (Canakci 2007). This content reduces the transesterification kinetics and the amounts of fatty-acid methyl esters due to soap formation (Romano 1982; Freedman et al. 1984; Canakci and Van Gerpen 1999). The additive effects of these impurities have been largely responsible for limiting the use of brown grease.

Table 2-13 Fatty Acid Distribution of Select Feedstocks (from Canakci 2005)

	Fatty acid distribution (% by weight)								
Product	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3	Saturation level (%)	References
Rapeseed oil	–	3.49	–	0.85	64.4	22.3	8.23	4.34	Goering et al. (1982)
Sunflower oil	–	6.08	–	3.26	16.93	73.73	–	9.34	Goering et al. (1982)
Sunflower oil	–	8.6	–	1.93	11.58	77.89	–	10.53	Goering et al. (1982)
Lard	1–2	28–30	–	12–18	40–50	7–13	–	41–50	Linstromberg (1970)
Tallow	3–6	24–32	–	20–25	37–43	2–3	–	47–63	Linstromberg (1970)
Soybean oil	–	10.58	–	4.76	22.52	52.34	8.19	15.34	Canakci (2007)
Yellow grease	2.43	23.24	3.79	12.96	44.32	6.97	0.67	38.63	Canakci (2007)
Brown grease	1.66	22.83	3.13	12.54	42.36	12.09	0.82	37.03	Canakci (2007)

2.5. Biogas

Methanogenesis is the process by which organic substrates (a category that includes all of the focus feedstocks in sections 2.1-2.4) are digested into methane in the absence of oxygen. Through a consortia of organisms, these organic substrates are hydrolyzed, fermented, and finally converted into biogas by archaea known as methanogens. Biogas composition varies significantly depending on the substrate, but it is typically composed of 40–65% methane, 30–40% carbon dioxide (CO_2), and various impurities, including hydrogen sulfide (H_2S), ammonia, and siloxanes (Hosseini and Wahid 2014). Recent analyses have shown little-to-no H_2S (<5ppm) present in biogas streams generated from agricultural residues (soybean residue, corn stover, miscanthus, and bagasse) (Guarnieri et al. 2016). Biogas produced from wastewater tends to have a higher methane content (higher specific energy), while biogas produced in a landfill tends to have a higher percentage of carbon dioxide (lower specific energy).

2.5.1. Resource Assessment

Biogas is primarily used to produce electricity, and a very small number of projects produce bio-based compressed natural gas (CNG) to power natural gas vehicles. An NREL resource assessment estimates the total methane potential from landfill material, animal manure, wastewater, and industrial/ institutional/commercial organic waste at approximately 420 billion cubic feet (Bcf) or 431 Tbtu (NREL 2013). The spatial distribution of these resources is shown in Figure 2-19 and summarized in Table 2-14. If the AD of lignocellulosic biomass resources is included in the biogas potential estimates, this number increases to 4.2 trillion cubic feet, 4.3 quadrillion Btu, or 35 billion GGE (NREL 2013). This volume could displace 46% of current natural gas consumption in the electric power sector and the entirety of natural gas consumption in the transportation sector (NREL 2013). Biogas is a well-distributed resource, given that it is produced from waste streams that are proportional to the population.

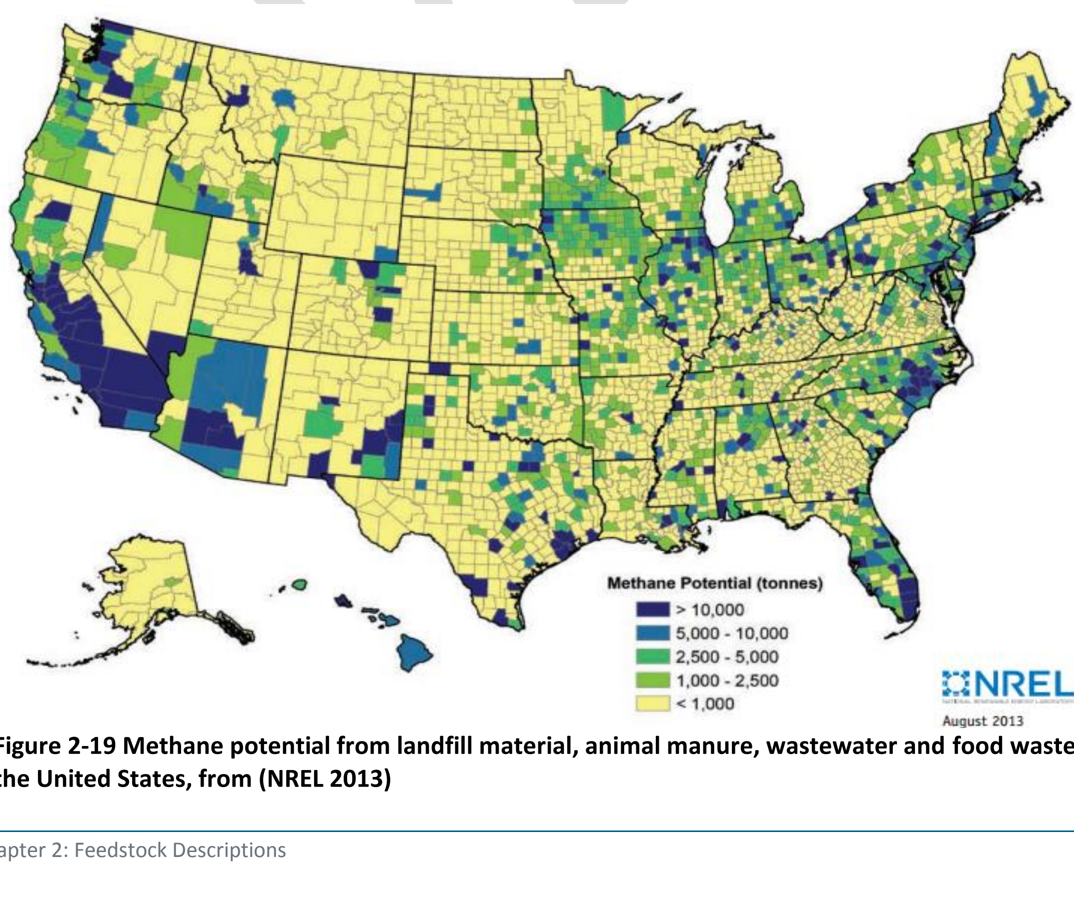


Figure 2-19 Methane potential from landfill material, animal manure, wastewater and food waste in the United States, from (NREL 2013)

Table 2-14. Annual Methane Potential from Biogas Sources (adapted from NREL 2013)

Methane Potential from Biogas Sources	Potential - Annual Resource Utilization			
	Estimated Methane Potential (bcf)	Inherent Energy Content (TBtu)[1]	Electricity Generation Potential (GWh)[2]	Fuel Potential (MM GGE)[3]
Wastewater	125.05	128.2	9,110.0	1,104.1
Landfills[4]	131.23	134.5	9,560.2	1,158.7
Animal Manure	101.85	104.4	7,419.9	899.3
Organic Waste	61.90	63.4	4,509.5	546.5
Total	**420.03**	**430.5**	**30,599.5**	**3,708.6**

Table adapted from NREL 2013, nrel.gov/docs/fy14osti/60178.pdf

[1] Methane LHV, 1025.0 Btu/scf; 293.07 GWh/TBtu

[2] Electric Conversion Efficiency 24.3%, Based on Table 8.2 of the EIA Electric Power Annual reports the average tested heat rates by technology and energy source from 2007 to 2013.

[3] 116,090 Btu/gal, does not account for conversion efficiency

[4] Includes candidate landfills only (from 2013) as defined by the EPA's Landfill Methane Outreach Program, epa.gov/lmop/projects-candidates/

More than 890 livestock and landfill digesters currently produce more than 19,368 GWh (energy equivalent) per year, as shown in Table 2-15. A further 1,241 anaerobic digesters exist at WWTPs, with 857 actively utilizing this energy for heating digesters, generating on-site electricity, or other purposes (Shen et al 2015). If sludge from the facilities treating more than 40 million gallons of water per day the United States were to be subsequently digested anaerobically, it could generate an additional 9,110 GWh per year or enough power for 830,000 homes annually (Shen et al 2015). To date, biogas in the United States has remained largely untapped as a resource, primarily due to the size of domestic natural gas reserves, which have increased 79% over the last decade. The abundant supply of natural gas has put downward pressure on natural gas spot prices and created little appetite for investment in renewable methane production until the rise of RIN incentives.

Table 2-15 Operating Biogas Systems in the United States

Biogas Source	Number of Facilities	Energy Equivalent Generation (GWh)	Reference
Livestock	242	981	As of May 2016 (EPA AgSTAR 2015)
Landfill	648	18,387	As of March 2016 (EPA LMOP 2015)
WWTP	1,241	n.d.	(Shen et al. 2015)
Total	**2,131**	**>19,368**	

Livestock Digesters: 242 Operational Livestock Digesters (981 million kWh equivalent energy generated) as of May 2016, EPA AgSTAR 2015. Available from epa.gov/agstar/agstar-data-and-trends

Landfill Digesters: 648 Operational Landfill Digesters (2,099 MW electricity capacity and 304 mmscfd) as of March 2016: EPA LMOP 2015. Available from epa.gov/lmop/projects-candidates/

2.5.2. Collection and Processing

For distributed biogas generation, the biogas must first be collected in a gathering system. Landfill gas collection methods vary with a number of factors (e.g., volume of waste, gas well spacing, etc.), but system design usually incorporates vertical and horizontal wells that serve as collection points for the generated biogas (EPA 2015). In the most aggressive landfill gas collection operations, biogas capture begins about one year after the initial waste disposal. Collection efficiency during this phase is low, however, due to highly permeable landfill covers. Once a landfill cell has been closed, regulations mandate that biogas capture must begin within six years (Figure 2-20).

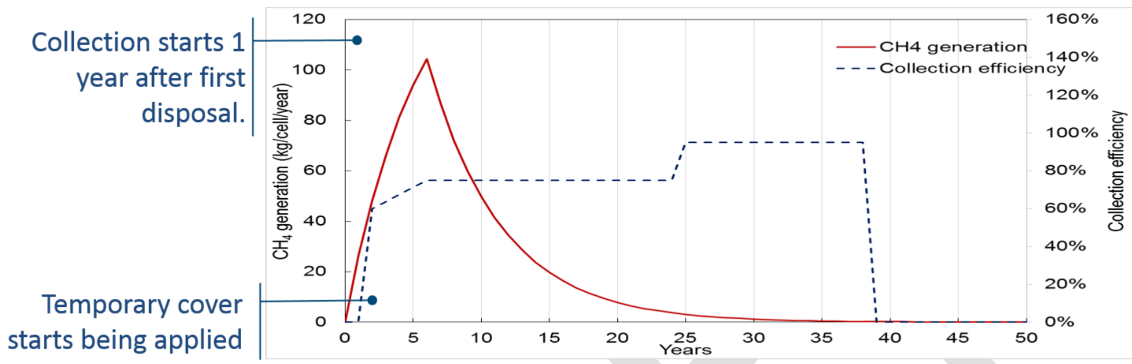


Figure 2-20 Methane generation and collection efficiency for a single cell in an aggressive methane capture scenario from (Han et al. 2016)

In AD operations at WWTPs and manure digestion operations, biogas collection equipment is inherently included to enable flaring, venting, or capture of the biogas. For these sources of biogas, however, emissions are not regulated as they are for landfills. While biogas capture and utilization is the best case, combustion or flaring is preferable to venting, given the potency of methane as a GHG: 21 to 36 times greater than that of CO_2 (IPCC 2009; EPA 2016). A more detailed discussion of biogas utilization and upgrading can be found in Chapters 3 and 4.

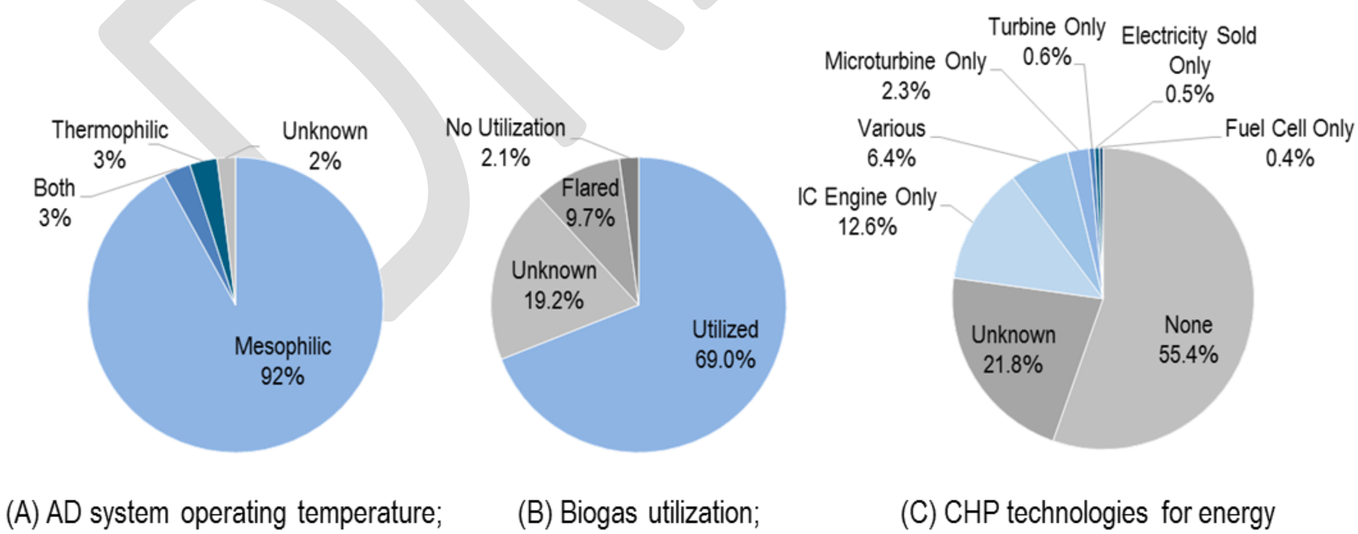


Figure 2-21 Summary of biogas utilization at WWTPs in the United States (Shen et al 2015)

2.5.3. Feedstock Characteristics

Biogas composition can vary seasonally, particularly at landfills where the landfilled materials contain higher organic fractions from yard wastes. Siloxanes represent an additional constituent that causes deleterious effects in biogas. Siloxanes, which are present in personal hygiene, health care, and industrial products, accumulate in wastewater and landfills and can easily volatilize (Wheless and Pierce 2004). When the biogas is combusted, siloxanes react to form silicon dioxide, causing deposits in combustion equipment and contributing to premature equipment failures (Wheless and Pierce 2004). Another contaminant in biogas is H_2S, which is both highly toxic and corrosive at low concentrations, thereby requiring cleanup. Cleanup of H_2S is most commonly accomplished with scrubbers or through the use of iron sponge technology (reaction with iron oxide).

Table 2-16 Biogas compositions, adapted from (Rasi et all 2007)

Biogas Source	CH_4 (%)	CO_2 (%)	O_2 (%)	H_2S (ppm)	References
Landfill	44-68	24-40	1-2.6	15.1-427.5	(Rasi et al 2007), (Allen et al 1997), (Eklund et all 1998), (Jaffrin et al 2003).
Sewage Digester	58-63%	34-39%	<1	b.d. - 62.9	(Rasi et al 2007), (Spiegel and Preston 2003), (Stern et all 1998), (Spiegel and Preston 2000)
Farm Digester	55-58	37-28	<1	32-169	(Rasi et al 2007)

2.6. CO_2 Streams

Emissions of carbon dioxide, a GHG, have been a major target of international climate change agreements (Paris Agreement 2015). Under the *U.S. Climate Action Plan* and *Clean Power Plan,* the United States has targeted a 32% reduction in CO_2 emissions relative to 2005 levels—a reduction of 789.25 million tons. Waste CO_2 can be used in several forms to generate energy, including (1) production of microalgae for conversion into liquid or gas-phase fuels, (2) capture of mixing energy (Hamelers et al., 2014), and (3) development of syngas. Waste CO_2 has numerous other beneficial and potentially energy-saving uses, including fertilizer production, cement production, plastics production, chemical development, and food industry use.

Types of CO_2 Streams

Biogenic
- Biogas production
- Brewery operations
- Ethanol biorefineries

Thermogenic
- Cement manufacturing
- Combustion
- Oil and gas extraction

For purposes of this document, there are two main types of CO_2 streams: (1) biogenic, those directly produced by a biological process, and (2) thermogenic, those not directly produced by a biological process. Natural CO_2 seeps are excluded from this analysis. BETO is required to focus on wastes acted on by some biological process; thermogenic sources of CO_2 must therefore go through a biological conversion process to be of interest to BETO. This same condition does not apply to biogenic sources; they can go through either biological or thermochemical conversion and still be of interest to BETO.

2.6.1. Resource Assessment

EPA's Greenhouse Gas Reporting Program (GHGRP) is designed to capture and monitor the largest U.S. facilities with CO_2 or CO_2-equivalent (CO_2e) emissions of at least 25 kilotons per year. The program has recorded 8,080 waste CO_2 point sources in the conterminous U.S. (CONUS) across nine industries as of 2014 (GHGRP; EPA 2016).

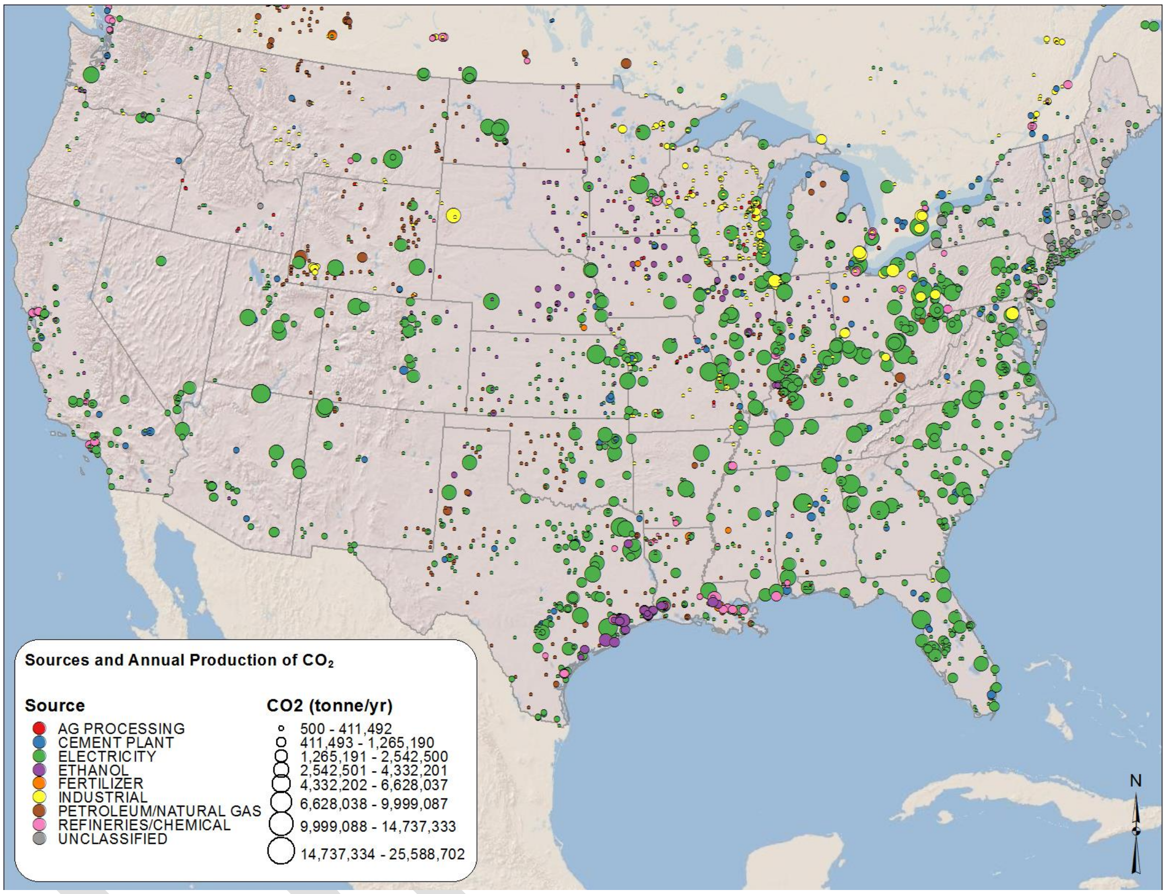


Figure 2-22 2013 sources and production of CO_2 in the Conterminous United States

Table 2-17 CO_2 production from CONUS electric generating units (EGUs) and ethanol production facilities without annual CO_2 production constraint (i.e. not limited to sources > 25 kt/yr) (adapted from (USDOE 2016).

Type	Count	Generation ($MTCO_2$/yr)	Total CONUS CO_2 (%)	Geographic Distribution
Coal-fired EGUs	1,339	2,677	72	Widely distributed, but limited in the Pacific Northwest
Natural gas EGUs	1,774	394	11	Widely distributed, primarily in California, Southeast, and the Mid-Atlantic
Ethanol Production	317	141	4	Primarily Midwest and Gulf Coast

The United States produced 5,503 MMt of CO_2 in 2013. Electricity generation contributed 37% (2,038 MMt); transportation combustion, 31% (1,713 MMt); and industrial combustion, 14.7% (812 MMt). The vehicle emissions, of course, are non-point sources and infeasible for use (EPA 2016).

Approximately 87% of point-source CO_2 emissions within CONUS come from coal-fired electric generating units, natural gas electric generating units, and ethanol production (Table 2-17). These sources were the subject of a CO_2 co-location/utilization study as a part of the US DOE *2016 Billion Ton Study* (USDOE 2016) addressing autotrophic microalgae production.

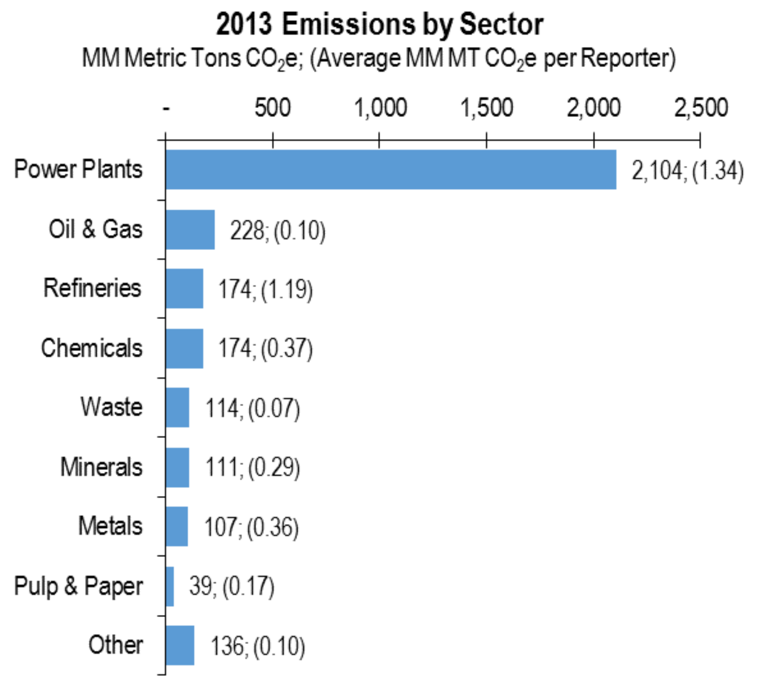


Figure 2-23. Sector-specific reporting of direct CO_2-e emissions (EPA, 2013).

2.6.2. Collection and Processing

CO_2 is produced at a variety of scales and locations, ranging from industrial and chemical processing to electricity production from natural gas and coal-based fuels (Figure 2-22). Most of the smaller point sources and those not close to pipelines are merely vented. Presently, larger facilities also vent their carbon dioxide, but efforts are underway to collect and store the CO_2 (e.g. Kemper Project). The difficulty with CO_2 is not in identifying the point sources, but in finding an economical process to collect and either store or use the gas and navigate the seasonal production and utilization cycles.

CO_2 is typically removed from a mixed gaseous stream using an amine solution, although it can also be captured using either minerals or zeolites. CO_2 may also be captured using chemical adsorption or cryogenic separation, though these methods have not been as widely deployed on a commercial basis. Captured CO_2 can be moved in pipelines, tanker trucks, rail cars, or canisters (e.g., food-grade CO_2, fire extinguishers), or even as a refrigerated solid (dry ice) [because CO_2 sublimes at atmospheric pressure, liquid CO_2 can only be had under elevated pressures]. Some facilities readily collect their CO_2 as dry ice for transport or use (e.g., the Bacardi distillery in San Juan, Puerto Rico).

The chief difficulty in converting CO_2 to other chemicals is the stability of its constituent chemical bonds. Conversion of CO_2 into most other chemical compounds is an endothermic process, meaning it requires energy. However, interest is growing in pairing this energy-consuming process with an energy-generating process. One idea calls for using CO_2 as a concentrated feedstock to support photosynthesis. This idea is being actively pursued to culture autotrophic or mixotrophic microalgae, as commercially supplied CO_2 can represent 20-25% of algal biofuel plant operating costs (Coleman et al. 2015). Hydrogen (H_2) can also be reacted with CO_2 in a reverse water-gas shift reaction to produce CO and H_2O. The CO has many uses, including in power generation, Fischer-Tropsch synthesis, or in biochemical processes. These represent but a few of the many pathways available for CO_2 utilization.

2.6.3. Feedstock Characteristics

CO_2 purity is largely dependent on the producing source and the nature of the CO_2 capturing systems. CO_2 produced in coal-fired and natural gas power plants is typically composed of less than 15 mol% CO_2 due to their reliance on air for combustion (79 mol% nitrogen) (Figueroa et al. 2008). Coal-derived flue gases are also high in volatile organic species, SOx, NOx, and metals, all of which are removed via air pollution control equipment. Conversely, CO_2 produced from ethanol plants can yield very high-purity (>99% pure) CO_2 emissions (Coleman et al 2015).

Table 2-18 Typical flue gas composition for coal-fired vs natural gas-fired power plants, adapted from (Xu et al 2003).

Flue Gas Composition	Coal-fired	Gas-fired
CO_2	12.5-12.8%	7.4-7.7%
H_2O	6.20%	14.60%
O_2	4.40%	4.45%
CO	50 ppm	200-300 ppm
NO_x	420 ppm	60-70 ppm
N2	76-77%	73-74%
SO_2	420 ppm	-

2.7. Associated Natural Gas

Given the price of liquid fuels, oil production is often prioritized in upstream oil and gas operations. As oil is extracted from the wells, some of the associated natural gas is also recovered; however, if this product cannot be easily transported to market (i.e., via a nearby pipeline), that associated natural gas is simply flared or even vented. Collecting and converting this associated natural gas has the potential to harness a significant source of energy and prevent potent GHG emissions.

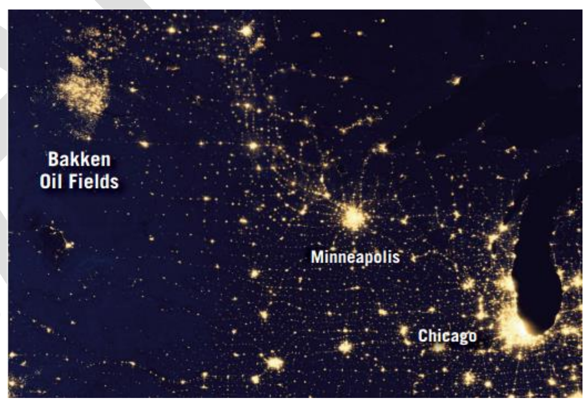


Figure 2-24 Natural gas flares as observed from space.

Credit: NASA Earth Observatory/NOAA NGDC ©2012

The well heads tend to be geographically distributed, and the timeframe to construct infrastructure connecting them to existing gathering lines is typically short. Competing uses for this natural gas include power for well-pad operations and drilling or fuel for the vehicle fleet (as CNG). Currently, these uses are insignificant relative to the size of the resource that is vented or flared. Associated natural gas can be thought of in the same vein as upgraded biogas—although once the liquids have been extracted, the associated natural gas possesses a significantly higher energy content than biogas.

2.7.1. Resource Assessment

The discovery of massive shale oil reserves in some areas of the United States (e.g., North Dakota's Bakken Shale Formation in the Williston Basin) significantly increased domestic reserves—as well as the amount of associated natural gas that is produced but not collected. In 2014 alone, North Dakota accounted for 129.4 billion of the 288.7 Bcf of natural gas vented/flared at oil rigs nationwide. Figure 2-25 indicates that wells in North Dakota and Texas account for the majority of natural gas currently being vented/flared at oil rigs. Following the sharp reduction in crude oil prices, the number of oil rigs dropped sharply to 750 in 2015 and 441 in 2016 (Baker Hughes 2016).

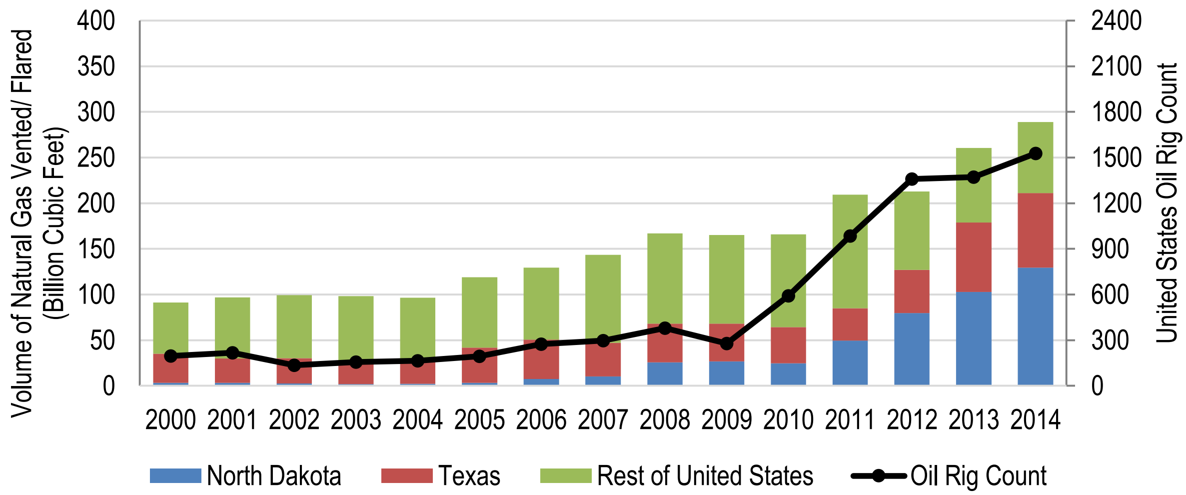


Figure 2-25 Volumes of natural gas flared/vented in the United States and domestic oil rig count adapted from (EIA 2016; Baker Hughes 2016)

2.7.2. Collection and Processing

Natural gas producers generally phase-separate the natural gas from any oil and other condensates and then send it to a "midstream" gathering infrastructure. During these steps, the gas is cleaned of impurities and diluents (e.g. N_2, H_2S, H_2O, or CO_2) and compressed for long-range transmission. Typically, a portion (5-10%) of the natural gas is consumed as it provides power to these operations.

Figure 2-26 Natural gas flaring in North Dakota. Photo Credit: Jim Wilson/The New York Times

Conversely, "associated natural gas" is not the primary product of oil-drilling operations and is not collected in any large way. In many cases, oil-drilling operations have outpaced the construction of new infrastructure to collect and process the associated gas (e.g., Bakken in North Dakota). Notably, this is not limited to wells that lack access to gas gathering infrastructure. In North Dakota, 45% percent of flaring occurs at wells that are connected to gas gathering systems but face pipeline capacity and compression challenges (CERES 2013). In some cases where the gas is not collected and processed, low-pressure pipelines aggregate the natural gas from one or more wells for flaring.

2.7.3. Feedstock Characteristics

The composition of natural gas can vary slightly from basin to basin, but it is largely homogenous nationwide. Bakken gas composition contains a higher fraction of light petroleum gases; it is approximately 55% methane, 22% ethane, 13% propane, 1.35% other hydrocarbons, 3% nitrogen, and 0.5% carbon dioxide. As a result, Bakken gas possesses a significantly higher energy density than pipeline natural gas (>1,400 Btu/scf, as opposed to 1,000 Btu/scf) (Wocken et al 2013).

2.8. Other Waste Feedstocks

The feedstocks described below are treated lightly because they fit into one of the following categories: they currently lack a biofuel product (glycerol), they have been addressed in other BETO reports (black liquor), they are used as animal feed (dried distillers grains with solubles (DDGS)), or they are not yet quantified. These feedstocks are mentioned here in the interest of providing a view of the overall waste resource landscape.

2.8.1. Glycerol

Glycerol, also known as glycerin, is a co-product of biodiesel production. This non-toxic, colorless, and odorless liquid is used in food, cosmetics, and pharmaceutical products. As a result of the transesterification process, each gallon of biodiesel produced results in about one pound of glycerol. Based on this ratio, EIA's estimated total U.S. production of 1.268 billion gallons of biodiesel in 2015 would yield about 634,000 tons of glycerol. Biodiesel production has provided an oversupply of glycerol for U.S. markets, leading to low prices of around $0.10/pound for crude glycerol and higher prices for upgraded or refined glycerol (DOE 2016). Refined glycerol, in which impurities such as methanol, water, and other organic compounds have been removed, must achieve greater than 99% purity to be appropriate for food and pharmaceutical applications. Pharmaceutical-grade glycerol commands a significant premium over crude glycerol, trading for $0.65/lb (ICIS 2016). Emerging research focuses on biological methods to upgrade crude glycerol to higher-value chemicals and thereby drive down the cost of biodiesel production.

2.8.2. Black Liquor

Black liquor, or pulping liquor, is a by-product of the technology used in the pulping process to manufacture paper products. Black liquor is an aqueous solution of lignin residues, hemicellulose, and other chemicals. The U.S. pulp and paper industry is estimated to generate about 44 million dry tons of black liquor resin annually (NREL 2016), but most of it is used onsite at the pulp and paper mills to produce heat and power.

2.8.3. Dried Distillers Grains with Solubles

DDGS are a nutrient-rich co-product of ethanol produced via dry milling (dry milling accounts for 90% of the corn ethanol produced in the United States). About 44 million tons of DDGS were produced in 2014-15; approximately 75% (33 million tons) of that DDGS is used as a high-protein livestock feed, and 25% is exported (Wisner 2015).

2.8.4. Other Industrial Waste

Industrial facilities produce a significant quantity of aqueous waste during normal operations (e.g., wastewater from petrochemical operations, pulp and paper, ethanol biorefineries, etc.). Waste streams of this nature can be very difficult to remediate without specialized wastewater treatment processes; consequently, they often depress process economics. The nature and extent of the available resource has not been quantified at this time, but industrial waste is acknowledged as a high priority for future analysis. Strategies for valorizing some industrial waste streams (e.g. lignin) are currently being studied under existing BETO research and development (R&D) platforms. Lignin is recognized as a waste stream with high potential for applications beyond combined heat and power; given its prominence in the current BETO R&D strategy, it is not considered as part of this effort. Carbon monoxide rich streams represent another area of interest, however, conversion methods (biological and chemical) for these resources are currently significantly in BETO's existing R&D efforts.

2.9. Chapter 2 References

Allen, M. R., A. Braithwaite, et al. (1997). "Trace organic compounds in landfill gas at seven UK waste disposal sites." Environmental Science and Technology 31: 1054-1061.

Baker Hughes (2016). North America Rig Count. Accessed 4/15/2016. http://phx.corporate-ir.net/phoenix.zhtml?c=79687&p=irol-reportsother

Beecher, N.; Crawford, K; Goldstein N.; Lono-Batura, M.; Dziezyk, E. A National Biosolids Regulation, Quality, End Use and Disposal Survey, Northeast Biosolids and Residuals Association, Tamworth, NH, 2007.

BSR (2012). Food Waste: Tier 1 Assessment. Prepared for Grocery Manufacturers Association and Food Marketing Institute. http://www.foodwastealliance.org/wp-content/uploads/2013/06/FWRA_BSR_Tier1_FINAL.pdf

Buzby, Jean C., Hodan Farah-Wells, and Jeffrey Hyman. "The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States." USDA-ERS Economic Information Bulletin 121 (2014). Available from, http://www.ers.usda.gov/media/1282296/eib121.pdf

Canakci, M. (2007). "The potential of restaurant waste lipids as biodiesel feedstocks." Bioresource Technology 98:183-190. http://www.sciencedirect.com/science/article/pii/S0960852405005468

Canakci, M., J. Van Gerpen (1999). "Biodiesel production via acid catalysis." Transactions of the American Society of Agricultural Engineers 42: 1203-1210.

CERES (2013). "Flaring up: North Dakota Natural Gas Flaring More Than Doubles in Two Years." http://www.ceres.org/resources/reports/flaring-up-north-dakota-natural-gas-flaring-more-than-doubles-in-two-years

Chen, W.-T., et al. (2014). "Co-liquefaction of swine manure and mixed-culture algal biomass from a wastewater treatment system to produce bio-crude oil." Applied Energy 128: 209-216.

Coleman, A, M., M. S. Wigmosta, et al. (2015). "National Supply Curves for Algae Biomass: Resource-based Colloecation." 2015 Algae Biomass Summit. 10/2/2015.

DOE (2016). 2016 Billion-Ton Report. Washington, DC, Department of Energy http://energy.gov/sites/prod/files/2016/07/f33/2016_billion_ton_report_0.pdf

ECN Phyllis2 https://www.ecn.nl/phyllis2/Browse/Standard/ECN-Phyllis#sludge (accessed on 3.15.16)

EIA - MBR (2016). Monthly Biodiesel Production Report. Washington, DC, Department of Energy, Energy Information Administration. http://www.eia.gov/biofuels/biodiesel/production/

EIA - NG (2016). Natural Gas Gross Withdrawals and Production. Washington, DC, Department of Energy, Energy Information Administration. Accessed 4/15/2016. https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_VGV_mmcf_a.htm

Eklund, B., E. P. Anderson, et al. (1998). "Characterization of landfill gas composition at the fresh kills municipal solid-waste landfill." Environmental Science and Technology 32: 2233-2237.

EPA (2012). Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012. Washington, DC, United States Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-09/documents/2012_msw_fs.pdf

EPA (2015a). Advancing Sustainable Materials Management: 2013 Fact Sheet. Assessing Trends in Material Generation, Recycling and Disposal in the United States. Washington, DC, United States Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-09/documents/2013_advncng_smm_fs.pdf

EPA (2015b). Postconsumer Food Diverted Through Donation, Animal Feed, Anaerobic Digestion, and Composting for 2013. Washington, DC, United States Environmental Protection Agency. https://www.epa.gov/sites/production/files/2015-12/documents/postconsumer_food_diverted_through_donation_animal_feed_anaerobic_digestion_composting_2013_04082015_508.pdf

EPA - LFG (2015). LFG Energy Project Development Handbook. Washington, DC, United States Environmental Protection Agency. https://www3.epa.gov/lmop/documents/pdfs/pdf_full.pdf

EPA - Inventory (2016). Inventory of U.S. Greenhouse Gas emissions and Sinks: 1990-2014. Washington, DC, United States Environmental Protection Agency. https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html

EPA - UGWP (2016). Understanding Global Warming Potentials. Washington, DC, Understanding Global Warming Potentials. Accessed 3/15/2016. https://www3.epa.gov/climatechange/ghgemissions/gwps.html

EPA - CWNS (2016). Clean Watersheds Needs Survey 2012: Report to Congress. EPA-830-R-15005. United States Environmental Protection Agency. January 2016. From https://www.epa.gov/sites/production/files/2015-12/documents/cwns_2012_report_to_congress-508-opt.pdf

EPA AgSTAR (2015). AgSTAR: Biogas Recovery in the Agricultural Sector. Washington, DC, United States Environmental Protection Agency. Accessed 10/23/2015. https://www.epa.gov/agstar

EPA LMOP (2015). Energy Projects and Candidate Landfills. Washington, DC, United States Environmental Protection Agency. Accessed 10/23/2015. https://www3.epa.gov/lmop/projects-candidates/

Feeding America (2016). "Food Waste in America." Feeding America. Accessed 4/1/2016, http://www.feedingamerica.org/about-us/how-we-work/securing-meals/reducing-food-waste.html

Figueroa, J. D., T. E. Fout, et al. (2008). "Advances in CO2 Capture Technology – The U. S. Department of Energy's Carbon Sequestration Program." International Journal of Greenhouse Gas Control 2:9-20. https://www.researchgate.net/publication/222431915_Advances_in_CO2_Capture_Technology-The_US_Department_of_Energy%27s_Carbon_Sequestration_Program

Freedman, B., E. H. Pryde, et al. (1984). "Variables affecting the yields of fatty esters from transesterified vegetable oils." JAOCS 61: 1638-1643.

Han, J. et al. (2016). In preparation

He, C., et al. (2015). "Products evolution during hydrothermal conversion of dewatered sewage sludge in sub- and near-critical water: Effects of reaction conditions and calcium oxide additive." International Journal of Hydrogen Energy 40(17): 5776-5787.

Hosseini, S. E., M. A. Wahid (2014). "Development of biogas combustion in combined heat and power generation." Renewable and Sustainable Energy Reviews 40: 868-875. http://www.sciencedirect.com/science/article/pii/S1364032114006649

IPCC (2009). Fifth Assessment Report (AR5). Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar5/

Jaffrin, A., N. Bentounes, et al. (2003). "Landfill biogas for heating greenhouses and providing carbon dioxide supplement for plant growth." Biosystems Engineering 86: 113-123.

Joseph, S. (2004). The potential for using tallow as a fuel for the production of energy. Prepared for Sustainable Energy Authority of Victoria. http://www.sustainability.vic.gov.au/-/media/resources/documents/publications-and-research/knowledge-archive/bioenergy-resource-in-victoria/archive-tallow-resource-assessment.pdf?la=en

Kellogg (2000). Kellogg, Robert L., Charles H. Lander, David Moffitt, and Noel Gollehon. 2000. "Manure Nutrients Relative to the Capacity of Cropland and Pasureland to Assimilate Nutrients: Spatial and Temporal Trends for the U.S." U.S. Department of Agriculture. Natural Resources Conservation Service. Available from, http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_012133.pdf

Kemper Project. "Kemper County Energy Facility: First-of-its-kind electricity plant to employ gasification and carbon capture technologies at this scale." Available from, https://en.wikipedia.org/wiki/Kemper_Project

Lee, K (2013). "Central Sands Dairy beds with sand and digests too." Progressive Dairyman. January 13, 2013. Available from, http://www.progressivedairy.com/topics/manure/central-sands-dairy-beds-with-sand-and-digests-too

Liao, W., C. Frear, et al. (2007). "Biomass Inventory Technology and Economics Assessment: Report 1. Characteristics of Biomass." Washington State University Center for Bioproducts and Bioenergy. http://www.ecy.wa.gov/climatechange/2008CATdocs/IWG/bw/071108_bitea.pdf

Malins, K., et al. (2015). "Bio-oil from thermo-chemical hydro-liquefaction of wet sewage sludge." Bioresoure Technol 187: 23-29.

McCarty, P. L., Bae, J., and Kim, J., "Domestic Wastewater Treatment as a Net Energy Producer – Can This be Achieved?," Environmental Science & Technology, 45(17), 7100-7106 (2011).

Midgett, J. S., et al. (2012). "Assessing feedstocks and catalysts for production of bio-oils from hydrothermal liquefaction." Waste and Biomass Valorization 3(3): 259-268.

Milbrandt, A. et al (2016). In progress.

NREL. (2013). "Biogas Potential in the United States." NREL/FS-6A20-60178. Golden, CO: National Renewable Energy Laboratory. Available from: http://www.nrel.gov/docs/fy14osti/60178.pdf.

NREL (2016). 2013 Bioenergy Market report. Prepared for the US Department of Energy Bioenergy Technologies Office. http://www.nrel.gov/docs/fy16osti/63468.pdf

Ogejo (2015). Ogejo, J.A. "Manure Production and Characteristics." Virginia Tech University. Research based information from America's land-grant universities enabled by extension.org. October 26, 2015. Available from, http://articles.extension.org/pages/15375/manure-production-and-characteristics

Paris Agreement 2015. Paris Climate Conference (COP21). December 2015. Available from, http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm

Perez, L. "Outlook '16: US glycerine market faces long supply." 12/31/2015. http://www.icis.com/resources/news/2015/12/31/9952515/outlook-16-us-glycerine-market-faces-long-supply/

Rasi, S., A. Veijanen, et al. (2007). "Trace compounds of biogas from different biogas production plants." Energy 32: 1375-1380. http://www.sciencedirect.com/science/article/pii/S0360544206003033

Ro, K.S. et al. (2010) "High-temperature pyrolysis of blended animal manures for producing renewable energy and value-added biochar." Ind. Eng. Chem. Res. 49: 10125-10131.

Romano, S. (1982). "Vegetable oils- a new alternative." Vegetable Oils Fuels- Proceedings of the International Conference on Plant and Vegetable Oils as Fuels, ASAE Publication 4-82: 106-116.

NRCS (2012). "Agricultural Waste Management Field Handbook: Chapter 3 Agricultural Wastes and Water, Air, and Animal Resources. U.S. Department of Agriculture. Natural Resources Conservation Service. February 2012. Available from, http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=31441.wba

SCS (1992) "Agricultural Waste Management Field Handbook: Chapter 3 Agricultural Wastes and Water, Air, and Animal Resources. U.S. Department of Agriculture. Soil Conservation Service. 1992.

Shen, Y., J. L. Linville, et al. (2015). "An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs." Renewable and Sustainable Energy Reviews 50: 346-362. http://www.sciencedirect.com/science/article/pii/S1364032115003998

Spiegel, R. J., J. L. Preston (2000). "Test results for fuel cell operation on anaerobic digester gas." Journal of Power Sources 86: 283-288.

Spiegel, R. J., J. L. Preston (2003). "Technical assessment of fuel cell operation on anaerobic digester gas at the Yonkers, NY, wastewater treatment plant. Waste Management 23: 709-717.

Stern, S. A., B. Krishnakumar, et al. (1998). "Performance of a bench-scale membrane pilot plant for the upgrading of biogas in a wastewater treatment plant." Journal of Membrane Science 151: 63-74.

Swisher, K. (2015). “Market Report.” Render Magazine April 2015: 10-16. https://d10k7k7mywg42z.cloudfront.net/assets/55281d9ec0d6715235004d2e/MarketReport2014.pdf

Sustainable Chesapeak (2016). "About the Farm Manure-to-Energy Initiative." Extension.org. Published March 16, 2016. Available from, http://articles.extension.org/pages/68454/about-the-farm-manure-to-energy-initiative

USDA (1996). "Documentation for Manure Characteristics, Appendix II-Manure Characteristics." Natural Resources Conservation Service, United States Department of Agriculture. November 1996. Available from, www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/nra/rca/?cid=nrcs143_014154

USDA (2009). MacDonald, J. M., et al. "Manure use for fertilizer and for energy: report to Congress. USDA-ERS Publication No. AP-037." June 2009. http://www.ers.usda.gov/publications/ap-administrative-publication/ap-037.aspx

USDA (2013). “ERS’s Food Loss Data Help Inform the Food Waste Discussion.” United States Department of Agriculture. June 3, 2013. Available from, http://www.ers.usda.gov/amber-waves/2013-june/ers-food-loss-data-help-inform-the-food-waste-discussion.aspx#.V6uQlYMrJhG

WERF. "Genifuel Hydrothermal Processing Bench Scale Technology Evaluation Project." 2016 (in preparation). Prepared by Leidos, Inc., Framingham, MA.

Westendorf, M. L., Zirkle Pas, et al. (1996). “Feeding Food or Table Waste to Livestock.” The Professional Animal Scientist 12: 129-137.

Wheless, E., J. Pierce (2004). “Siloxanes in Landfill and Digester Gas Update.” http://scsengineers.com/wp-content/uploads/2015/03/Pierce_2004Siloxanes_Update_Paper.pdf

Wisner, R. (2015). “Estimated U.S. Dried Distillers Grains with Solubles (DDGS) Production & Use.” Iowa State University Agricultural Marketing Resource Center. Accessed 8/12/2016. http://www.extension.iastate.edu/agdm/crops/outlook/dgsbalancesheet.pdf

Wocken, C., G. Dunham, et al (2013). “Utilization of Associated Gas to Power Drilling Rigs – A Demonstration in the Bakken.” 21st Williston Basin Petroleum Conference. 4/30/2013.

WRAP 2010. Food Waste chemical Analysis. Banbury, UK, The Waste and Resources Action Programme. http://www.wrapcymru.org.uk/sites/files/wrap/Technical_report_food_waste_characterisation_Wales_2009x2.9086.pdf

Xiu, S., et al. (2011). "Enhanced bio-oil production from swine manure co-liquefaction with crude glycerol." Energy Conversion and Management 52(2): 1004-1009.

Xu, X., C. Song, et al (2003). “Separation of CO2 from Power Plant Flue Gas Using a Novel CO2 ‘Molecular Basket” Adsorbent.” Fuel Chemistry Division Preprints 48: 162-163.

Yin, S, et al (2010). "Subcritical hydrothermal liquefaction of cattle manure to bio-oil: effects of conversion parameters on bio-oil yield and characterization of bio-oil." Bioresource Technology 101.10 (2010): 3657-3664.

Zhang, R., H. M. El-Mashad, et al. (2007). “Characterization of food waste as feedstock for anaerobic digestion.” Bioresource Technology 98:929-935. http://www.sciencedirect.com/science/article/pii/S0960852406000940

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3. Current and Future Competitive Market Analysis

Enterprises currently interested in transforming today's wet and gaseous waste streams into energy and other products of value will be well-positioned to take advantage of the growing marketplace and attractive incentives for sustainable products. For example, collecting biogas from landfills and CAFOs and converting it into biofuel now constitutes a "cellulosic biofuel pathway" under the Renewable Fuel Standard. [1] A recent NREL study using the lab's in-house Waste-to-Energy System Simulation (WESyS) model indicates that this landfill and CAFO biogas could annually generate up to 379 TBtu, which could qualify for renewable identification number (RIN) credits. The same market benefit applies to Gas-To-Liquids (GTL), as demonstrated by ENVIA Energy's GTL facility in Oklahoma City, now under construction. Under the same recent EPA rule changes, electricity generated from biogas and demonstrably used (e.g., through contract) in electric vehicles would also qualify for RIN credits. Along with other market incentives—such as low carbon fuel standards and renewable electricity credits (RECs)—the investment attractiveness of waste-to-energy (WTE) projects is poised to increase.

Initial WTE production economics may be particularly favorable as many of the operations that produce these raw materials formerly had to pay for their disposal (e.g., waste water remediation, tipping fees). The economic attractiveness of using materials of negligible or negative present value will rapidly fade as the value of these once-neglected resources becomes evident and other WTE operations compete for them. Economic planners must be aware of future competition, projected price trends, and opportunities to take advantage of existing or shared infrastructure as they shape robust, economically sustainable WTE operations.

3.1. Municipal Wastewater Treatment Derived Sludge and Biosolids

3.1.1. Current Assessment

Current uses or markets for sludge from WRRFs include power generation, fertilizer, top soil for golf courses, and reclamation of brown fields. The non-potable water produced from these end uses constitutes another value-added byproduct. In the United States, 1,241 WWRFs operate AD systems to utilize their biogas. The overall thermal and energy potential of these systems is estimated at 2.03 x 10^8 MMBtu per year. Of the WRRFs operating ADs, 270 currently produce electricity, which is primarily used on-site. Only 74 of that number export power to the grid (Shen 2015). According to the WEF 2015 fact sheet on biosolids, WRRFs generate 7.1 million dry tons of biosolids (includes only beneficially reused sludge, not total sludge) each year (based on 2004 US EPA data).

3.1.2. Emerging and Future Applications

The original mission for WRRFs narrowly focused on the treatment of wastewater to protect human health and the environment. Even as these facilities begin generating energy and other products in support of healthy, economically vibrant communities, their primary mission is and must remain unchanged. All target markets for WRRF sludges will need to consider regulatory requirements established by the EPA. The EPA issues water discharge permits that specify quality criteria for all treated water. If treatment efforts fail to meet these criteria, the facility may be subject to enforcement

[1] In 2014 the U.S. Environmental Protection Agency (EPA) ruled that CNG and liquefied natural gas (LNG) produced from biogas fall under that cellulosic biofuel pathway.

action, including fines. The threat of enforcement is a powerful motivator, traditionally creating a singular strategic focus among facility managers. The resulting culture emphasized permit compliance, often at the expense of other actions that were in the long-term interest of water treatment operations, including investments in energy efficiency to reduce costs. While these permits are essential to ensure clean water, they have historically played an outsized role in the design and operation of today's water utilities, limiting innovation.

The drawbacks of past prescriptive approaches are now widely recognized, and today's forward-thinking regulatory bodies increasingly emphasize performance-based incentives and policies that foster innovation while continuing to safeguard public health and the environment. Evolving technologies and markets necessitate close coordination across WRRFs, technology developers, regulatory bodies, and governments to figure out flexible approaches to achieve sustainable operations while upholding important priorities and protections.

New potential markets for WRRFs include biofuels production (e.g., diesel, jet fuel, and gasoline) as well as secondary markets for dimethyl ether, hydrogen, and other novel bioproducts (DOE 2015). New technologies will enhance AD, gas-to-liquids, and chemical catalysis conversion processes, enabling more efficient recovery and conversion of the carbon and nutrients in wastewater (e.g., biofuel energy via microbial fuel cells and thermal conversion of biosolids utilizing gasification or pyrolysis) (NBS 2011).

3.2. Animal Waste

3.2.1. Current Assessment

Established markets for animal waste include biogas production, fertilizer, and bedding. Two-thirds of market revenues from animal waste are derived from the sale of fertilizer, and one-third are from biogas production.

3.2.1.1. Biogas

As defined previously, a CAFO is an AFO with more than 1,000 animal units (with a unit equivalent to 1,000 pounds live weight). An estimated 450,000 AFOs currently operate in the United States (NRCS 2016). In 2015, about 247 CAFOs were actively capturing and converting biogas to energy, with a collective generation capacity of 1,670 MW (AgSTAR). CAFOs are estimated to have a maximum economic production potential of approximately 2.1 million tons of biogas per year or 1.75 TBtu per day. Only about 3% of this biogas is captured by existing digesters (Saur 2014).

Anaerobic digesters can be classified by the way in which the manure slurry is handled and fed to the system. Batch systems (e.g., *covered lagoons)* store the slurry in holding ponds or lagoons to be loaded into the anaerobic digester in batches. In contrast, continuous feed systems (i.e., *continuous mix* or *plug flow*) allow the slurry to enter the anaerobic digester nonstop. Continuous slurry anaerobic digesters using dairy manure provide the highest biogas yields. The three major processes and end uses for biogas from animal residue AD digesters are as follows:

1. Combust the biogas to generate electricity for use onsite or for sale to the grid
2. Compress the biogas for use as a CNG vehicle fuel
3. Further upgrade the biogas to 99% CH_4 for distribution in existing natural gas pipelines.

Major current policies in the United States that can generate revenue from biogas in WTE projects are summarized in Table 3-1. A renewable energy certificate (REC) is a record that a megawatt-hour of electricity was generated from a renewable source and can be used to comply with state renewable and alternative portfolio standards. Market price varies by state, but the average has been around $1.00 per MWh generated (Informa Economics 2013). The revenue from a REC is small relative to the U.S. Production Tax Credit (PTC) of $11 per MWh generated (AgSTAR). The PTC is a national policy for renewable electricity and includes production from biogas. The duration of the credit is 10 years after the date the facility is placed in service for all facilities placed in service after August 8, 2005.[1] The RIN credit and California's Low Carbon Fuel Standard (LCFS) credits are for renewable transportation fuels (such as CNG) only. In limited approved cases where pipeline natural gas (PNG) and electricity are being used by electric and gas vehicles there are revenue opportunities from RIN and LCFS credits. There is an excise tax credit for renewable gas, but it is slightly offset by the tax on alternative fuels.

Table 3-1 Sources of potential additional revenue for U.S. biogas

Revenue Source	Energy Product	Value	Range	Units
Renewable Energy Certificate (REC)	Electricity	U.S.: $1.00 CA: $4.25	U.S.: $0.25 - 3.00 CA: $4.25 - 12.75	USD per MWh
Renewable Electricity Production Tax Credit (PTC)	Electricity	US: $11.00		USD per MWh
Renewable Identification Number (RIN)	CNG, PNG, and Transportation electricity [1]	Average for 2015: $0.7	U.S. $0.00 - 2.00	USD per RIN [2]
California: Low Carbon Fuel Standard (LCFS)	CNG, PNG, and Transportation electricity	Average: $45	CA: $18.00 - 73.00	USD per LCFS Credit [3]
Excise Tax Credit (minus alternative fuel tax) [4]	CNG	$0.32	-	USD per gge

Source: NREL milestone completion report: Waste-to-Energy system simulation model, by Daniel Inman, Ethan Warner, Anelia Milbrandt, Alberta Carpenter, Ling Tao, Emily Newes and Steven Peterson.

[1] Although generally recognized by the RFS program, the EPA has not yet approved a transportation electricity pathway to generate RINs

[2] A RIN is equal to ethanol gallon equivalent of fuel.

[3] One LCFS credit generated per ton of avoided CO_2-e

[4] Excise Tax Credit ($0.50) – Alternative Fuel Tax ($0.18) = $0.32

3.2.1.2. Fertilizer

One use of CAFO-produced manure is fertilizer. In 2009 the USDA reported that about 5% of all U.S. cropland, approximately 15.8 million acres, was fertilized with livestock manure (USDA 2009). A major barrier to wider use of manure is that 52% of harvested land in the country is on non-livestock land, making the cost of transporting manure prohibitive in most cases (USDA 2009). Under the current system of animal production, more manure is available than can possibly be absorbed by the soil as fertilizer. To address this imbalance, the USDA continuously investigates additional uses for CAFO manure. Table 3-2 indicates the amounts of nitrogen and phosphorous available in animal manure (including CAFOs) produced in 2007, the last time a census of this type was performed (Ruddy 2006; USDA 2009b, Census Bureau 2012).

[1] Renewable Electricity Production Tax Credit, energy.gov/savings/renewable-electricity-production-tax-credit-ptc

Table 3-2 Estimated nitrogen (N) and phosphorus (P) produced from animal manure in 2007

Year	Estimated Mass of Animal Manure Nutrient Production		Estimated Farm Animal Manure Nutrient Production per Area of Farmland	
	(1000 kg of N)	(1000 kg of P)	(kg N per km²)	(kg P per km²)
2007	6,174,812	1,846,939	110,862	31,984

3.2.1.3. Bedding

Healthy dairy cows, when not feeding or being milked, rest on bedding material for up to three hours at a stretch. Materials for bedding may include sawdust, sand, and manure. Bedding for dairy cows is costly and a time-consuming component of dairy operations. The cost and availability of bedding fluctuates, and good bedding can be expensive and hard to find. Prior to use as bedding, the semi-solid (25% solids) material derived from a manure stream is run through a separator to reduce the moisture content. Utilization of manure as bedding is not currently practiced at a scale that would support its classification as a major co-product of the industry.

3.2.2. Emerging and Future Applications

NREL developed a system dynamics model of the U.S. WTE industry. The model uses cause-and-effect relationships in a dynamic, stock-and-flow framework to assess potential market responses to system changes; the framework relies on historic trends to determine the most likely cause-and-effect relationships.

NREL's WESyS takes a high-level view of the CAFO industry. The model was used to predict CAFO production of PNG, CNG, and electricity under seven different scenarios. Figure 3-1 and Figure 3-2 display those results, which suggest the potential growth of these markets in future years (NREL completion report).

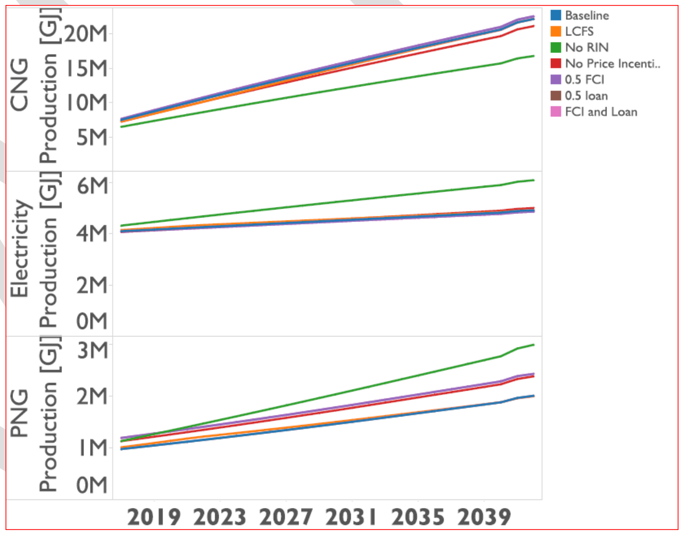

Figure 3-1 Compressed natural gas (CNG), electricity (Elec), and pipeline quality gas (PNG) production from confined animal feeding operations (CAFOs) in response to seven scenarios.

Notes: LCFS – low carbon fuel standard
FCI – Fixed capital investment grant of 50%
Loan – 50% loan guarantee for debt financing

Based on the scenarios studied, CNG from CAFOs appears to show greater market potential than CAFO-produced electricity or PNG. Of the various types of CAFOs examined, dairy CAFOs demonstrate the highest potential for CNG, electricity, *and* PNG. The seven scenarios explored in this study also highlight the role of RINS in boosting certain technologies. Specifically, the presence of RINs appears to encourage CNG production; in the absence of RINs, electricity production is favored, and CNG production drops by nearly a third, in comparison to baselines.

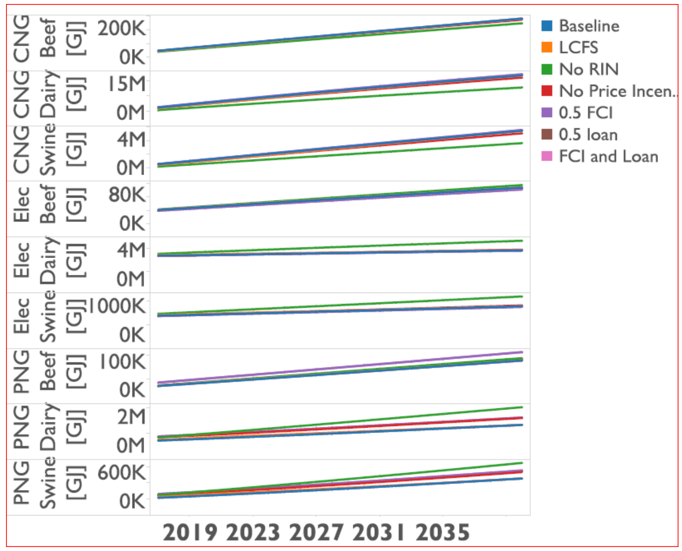

Figure 3-2 Compressed natural gas (CNG), electricity (Elec), and pipeline natural gas (PNG) production from beef, dairy, and swine confined animal feeding operations (CAFOs) in response to seven scenarios.

Notes: LCFS – low carbon fuel standard
FCI – Fixed capital investment grant of 50%
Loan – 50% loan guarantee for debt financing

CAFO operations and the USDA will continue to take an interest in expanding the use of manure as fertilizer, in recovering and recycling nutrients, and in addressing any associated environmental concerns. As long as supportive policies remain in place, wider deployment of anaerobic digesters and other technologies can be expected to build the value of CAFO operations in the future.

3.3. Food Waste

3.3.1. Current Assessment

Any waste-to-energy practices must be aligned with EPA's Food Waste Recovery Hierarchy. As identified in Figure 3-3, the top two tiers of this Hierarchy contain no opportunities for waste-to-energy. Tier 3 could provide opportunities, depending on the energy value of any excess scraps found to be unsuitable for animal feed. The bottom three tiers all represent significant potential for diversion to WTE. The viability of WTE applications increases as the value of competing uses declines and the likelihood of centralized collection rises. Food processing waste includes many diverse types of food and numerous sources, potentially posing challenges for developing economic handling processes to achieve the critical mass and acceptable composition required for waste-to-energy conversion.

Figure 3-3 Food Waste Hierarchy taken from BSR (2012).

As noted in the resource assessment section, industry generates a relatively small volume of food wastes in comparison to other sectors or entities. Industrial point sources of food waste are therefore likely to support smaller-scale waste-to-energy solutions, despite offering more homogenous waste composition and greater centralization. A nearly opposite scenario exists for residential, commercial, and institutional sources; these sources tend to generate significant volumes of food waste, but the waste streams are highly variable and widely distributed.

In 2010, landfill tipping fees averaged $44.09 per ton and have increased nearly 5% since 2006 (Van Haaren et al 2010). Avoided cost is therefore key to the current value proposition for diverting food waste from landfills. While collection and transportation fees are likely stable, and built into the waste-collector/customer agreement, tipping fees are highly variable and expected to continue to increase. Average tipping fees in the Northeast can exceed $75 per ton, whereas tipping fees in the Midwest and Southeast can be $25–$35 per ton (Van Haaren et al 2013). These prices are typically dictated by the remaining landfill capacity combined with population size. As these wastes become more widely recognized as resources to be recovered, avoidance of tipping fees may become less of a factor. The economics of waste resource recovery technologies and markets will shift as waste resources gain value in response to a growing number of potentially profitable applications.

3.3.2. Emerging and Future Applications

Centralized waste-to-energy opportunities exist at waste transfer stations, where commingled waste streams from diverse entities undergo some level of sorting (for compost, recycling, and landfilling). In the future, organic wastes will either continue to go into landfills or be more productively diverted to composting or waste-to-energy applications. In some municipalities, local regulations are driving diversion strategies in response to landfill constraints as well as the costs associated with waste disposal in landfills. Wastes diverted to anaerobic digesters can provide ancillary benefits in the form of improved biogas yields and avoided fugitive biogas emissions. While the generation of electricity from landfill gas is widely practiced, the valorization of this landfill gas is still emerging. This valorization process is discussed in further detail in Section 3.5.

Nearly 200 communities in the United States recycle residential source-separated organics (SSO), which typically include yard grass clippings and woody debris, food scraps, and paper. Some highly urbanized cities in North America such as San Francisco and Seattle have begun to implement mandatory food scrap recycling programs with “Green Bin” curbside pickup to relieve pressure on their declining available landfill space, and to meet the environmental expectations of citizens. Other cities, such as Portland and Austin, have integrated “Pay as You Throw” pricing schemes into their curbside solid waste services to encourage Green Bin SSO recycling. In Portland, the SSO recycling program has reduced the amount of garbage going to the landfill by 36%. While most cities with SSO recycling send their organic waste to composting facilities, a few, such as Richmond B.C., have installed large, centralized anaerobic digestion facilities that are specifically designed to handle high-solids SSO streams such as food scraps and yard waste (Yepsen 2015).

Co-digestion of organic wastes at wastewater treatment plants has emerged as the most prominent alternative to support landfill diversion efforts. However, this approach generally entails additional transportation costs to move the high-moisture waste to the digester. The EPA is currently assessing this solution and recently completed an information collection effort. In particular, food waste producers of sufficient size to justify the capital and operating expense may benefit from the digestion of sole-source food wastes. As discussed in the context of biogas, the value of RNG RINs could spur wide adoption of this pathway.

3.4. Fats, Oils, and Greases

3.4.1. Current Assessment

3.4.1.1. Domestic Biodiesel Production

Biodiesel production through the transesterification of animal fats and yellow grease is a highly mature technology. Of the 166 biodiesel facilities, 53 specifically call out FOGs as feedstocks for a total rated capacity of 714 MM gallons annually (Biodiesel Magazine 2016). Many of these facilities accept multiple oils and fats as a means to insulate themselves from feedstock price variability.

From 2011 to 2015, the consumption of feedstocks to produce biodiesel increased 31%. Over the same four-year period, animal fat consumption for biodiesel remained relatively constant, in comparison, grease utilization (overwhelmingly yellow grease) grew 106% (see Figure 3-4 and Table 3-3). This rapid growth was driven by an upsurge in domestic biodiesel consumption that sufficiently overcame exports of yellow grease that decreased by more than 40%, predominantly to Europe and Latin America (Swisher 2015). This drop in exports can be explained by increasing crude oil prices, which make the domestic production of biodiesel more lucrative than exporting the grease for foreign biodiesel production.

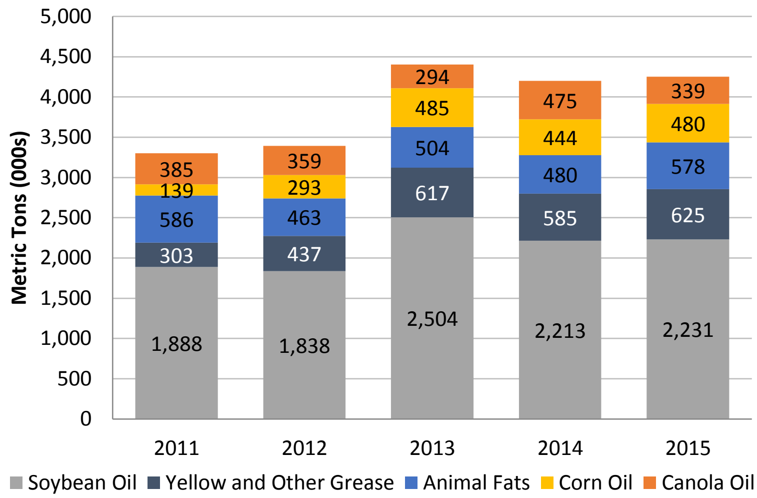

Figure 3-4 US inputs to Biodiesel production, adapted from (EIA - MBR 2016).

Europe, in particular, puts a premium on yellow grease—as regulations prohibit the import of genetically modified crops and their derived oils (e.g. soybeans, rapeseed) for biodiesel production or other uses. Yellow grease therefore possesses significant potential for further domestic energy production, particularly as prices have been heavily discounted relative to soybean and canola oils.

Table 3-3 U.S. Production, consumption, and export of yellow grease (adapted from Swisher 2015; EIA-MBR 2016)

Year	Production (MM Tons)	Total Consumption		Consumption by Biodiesel		Export	
		(MM Tons)	(%)	(MM Tons)	(%)	(MM Tons)	(%)
2011	906.4	340.1	38%	214.1	24%	566.2	62%
2012	884.4	432.4	49%	305.5	35%	452.1	51%
2013	900.8	539.8	60%	476.4	53%	361	40%
2014	931.8	598.4	64%	488.2	52%	333.4	36%

Biomass-based diesel includes both biodiesel (produced via transesterification) and renewable diesel (produced via hydroprocessing of lipids). Both types of biomass-based diesel qualify for RINs under the

RFS. To date, biodiesel produced from waste oils and animal fats has constituted nearly all biomass-based diesel reported by the EPA RFS Program, totaling nearly 2.8 billion RINs in 2015 (EPA RFs Program 2016). Currently D4 RINs (for biomass-derived diesel) are valued at $0.82 per RIN (PFL 2016). In comparing current biodiesel prices (which do not include RINs) to the price of petroleum-derived diesel, the RINs bring B100 close to cost parity: for Quarter 1 of fiscal year 2016, the on-highway average cost of diesel was $2.08/gallon, and the cost of B100 was $2.96 ($2.14 when accounting for RINS) (USDA 2016b). However, this type of cost parity relationship does not account for the differences between production cost and selling price for bio- vs petroleum-based diesel. Achieving production cost parity in addition to sale price parity may be important for bio-based transportation fuels to become truly competitive with fossil alternatives. These considerations should be accounted for in future techno-economic analyses.

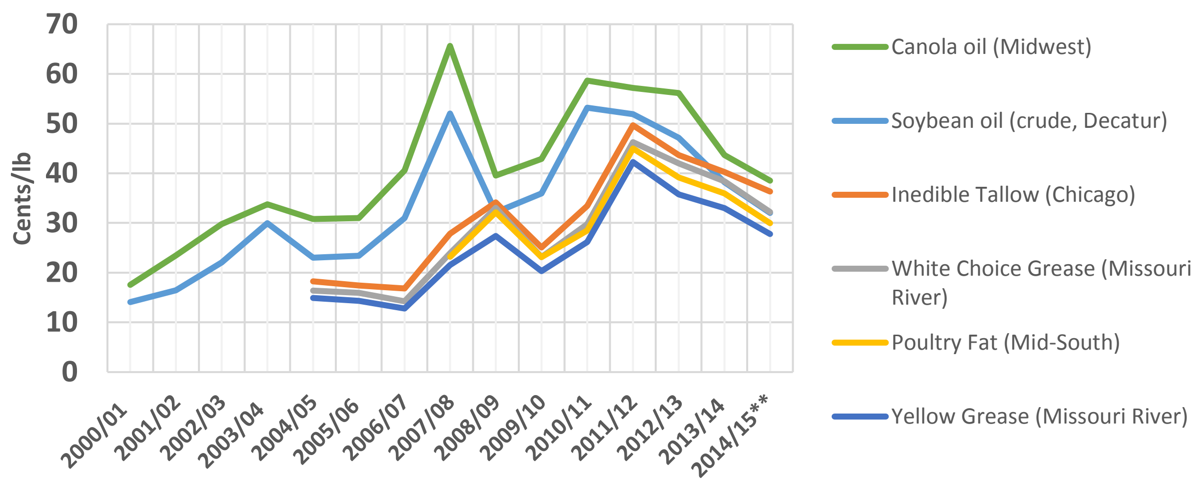

Figure 3-5 Historical pricing information for vegetable oils, fats, oils and greases (Swisher 2013; Swisher 2014; Swisher 2015; USDA 2016a)

Note: Data for vegetable oils is for market year, while the data for FOGs is for calendar year.

3.4.1.2. Other Hydrocarbon Biofuels

Renewable hydrocarbon fuels represent a further emerging market for fats, oils, and greases. The United States currently has the capacity to transform vegetable oils, fats, and greases into 211 million gallons of renewable hydrocarbons annually, though operations have been limited to date (NREL 2013). Renewable hydrocarbon fuels differ from biodiesel in that they are hydrogenated esters and fatty acids (HEFA)—as opposed to fatty acid methyl esters, which contain oxygen. Consequently, renewable hydrocarbon fuels or HEFAs possess superior cold-flow properties and can be blended up to 50% with conventional jet fuel (NREL 2016). With the expected growth in the renewable jet fuel market, HEFA presents a significant growth opportunity that is actively being pursued for these feedstocks.

3.4.2. Emerging and Future Applications

Brown grease remains almost completely unutilized despite constituting nearly 25% of the total FOGs produced. Impurities, high free-fatty acid content, and high moisture content render brown grease unsuitable for transesterification reactions. Consequently, most brown grease that is collected is subsequently landfilled, sent to AD for co-digestion (at low blends), or incinerated.

Technologies to utilize brown grease could exploit both the energy density of the feedstock and its current low/negative price. Furthermore, brown grease is commonly aggregated at wastewater treatment facilities, obviating the need to establish aggregation practices (NREL 1998). One option is to mix the collected brown grease with sludge produced at the treatment facility to create a lipid-rich feed stream for fuel production. Increasing the lipid content in algae HTL feeds has been shown to significantly boost biocrude yields, but the quantities of brown grease available at these facilities may constrain processing options. Technology opportunities are discussed further in Chapter 4.

3.5. Biogas

3.5.1. Current Assessment

3.5.1.1. Combined Heat and Power (CHP)

The prevailing use of biogas is for onsite CHP generation, which is a highly mature technology. Biogas shares some properties with natural gas and contains some methane. However, biogas contains a higher portion of non-combustible gases and thus has a relatively lower energy content than natural gas. Prior to combustion in CHP applications, the biogas must first be “conditioned” to remove trace constituents (H_2S and siloxanes). In some cases, CHP systems are specially modified to enable stable combustion of the biogas, with its low specific calorific content [Hosseini and Wahid 2014]. A higher calorific fuel such as natural gas can be blended into biogas combustion systems to even out the fuel rate. This also helps to maintain an elevated furnace temperature that prevents the condensation of corrosive species, such as H_2S and water (Walla and Schneeberger 2008). Modern biogas plants (including biogas produced via AD) typically exhibit electrical efficiencies of 30% to 40%, electricity output of 50 kW to 2.4 MW, and thermal efficiencies of around 50% (Walla and Schneeberger 2008 and Poschl et al 2010). By comparison, modern natural gas combined cycle units operate at near 50% efficiency (NETL 2007).

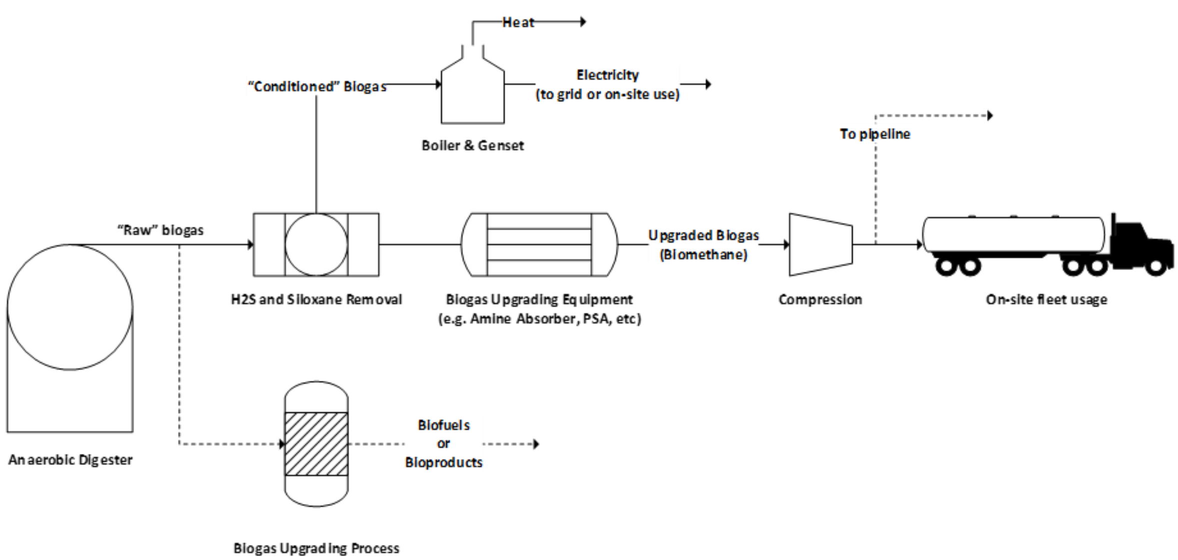

Figure 3-6 Current and emerging applications for biogas

Note: Solid lines indicate processes that are in commercial practice; dashed lines indicate processes that are emerging or have only limited adoption to date.

Every biogas production source can produce documented examples of onsite CHP from biogas: WWTPs, landfills, manure digesters, agricultural residue digesters, biorefineries, etc. In some cases, such as in Miami Dade, landfill gas is piped to a neighboring recovery facility at the wastewater treatment facility and is combined with wastewater derived biogas. The combined gases are converted into electricity to power operations at the wastewater treatment plant (Miami-Dade 2015). The conversion technologies for this waste utilization strategy are highly mature and readily available off-the-shelf. Commingling of biogas sources that are not within close proximity is extremely rare due to the cost of pipelines and compression. Techno-economic feasibility of this approach is largely contingent on the size of the point biogas source and local power rates (Murray et al. 2014).

3.5.1.2. Upgrading to Biomethane

When biogas is upgraded to biomethane (renewable natural gas), the CO_2 content must be significantly reduced (often to less than 1%) to meet heating value requirements (Lucas 2015). This CO_2 reduction can be accomplished through a variety of methods, including amine absorption, pressure swing adsorption, water scrubbing, membrane separation, and cryogenic techniques. All of these technologies are highly mature and have been deployed extensively, predominantly in Europe (Patterson et al. 2011). Once the biogas has been upgraded to biomethane, it can be combusted in conventional natural gas furnaces, compressed for CNG, liquefied for LNG (on site transportation use), or injected into natural gas pipelines.

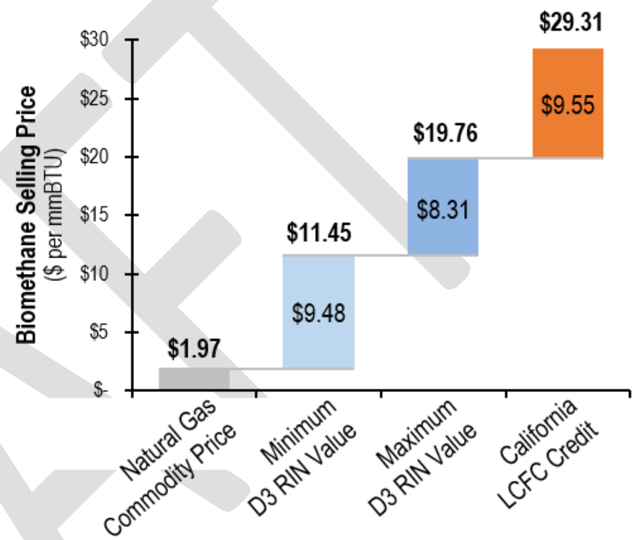

Figure 3-7 Pricing of biomethane depending on available RIN prices and California's Low Carbon Fuel Standard credit

When biogas is upgraded to biomethane, the resulting CNG/RNG becomes eligible for RINs if used for transportation purposes. The classification of biogas as a D3 cellulosic RIN in July 2014 has stimulated interest in WTE, particularly the use of biogas for applications beyond CHP. In 2015, close to 99% or 139.9 million of the 141.3 million RINs reported to the EPA were for biogas derived from WWRFs, animal manure digestion, landfills, other AD operations, and other sources (EPA RFS Program 2016). Those 139.9 million D3 RINs correspond to about 10.26 Bcf of biomethane per year[1]. Since vehicle consumption of natural gas rose 17% in 2014 to about 2,940 mmcf per month (EIA 2016), biogas-derived RNG/CNG could potentially displace approximately 31% of the total 34.4 Bcf of natural gas used in vehicles annually (EIA 2016).

[1] 1 RIN equals 77,000 Btu of CNG or LNG (40 CFR 80.1415) and 1 million btu = 1,050 standard cubic feet of natural gas (engineeringtoolbox.com/heating-values-fuel-gases-d_823.html)

In the current policy environment, D3 RINs are accelerating the installation of biogas upgrading infrastructure at sites that generate sufficient volumes of biogas. Because D3 cellulosic biofuels are a subset of D5 advanced biofuels, the D5 RIN price ($0.73) effectively sets the minimum price for D3 RINs. At the same time, the D5 RIN price plus the cellulosic waiver credit (CWC) set the maximum price for D3 RINs (CME 2016). Therefore, the effective D3 RIN would be currently valued between $0.73 and $1.37. Converting these RINs to million Btus (mmBtu) results in an effective RIN value of $9.48/mmBtu–$17.79/mmBtu. By comparison, the current spot price for natural gas is $1.97/mmBtu, indicating there is an exceptional premium for CNG and LNG derived from biogas (CME 2016). The value of the CNG/RNG is further increased under California's Low Carbon Fuel Standard of approximately $109/ton CO_2, which corresponds to an additional $9.55/mmBtu.[1] The overwhelming majority of biogas RINs to date pertain to fuels for on-site fleet vehicles (e.g., trash trucks).

3.5.1.3. Conversion to Fuels and Chemicals

Recent projects have used gasification and Fischer-Tropsch technologies to convert biogas, specifically landfill gas, into liquid fuels and chemicals. In one such project, landfill gas from the East Oak Landfill in Oklahoma is converted into syngas and subsequently the syngas is catalytically converted into Fischer-Tropsch liquids, including diesel, gasoline, jet range fuels, and specialty chemicals, such as paraffin wax and synthetic motor oil. The use of landfill derived biogas qualifies fuels for RIN credits. Novel technology increases the economic attractiveness of this process over other gas-to-liquid technologies, which often require significantly larger economies of scale (e.g., methanol-to-gasoline) (McDaniel 2014).

3.5.2. Emerging and Future Applications

3.5.2.1. Integration with Natural Gas Infrastructure

To date, the high costs of pipeline infrastructure ($50-$300/ft) and the complexity of negotiating and executing interconnection agreements (Lucas 2015) have severely limited the number of biomethane interconnections with natural gas infrastructure in the United States (e.g., SoCalGas). Lifecycle costs for interconnections can be significant, depending on the scale of the system and the length of the pipeline extension. For example, 19% of the lifecycle costs for a 750 thousand scfd facility with a two-mile pipeline extension can be attributed to the pipeline extension, even with a significant subsidy (Lucas 2015). Biomethane used by utilities would not be eligible for RINs unless used for transportation purposes. Consequently, to achieve significant penetration into utility markets, policy incentives would need to offset the costs of interconnection and upgrading. Long term, while the RINs are extremely lucrative for this technology, municipalities and commercial entities are reluctant to make business investments that rely on these policy incentives for economic viability. In the absence of RINs, displacing natural gas with biomethane will require the development of substantially

Cellulosic Waiver Credit

For any year in which the projected volume of cellulosic biofuel produced is less than the applicable volume of cellulosic biofuel set forth in the Clean Air Act, the EPA must reduce the required volume of cellulosic biofuel for that year to the projected volume, and must provide obligated parties the opportunity to purchase cellulosic waiver credits (CWC). The price of these credits is determined using a formula specified in the CAA.

The CWC price for 2016 is $1.33.

epa.gov/sites/production/files/2015-11/documents/420b15092.pdf

[1] Assumes carbon offset intensity for dairy biogas of 13 gCO_2/MJ

lower-cost biogas upgrading technologies (other than pressure swing adsorption, amine adsorption, etc.).

3.5.2.2. Digestion of Agricultural Residues

Although the United States has enjoyed low natural gas prices, high prices for natural gas in Europe have led to a significant number of operations that utilize crop residues to produce biogas. Anaerobic digester operators commonly use crop residues as a means to control the digestate composition (e.g., carbon-to-nitrogen ratio) and maintain the solids content in the digester (Braun et al. 2011). In Germany (2011), 26% (1.6 million) of the 6.2 million acres dedicated to corn cultivation supply biogas plants (Bilek 2011). This large dedication of croplands has led to concerns regarding land use changes, crop diversity, water quality impacts, and food availability (akin to corn grain ethanol concerns). Unlike corn grain ethanol, however, the whole crop is typically digested in these processes and factored into the methane yields per hectare. Research is now underway to explore sustainable landscape design for biogas energy crops.

As the United States bioeconomy evolves, AD of agricultural residues could serve as a bridging technology to spur the growth of the cellulosic crop industry while cellulosic ethanol and other biorefineries are being built and commissioned prior to start up. NREL researchers estimate that the nation can potentially produce enough biogas (4.2 TCF per year) to displace all natural gas used by the transportation sector (894 Bcf) as well as 34% of the natural gas used in the electric power sector (9.67 TCF) (EIA 2016). The technologies to digest these residues are highly mature, having been deployed extensively in Europe. One challenge to this opportunity is the difficulty of digesting lignin, as it is significantly recalcitrant and can require residence times of up to 50 days for digestion.

3.5.2.3. Biological or Chemical Biogas Upgrading

Methanotrophic microorganisms utilize methane as their sole source of carbon by “activating” methane and assimilating it into their central metabolism. Genetic engineering of these organisms has the potential to produce a multitude of end products, including hydrocarbons and high-value co-products. Methanotrophic organisms have already been used at commercial scale to produce single-cell proteins from natural gas at low-commodity prices (Al Taweel et al. 2012). Biogas presents a unique opportunity in that these organisms often possess a native tolerance to the impurities found in biogas (H_2S, NH_3) as they are typically cultured from sediments where these types of compounds can be found. This tolerance may obviate cost- and scale-prohibitive biogas conditioning and/or upgrading.

Biological upgrading of biogas is also significantly easier to scale down for distributed use than conventional gas-to-liquids conversion pathways, which can require large economies of scale and large sources of biogas. As individual point sources of biogas are quite small relative to the natural gas volumes available in pipelines, smaller, modular conversion processes are more amenable to biogas. Biological processes could offer economic opportunities at these scales.

3.6. CO_2 Streams

3.6.1. Current Assessment

Broadly speaking, little value has been attached to CO_2 waste streams, and they remain largely untapped due to economic rather than technological reasons. CO_2 separation and purification technologies are available, including amine absorption, cryogenic separations, and pressure-swing adsorption, but none have been widely adopted due to prohibitively high capital and operating costs.

Even under ideal conditions in state-of-the-art coal facilities, thermodynamic estimates indicate that carbon capture systems carry an energy penalty of 27–43%, depending on the base plant's efficiency (Kreith 2013). Similarly, a NETL analysis estimates that adding carbon capture and sequestration technology to a natural gas combined cycle facility would reduce its efficiency 7%: from 50.8% to 43.7% (NETL 2007). The DOE Office of Fossil Energy (FE) is pursuing improvements in the efficiency of CO_2 separation from mixed gas streams to advance post-combustion carbon capture technologies and help coal and natural gas power plants meet required GHG emissions reduction targets.

Currently, the only commercial use for large quantities of CO_2 is in enhanced oil recovery, where the gas is used to maintain pressure in mature and depleted oil and natural gas wells. Mature, sandstone oil fields, such as the Cushing Oil Field in Oklahoma (developed in the 1910s), often left more than half of the reserves untapped as pressures decreased. In 2008-2014, rising crude oil prices spurred interest in enhanced oil recovery operations (EOR) for these vast, uncovered reserves, but subsequent crude oil price declines have made EOR cost-prohibitive.

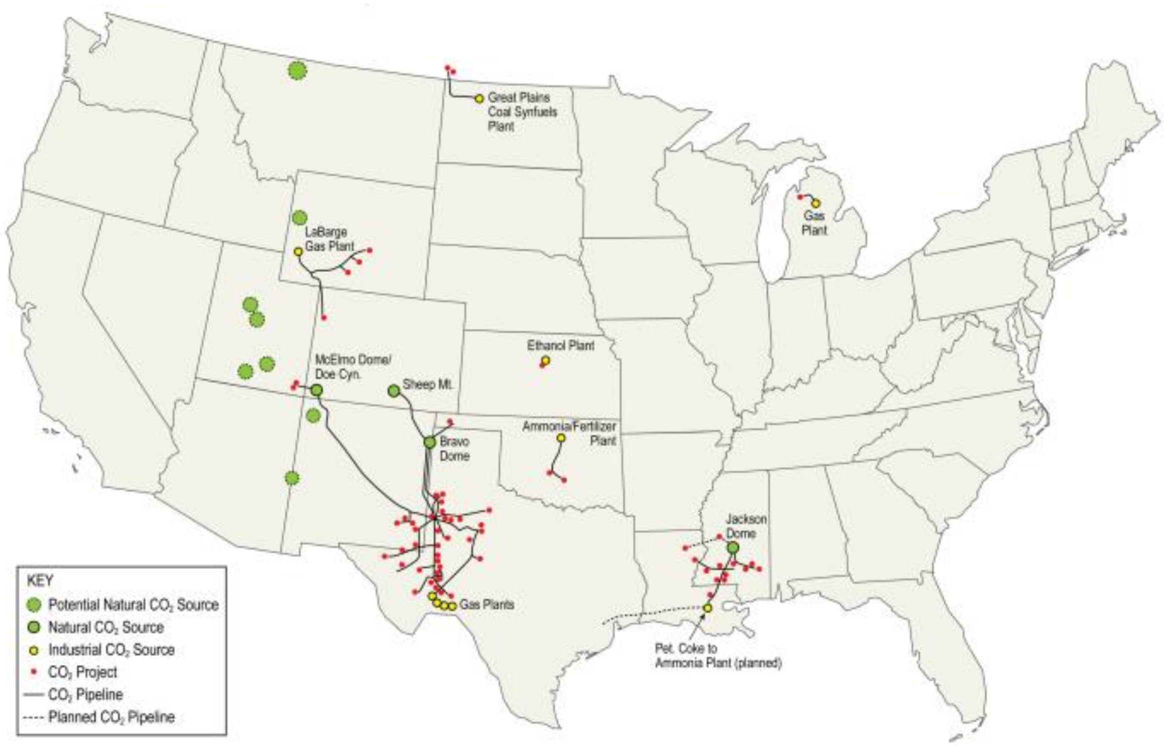

Figure 3-8 Location of current CO_2 EOR projects and pipeline infrastructure (NETL 2010).

Infrastructure development is an important factor in enabling the cost effective collection and use of CO_2 resources. As shown in Figure 3-8, the Permian basin of west Texas has seen significant infrastructure investment: more than $1 billion on 2,200 miles of transmission and distribution pipelines, resulting in a cost of $0.25-$0.75 per thousand cubic feet for transport (NETL 2010). In the case of EOR, Infrastructure investments like this can contribute 25% to 50% of the total cost per barrel of oil recovered (NETL 2010).

3.6.2. Emerging and Future Applications

Any technology that seeks to use CO_2 for the purposes of waste-to-energy will encounter similar CO_2 capture/separation cost and infrastructure challenges to those encountered by enhanced oil recovery efforts. A variety of approaches are available to convert CO_2 into fuels and products, including the use of algae and autotrophic organisms (organisms that can fix CO_2 as a carbon source). Initial ventures to develop biofuels and bioproducts from carbon dioxide may benefit by engaging in off-take agreements with existing CO_2 pipelines. At a price of $0.7–$2.0 per thousand cubic feet, this would equate to a CO_2 price of $14–$39 per metric ton, and a carbon price of $50–$144 per metric ton. This represents a significant carbon savings relative to corn stover, which at $80–$120 per Mt would equate to a carbon price of $334–$502 per Mt (INL 2013).[1] Specific technologies and organisms for utilizing CO_2 will be discussed in Chapter 4.

3.7. Associated Natural Gas

3.7.1. Current Assessment

In addition to restricting the venting or flaring of natural gas to avoid negative impacts on sustainability, state-level regulations are spurring the adoption of sustainable well-site technologies and solutions. In July 2014, North Dakota published regulations on gas flaring to drive toward 90% natural gas capture by 2020 (Seeley 2014). Under those regulations, wells capturing 60% or less of their associated gas could face an oil production cap of 200 bbl/day (Seeley 2014). Beginning November 1, 2016, oil and gas companies in North Dakota must capture 85% of the natural gas produced from their wells (Scheyder 2015). In other shale formations specifically targeting natural gas, Clean Air Act regulations require gas gathering pipelines to be in place before a well is completed.

The Bakken field in North Dakota and Montana has the largest volume of flared natural gas. Production rates are typically highest immediately after conventional oil and gas wells are drilled. These production characteristics are exacerbated with shale wells, in which production volumes are significantly front-loaded and exhibit extremely sharp decline rates within the first several years of operation: often 80-90% in year one and 40-60% in years two and three. Decline rates in subsequent years are relatively unknown, due to a lack of operational history in these types of formations; a highly conservative estimate (20% decline thereafter) would have more than 85% of the ultimate recovery occur in the first three years.

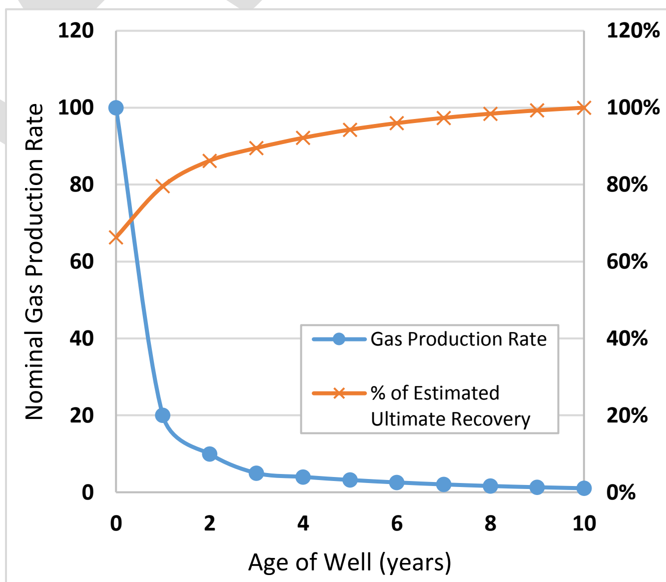

Figure 3-9 Nominal production of a typical shale well. Decline rate is assumed to be 80% in year 1, 50% in years 2 and 3, and 20% thereafter.

[1] Assumes 59.76% structural carbohydrates which are 40% carbon, therefore digestible carbon is 23.9% by mass.

The production characteristics of shale wells pose significant infrastructure sizing challenges for any process that seeks to valorize the associated gas production. If the gas infrastructure is sized for peak or near-peak production, the compressors, pipelines, and other infrastructure will be dramatically oversized as the field rapidly matures. The resulting capital and operating expenditures are disproportionately high relative to gas throughput. Alternatively, if the infrastructure is sized for the field at a more mature stage of development, flaring or venting will be necessary if the infrastructure cannot accommodate the gas production rate during the earlier stages of well production. The Bakken and other shale oil fields have often opted for the latter approach, resulting in the following potential scenarios.

Gas is produced from a single well with no gas gathering infrastructure. According to the terms of their leasing agreements, operators are typically required to drill at least one well within five years if they wish to retain access to the oil and gas minerals. This timeline often results in well pads with single wells and no gas gathering infrastructure yet in place. As commodity prices recover, expectations call for infill drilling of additional wells and the provision of incentives to capture the produced gas volumes. Today, nearly seven hundred single-well drilling pads are flaring 100% of their produced gas (UND EERC n.d.). Realistically, significant infill drilling is unlikely to occur until crude oil prices climb above $75/bbl. Opportunities in this situation would need to accommodate rapid decline rates of the initial well followed by a sharp increase in natural gas availability when infill drilling occurs.

Multiple wells are on a drilling pad with either constrained or no gas gathering infrastructure. More than 800 well sites are currently unconnected to gas gathering infrastructure and 4,000 are connected (UND EERC n.d.). Approximately 50% of the gas flared today is connected to a gas gathering pipeline, but use of the pipelines is limited either by back pressure or lack of capacity at the downstream gas processing plant. It is anticipated that infill drilling will resume as crude oil prices recover. Once more, the use of waste-to-energy technologies would be most valuable in the first 6-12 months, when gas production might exceed pipeline capacity or the gas gathering interconnection is not yet in place.

A station is built in the pipeline infrastructure between the drilling pad and the gas processing plant. A compression station or other intermediate site upstream of the gas plants could combine the gas from multiple drilling pads. By tapping into numerous drilling pads, a more continuous and larger supply of gas could be made available. This would also reduce pipeline pressures and allow more upstream wells to produce into the pipeline instead of flaring. A slightly more centralized operation could provide better access to utilities (process water, electricity, steam).

Wells are constructed in close proximity to a natural gas processing plant. As of 2013, there were 26 existing or planned natural gas processing plants in the Bakken field, with a processing capacity of 1.024 billion scfd (Ndpipelines.files.com 2012). Processing natural gas at a centralized facility could provide a continuous and predictable supply of methane gas with full access to utilities. The gas processing plant would also eliminate the varying compositions of natural gas liquids and other species. An in-field gas processing plant is the most upstream source of nearly pure methane available to technologies.

3.7.2. Emerging and Future Applications

Many technologies for the small-scale upgrading of associated natural gas lack the technological maturity to exert an immediate impact on the large volumes of natural gas currently being flared in isolated fields like the Bakken. The Bakken field may offer a real-world test-bed for technologies to

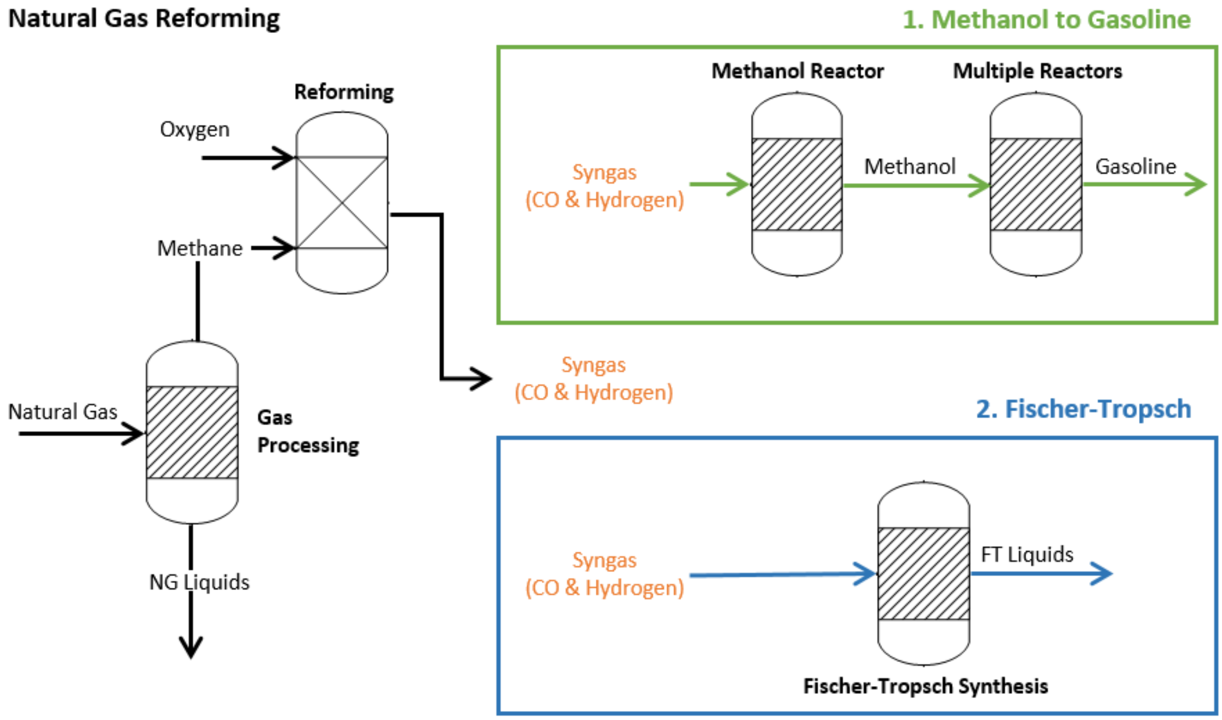

Figure 3-10 Simplified block flow diagram for several GTL processes.

utilize these associated gas resources. As the field matures and production rates continue to decline, however, the Bakken seems unlikely to represent a long-term (more than 20-year) waste-to-energy well-pad opportunity. As future shale-oil formations are discovered and developed, similar situations may emerge and present mid- to long-term commercial potential.

A variety of research and investments have explored the opportunities to develop gas-to-liquids facilities for associated natural gas. A number of companies and technology providers have developed solutions for converting natural gas to liquids (GTL). Figure 3-10 demonstrates a block diagram of natural gas reforming to syngas (CO & Hydrogen) and two gas to liquids technologies: 1) Methanol to Gasoline and 2) Fischer-Tropsch Synthesis.

Techno-economic analyses indicate that processes involving the oxidation of methane and subsequent upgrading may require significant economies of scale. Typically, the required scale is on the order of 10,000 bpd of output or an approximate methane feed rate of 100 million scfd. By comparison, a single facility at this scale would represent the full capacity of a handful of existing natural gas processing facilities. On a CAPEX basis, a facility at this scale could cost an estimated $1B (Ndpipelines.files.com 2012; Hamilton 2014). Investment in this type of project was possible when significant premiums were being paid for liquid vs gaseous fuels (on an energy basis). With crude oil futures below $50/bbl through 2018, large-scale GTL projects (>10,000 bpd) seem unlikely in the near future and are not suitable for most associated gas applications.

A variety of smaller-scale gas-to-liquids technologies (<2,000 bpd) are emerging and are being deployed to provide smaller, modular solutions. These smaller-scale GTL technologies seek to valorize associated gas through novel reactor designs or novel catalysts that can minimize downstream processing. In addition, many of the opportunities for biological upgrading of biogas could be viable for associated natural gas. These biological upgrading technologies may be more amenable to the scales, impurities, and flow rate variabilities present in these fields. Once more, however, these modular opportunities face significant challenges, such as lack of available utilities.

3.8. Chapter 3 References

AFDC (2016). Clean Cities Alternative Fuel Price Report. Washington, DC, Department of Energy, Alternative Fuels Data Center. http://www.progressivefuelslimited.com/Web_Data/pfldaily.pdf

AgSTAR. "Livestock Anaerobic Digester Database." Environmental Protection Agency. http://www2.epa.gov/agstar/

Al Taweel, A. M., Q. Shah, et al. (2012). "Effect of Mixing on Microorganism Growth in Loop Bioreactors." International Journal of Chemical Engineering 2012. http://www.hindawi.com/journals/ijce/2012/984827/

Bilek, A. (2011). "The German Biogas Experience: Opportunities and Key Experiences for Future US Deployment." The American Council on Germany. http://acgusa.org/files/The_German_Biogas_Experience-Bilek-Final_Report.pdf

Biodiesel Magazine (2016). US Plants. Biodiesel Magazine Accessed 4/2/2016. http://www.biodieselmagazine.com/plants/listplants/USA/

Braun, R., P. Weiland, et al. (2011) Biogas from Energy Crop Digestion. IEA Bioenergy Task 37- Energy from Biogas and Landfill Gas. http://www.iea-biogas.net/files/daten-redaktion/download/energycrop_def_Low_Res.pdf

Census Bureau 2012. "Statistical Abstract Section 17: Agriculture." Table 825, U.S. Census Bureau. 2012. Available from, https://www.census.gov/prod/2011pubs/12statab/agricult.pdf

Christensen, C. (2000) "The Innovator's Dilemma." Harper Business Essentials.

CME - D5 (2016). D5 Advanced Biofuels RINs (Argus) 2015 Futures Quotes. CME Group. Accessed 10/23/2015.

CME - NG (2016). Henry Hub Natural Gas Futures Quotes. CME Group. Accessed 10/23/2015.

DOE (2015). Waste-to-Energy Workshop Summary. Washington, DC, Department of Energy: 53.

EIA - MBR (2016). Monthly Biodiesel Production Report. Washington, DC, Department of Energy, Energy Information Administration. http://www.eia.gov/biofuels/biodiesel/production/

EIA - MER (2016). Monthly Energy Review. Washington, DC, Department of Energy, Energy Information Administration. Accessed 4/1/2016. http://www.eia.gov/totalenergy/data/monthly/

EIA - NG (2016). Natural Gas Consumption by End Use. Washington, DC, Department of Energy, Energy Information Administration. Accessed 4/1/2016. http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

EPA RFS Program (2016). Renewable Identification Number (RIN) Data for Renewable Fuel Standard Program. Washington, Dc, United States Environmental Protection Agency. Accessed 4/12/2016. https://www.epa.gov/renewable-fuel-standard-program/renewable-identification-number-rin-data-renewable-fuel-standard

Hamilton, P. (2014). Direction of Large and Small Scale GTL Plants. GTL North America 2014. 6/4/2014.

Informa Economics 2013. "National Market Value of Anaerobic Digester Products." Prepared for Innovation Center for U.S. Dairy. February 2013. Available from, http://www.americanbiogascouncil.org/pdf/nationalmarketpotentialofanaerobicdigesterproducts_dairy.pdf

INL (2013). "Feedstock Supply System Design and Economics for Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels." Idaho National Laboratory. https://bioenergy.inl.gov/Reports/Design%20Case%202017.pdf

Kreith, F. (2013) Principals of Sustainable Energy systems. CRC Press.

Lu 2012. Lu, Qin, Zhenli L. He, and Peter J. Stoffella. "Land application of biosolids in the USA: A review." Applied and Environmental Soil Science 2012 (2012). Available from, http://www.hindawi.com/journals/aess/2012/201462/#B30

Lucas, J. (2015). "Utility Case Study: Build, Own and Operate." 4th Annual Anaerobic Digestion and Biogas Summit 2015. 12/2/2015.

McDaniel, J. (2014). "Smaller scale GTL." GTL North America. 6/4/2014.

Miami-Dade (2016). "South Dade Landfill." Miami-Dade Solid Waste Management. Page updated October 14, 2015. Available from, http://www.miamidade.gov/solidwaste/south-dade-fill.asp

Murray, B. C., C. S. Galik, et al. (2014). Biogas in the United States: An Assessment of Market Potential in a Carbon-Constrained Future." https://nicholasinstitute.duke.edu/sites/default/files/publications/ni_r_14-02_full_pdf.pdf

NBS 2011. "The Potential power of Renewable Energy Generation from Wastewater and Biosolids Fact Sheet." National Biosolids Partnership. 2011. Available from, www.resourcerecoverydata.org/Potential_Power_of_Renewable_Energy_Generation_From_Wastewater_and_Biosolids_Fact_Sheet.pdf

Ndpipelines.files.com (2012). Natural Gas Processing Capacity. https://ndpipelines.files.wordpress.com/2012/06/gas-plant-table-jan-2014.jpg

NETL (2007). "Fossil Energy Power Plant Desk Reference." Department of Energy, National Energy Technology Laboratory. http://www.netl.doe.gov/energy-analyses/pubs/Cost%20and%20Performance%20Baseline-012908.pdf

NETL (2010). "Carbon Dioxide Enhanced Oil Recovery." Department of Energy, National Energy Technology Laboratory. https://www.netl.doe.gov/file%20library/research/oil-gas/CO2_EOR_Primer.pdf

NPC (2013). "Task Force Formed to Examine Flaring, Identify Solutions." North Dakota Petroleum Council. 10/16/13. https://www.ndoil.org/latest-news/task-force-formed-to-examine-flaring-identify-solutions/

NRCS (2016). Animal Feeding Operations website. US Department of Agriculture, Natural Resources Conservation Service. Accessed June 16, 2016. Available from, http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/plantsanimals/livestock/afo/

NREL milestone completion report: Waste-to-Energy system simulation model. Authors - Daniel Inman, Ethan Warner, Anelia Milbrandt, Alberta Carpenter, Ling Tao, Emily Newes and Steven Peterson.

NREL (1998). Urban Waste Grease Resource Assessment. G. Wiltsee. https://www3.epa.gov/region9/waste/biodiesel/docs/NRELwaste-grease-assessment.pdf

NREL (2016). 2013 Bioenergy Market report. Prepared for the US Department of Energy Bioenergy Technologies Office. http://www.nrel.gov/docs/fy16osti/63468.pdf

Patterson, T., S. Esteves, et al. (2011). "An evaluation of the policy and techno-economic factors affecting the potential for biogas upgrading for transport fuel use in the UK." Energy Policy 39: 1806-1816. http://www.sciencedirect.com/science/article/pii/S0301421511000279

PFL (2016). PFL Markets Daily. Progressive Fuels Limited Accessed 4/12/2016. http://www.progressivefuelslimited.com/Web_Data/pfldaily.pdf

Poschl, M., S. Ward, et al. (2010). "Evaluation of energy efficiency of various biogas production and utilization pathways." Applied Energy 87: 3305-3321. http://www.sciencedirect.com/science/article/pii/S0306261910001790

Ruddy, B.C., D.L. Lorenz, and D.K. Mueller. 2006. County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982–2001: U.S. Geological Survey Scientific Investigations Report 2006-5012

Saur, G., and A. Milbrandt. 2014. Renewable Hydrogen Potential from Biogas in the United States. NREL/TP-5400-60283. Golden, CO: National Renewable Energy Laboratory.

Scheyder, E. (2015). "North Dakota postpones deadline for natural gas flaring rules." Reuters. 9/24/2015. http://www.reuters.com/article/us-north-dakota-flaring-idUSKCN0RO2KX20150924

Seeley, R. (2014). "North Dakota gives teeth to flaring reduction plan." Oil & Gas Journal. 7/2/2014 http://www.ogj.com/articles/2014/07/north-dakota-gives-teeth-to-flaring-reduction-plan.html

Shen (2015). Shen, Yanwen, et al. "An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: challenges and opportunities towards energy-neutral WWTPs." Renewable and Sustainable Energy Reviews 50 (2015): 346-362. Available from, http://www.sciencedirect.com/science/article/pii/S1364032115003998

Swisher, K. (2013). "Market Report." Render Magazine April 2013: 10-17. https://d10k7k7mywg42z.cloudfront.net/assets/515f00fd8ad7ca61ff000639/Apr13Render.pdf

Swisher, K. (2014). "Market Report." Render Magazine April 2014: 10-15. https://d10k7k7mywg42z.cloudfront.net/assets/533f2037f002ff0f280000d2/MarketReport2013.pdf

Swisher, K. (2015). "Market Report." Render Magazine April 2015: 10-16. https://d10k7k7mywg42z.cloudfront.net/assets/55281d9ec0d6715235004d2e/MarketReport2014.pdf

UND EERC (n.d.). Flaring Solutions Technology – Search. University of North Dakota Energy & Environmental Research Center. http://www.undeerc.org/flaring_solutions/Search.aspx

USDA (2016a). "Oil Crops Yearbook." United States Department of Agriculture. May 2016. Available from, http://www.ers.usda.gov/data-products/oil-crops-yearbook.aspx

USDA 2009. MacDonald, J. M., et al. "Manure use for fertilizer and for energy: report to Congress. USDA-ERS Publication No. AP-037." June 2009. Available from, http://www.ers.usda.gov/publications/ap-administrative-publication/ap-037.aspx

USDA-NASS 2009. "National Agricultural Statistics Service, Farms and Land in Farms, Final Estimates, 2003–2007." United States Department of Agriculture. February 2009. Available from, http://usda.mannlib.cornell.edu/usda/nass/SB991/sb1017.pdf

Van Haaren, R., N. Themelis, et al (2010). 17th Nationwide Survey of MSW Management in the U.S. http://www.seas.columbia.edu/earth/wtert/sofos/SOG2010.pdf

Walla, C., W. Schneeberger (2008). "The optimal size for biogas plants." Biomass Bioenergy 32:551-557.

WEF 2013. "Recognizing a Resource: Biosolids." Part 3: Trends & Drivers - Focusing on resource Recovery. National Biosolids Partnership. January 2013. Available from, wef.org/uploadedFiles/Biosolids/Biosolids_Resources/Newsletter/Newsletter_PDFs/NBP-RecognizingAResource-Biosolids-Part3-Jan13.pdf

4. Key Technology Challenges and Opportunities

Chapter one presented the workshop series sponsored by the DOE and collaborators, and observed the momentum within the wastewater community toward the "water resource recovery facility of the future"(DOE 2015b). Chapter 4 attempts to push the envelope technically. The stakeholder input elicited from the earlier series of three workshops, plus the stakeholder engagement event focused on feedback to an early draft of this document, was very valuable in its own right and also served as a launching pad for further investigation. In particular, analysis of the input received in these workshops (and related activities by others) has provided a foundation for further development of the DOE's understanding of the relevant technological landscape. Therefore, Chapter 4 strives to articulate a conception of relevant challenges and opportunities that is more than the sum of the parts of what has gone before.

As Chapter 2 makes clear, the wet and gaseous feedstocks under consideration are both distributed geographically compared to traditional petroleum refineries, and subject to compositional variation. The germane technological challenges and technologies are feedstock-specific to a certain degree; chapter four is accordingly organized into technologies applicable to wet and gaseous feedstocks, respectively. Additionally, the wet and gaseous feedstocks in question effectively force the question of economies of scale. The conventional wisdom has long been that processes such as Fischer-Tropsch and Methanol-to-Gasoline require extremely large facilities costing billions of dollars to make economic sense, and even then only under specialized conditions. In order for these feedstocks to achieve economic viability, that logic needs revision, and commercial examples are beginning to emerge. The economies of mass production may play a critical role, as might and notions of modular systems might play a critical role in the future. The relatively small scales involved might also create opportunities for families of technological solutions that do not make sense in conventional refineries but might enable transportable, transient, and modular systems.

It is worth reiterating that wet and gaseous waste feedstocks are different from BETO's traditional areas of emphasis. Energy crops, agricultural residues, and woody and herbaceous sources in general are relatively dry and mostly solid. In contrast, many wet waste streams rarely exceed 20% solids, even after pretreatment, and gaseous feedstocks are another creature entirely. These differences demand different technological approaches, and that distinction frames the discussion that follows.[1]

4.1. Aqueous/Wet Feedstock Conversions

One key to processing aqueous and wet feedstocks is to avoid thermal drying. The latent heat of vaporization of water makes the energy balance of any process that requires thermal energy for drying extremely challenging. In practical terms, this means that the energy required for drying can exceed the energy value of the final produced fuel. At the same time, aqueous feedstocks are generally pumpable, which can simplify handling. Further, water itself can contribute to desirable interactions, whether as a solvent (especially near its critical point), a reagent, or as an electrolyte in the form of an aqueous solution. In keeping with these advantages, this section targets anaerobic fermentation, various liquefaction processes, and electrochemical systems, with nutrient recycling as a potential value-added combination with other technologies.

[1] Algae is also a wet feedstock, and many of the same conversion technologies, such as hydrothermal liquefaction, are applicable. However, algae has been discussed thoroughly in a recent BETO report, as noted in Chapter 1.

4.1.1. Biological Processes

Biological conversion strategies, employing enzymatic or whole cell biocatalysts, offer an array of favorable bioprocess attributes, including high selectivity with minimal side reactions, high catalytic efficiency, and mild operating conditions. Additionally, as a result of their potential modularity and scalability, such biocatalytic approaches offer a number of advantages uniquely suited for conversion of wet waste streams, which are often remote and/or decentralized. However, bio-based platforms also face unique hurdles, including limited operating regions (temperature, pH), thermodynamic limitations related to mass transfer, substrate and/or product inhibition, and susceptibility to contaminants in feedstock streams. Biocatalytic approaches to wet waste conversion will thus need to employ targeted mitigation strategies to address these hurdles in an effort to realize bio-based platform potential.

4.1.1.1. Anaerobic Digestion

Anaerobic digestion (AD) of organic material is a naturally occurring process that has been harnessed for municipal wastewater treatment for at least 100 years (WERF 2011). In essence, AD involves microbes that digest organic wastes in the relative absence of oxygen. In controlled reactor systems, AD reduces the volumes of sludge that require disposal, renders those sludges less biologically active, and produces biogas. With appropriate cleanup, the biogas can be burned to produce both heat and power (CHP), or processed to produce transportation fuel compressed natural gas (CNG) or pipeline-ready renewable natural gas (RNG).

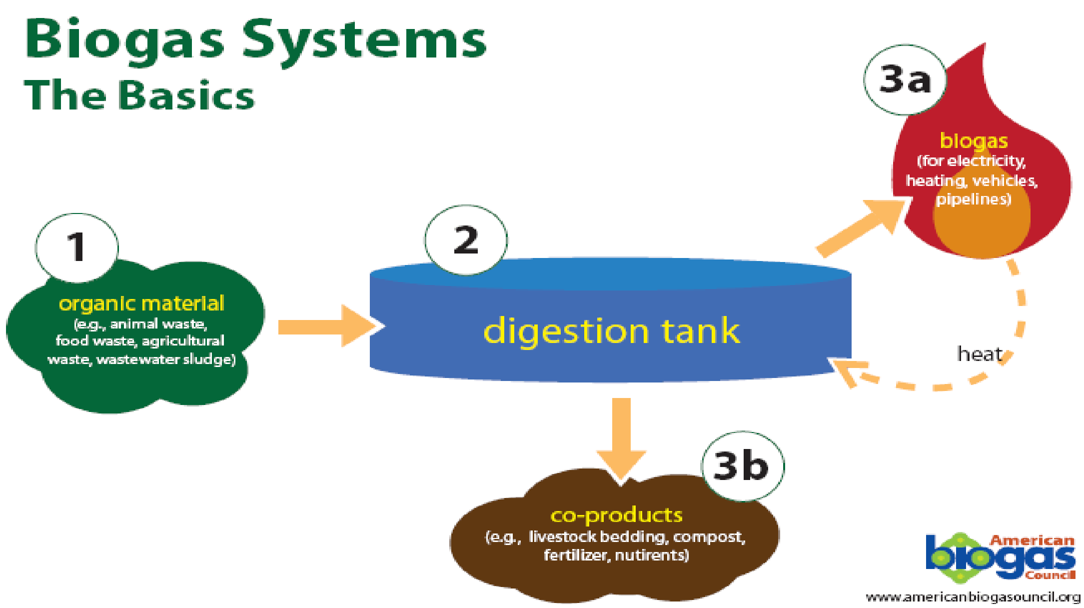

Figure 4-1 Biogas Systems – The Basics
Courtesy of American Biogas Council

While AD technology is widely deployed in municipal wastewater treatment facilities and has achieved some penetration in dairy farms, substantial opportunity for expansion remains (WEF 2012; EPA 2013; Batstone and Virdis 2014; USDA 2014; Shen et al. 2015).

Key challenges that emerged from the technical workshop series include the need to make AD cost-effective at scales below 5 million gallons per day (MGD) for wastewater treatment facilities, 500 cows for animal operations, and similar thresholds for other wet organic waste streams.

Additional identified possibilities included enhancing the percentage of methane in biogas and advancing fundamental understanding of heterotrophic methanogenic communities, including improved real-time sensing capabilities (DOE 2015e; DOE 2015b; Willis et al. 2015). Alternative reactor designs, such as various flavors of anaerobic membrane bioreactors (AnMBRs), also stood out as promising possibilities (Skouteris et al. 2012; Meabe et al. 2013; Andalib et al. 2014).

Opportunities may also exist in interrupting the methanogenesis stage of AD to produce fatty acids and other bioproduct precursors (Lee et al. 2014; Kondaveeti and Min 2015). Further, there may be significant opportunity for systems biology approaches to enhance AD via development of microbial consortia with enhanced rates of hydrolysis and/or methanogenesis.

So, while AD in its most basic form is a widely deployed technology, multiple possibilities exist for additional R&D to advance the state of the art, and, ultimately, real-world performance.

Enhanced Methane Production

As depicted in Figure 4-2, AD of municipal sludges includes four distinct steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (WERF 2011). Hydrolysis is generally the rate-limiting step (Christy et al. 2014); one promising set of strategies to accelerate this process are pretreatments that enhance the availability of intracellular materials (Abelleira et al. 2012). For example, thermal hydrolysis processes have proven effective in Europe and are just starting to see deployment in the United States. Cano et al. (Cano et al. 2015) claim that only thermal and ultrasound pretreatment technologies have a good chance of achieving positive energy balances. Other scholars argue differently. The peer-reviewed

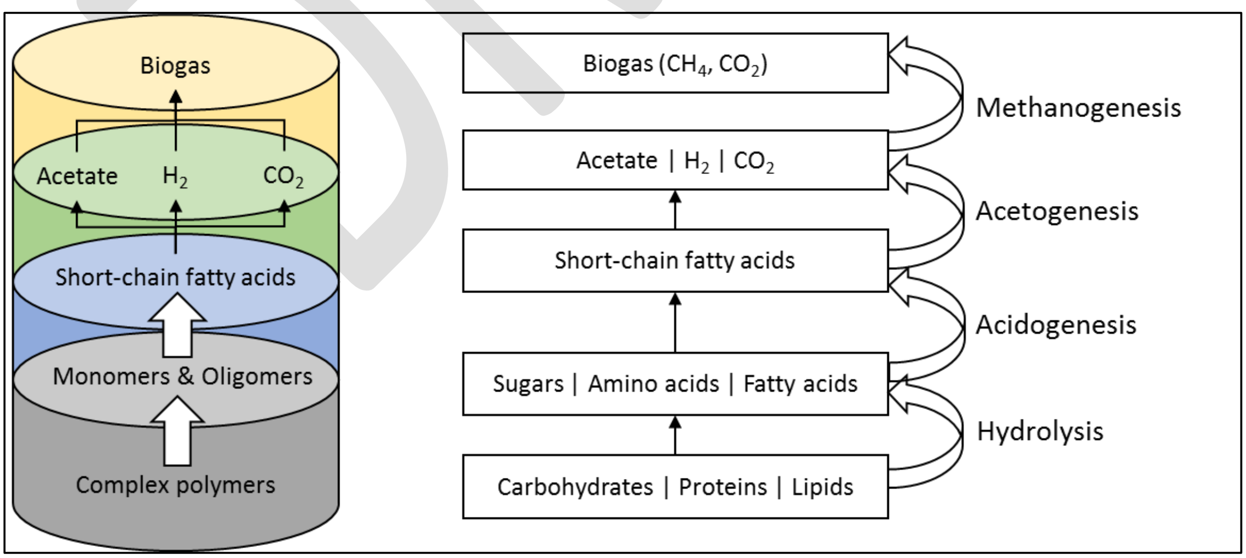

Figure 4-2 Stages of Anaerobic Digestion
Courtesy of Argonne National Laboratory

literature includes articles that advocate enzymatic pretreatments (Christy et al. 2014), bio-augmentation (Fotidis et al. 2014), and co-digestion of various other waste streams (Westerholm et al. 2012) as viable strategies. Co-digestion of food wastes in particular is already gaining traction in certain U.S. wastewater treatment facilities (WERF 2014).

Also, systems biology approaches may be able to contribute to the enhancement of hydrolysis and/or methanogenesis to improve methane yields. Strategies that minimize CO_2 production through tailored strain engineering could also be valuable. Promise may also lie in further investigations on enhancing the metabolic pathways of acidogenesis and methanogenesis aimed at of reducing solids retention time, and thus reactor capital costs. Other possibilities also exist in the literature (Nasr et al. 2012; Mota et al. 2013; Oh and Martin 2014). Additionally, the notion of dynamic membranes found voice in the March workshop and may offer intriguing avenues for future research, albeit at lower TRL levels (Alibardi et al. 2014; Xie et al. 2014). Finally, multiple strategies for improving efficiency and throughput are under investigation, at least at the bench scale (Garcia et al. 2013; Andalib et al. 2014; Aslam et al. 2014). So while “traditional” AD is clearly a mature and commercial technology, there may be enough novel variants in the R&D pipeline to merit additional exploration.

The question of whether the DOE should be investing in improving AD came up repeatedly throughout the series of workshops that inform this document. Foreshadowing the boundary discussions in Chapter 5, participants basically fell into two camps on the issue. There were those that felt that incremental improvements in AD would provide benefit, particularly to municipal systems that lack access to profit-motivated funding. As noted in the previous paragraph, gaps remain in the fundamental understanding of heterogeneous microbial communities, and there are possibilities for improving existing systems. On the other hand, there were those that noted that AD is in commercial play in the industrial and municipal wastewater treatment sectors and feel that only novel or disruptive technologies should be pursued by DOE. In this regard, pretreatment strategies such as thermal hydrolysis are starting to gain traction. Co-digestion also came up repeatedly. In short, the proper role of the DOE as an energy R&D organization in this space is still an open topic for conversation, as discussed in Chapter 5.

4.1.1.2. Anaerobic Membrane Bioreactors

The potential value of exploring alternative reactor designs for AD was among the strongest stakeholder messages elicited in the November 2014 workshop (DOE 2015e). This notion was further endorsed and developed in the March and April 2015 events (DOE 2015c; DOE 2015b), which included presentations from teams that have achieved energy-positive wastewater treatment without importing other organics at a pilot scale (Shin et al. 2014). While by no means the only topic of conversation or suggestion, various flavors of AnMBRs were prominent items of discussion. The core advantage of AnMBRs is that they offer the possibility of separating hydraulic retention time (HRT) from solids retention time (SRT) in secondary treatment of a variety of organic waste streams. The significance of this separation is its potential impact on capital costs. HRT is a key variable in sizing treatment facilities; the possibility of reducing it by an order of magnitude holds forth the promise of reasonably proportional reductions in capital costs. This factor alone offers game-changing opportunities in making AD cost-effective at distributed scales, and thus may merit R&D attention.

Fouling

Fouling is always a key issue in any membrane-based technology, and AnMBRs are no different (He et al. 2012; Lin et al. 2013). AnMBRs essentially place a membrane between a biologically rich environment and a relatively clean aqueous chamber. This strategy intrinsically poses multiple interacting challenges and possible solutions, mostly drawn from the March 2015 workshop (DOE 2015c):

- The energy requirements of the required periodic cleaning of the membranes are a key factor in determining overall energy balances (Ramos et al. 2014).
- Some designs depend on the formation of a biofilm on the upstream side of the membrane for their effectiveness. One participant at the March workshop raised the question of which species populate the putative biofilms first, and what the sequence of heterotrophic community development is.
- The need for energy-efficient sparging strategies was among the main topics of conversation.
- Notions of membranes designed to facilitate the development of useful biofilms also arose, as did the idea of dynamic membranes, in which a physical infrastructure might facilitate the development of a biological superstructure in real time.
- Relatively self-cleaning membranes by design were also a theme, as this might be a way to reduce the energy requirements for sparging or other kinds of cleaning.
- One participant advocated approaching membrane fouling as a default operational condition, suggesting that systems should be designed to operate in a "failed" state. While this position did not achieve consensus support, it was a novel contribution to the conversation.

In summary, the participants were very clear that fouling is a key issue in the commercial deployment of AnMBRs. While specific membrane and sparging improvements do have a role to play, approaches that view the specific technical problems as elements within larger systems have more promise in the long run. In other words, a systems approach to problem-solving is more likely to generate practical results than a narrow focus on particular technologies.

Methane Concentrations in Digestate

The second major challenge for AnMBRs that emerged from the workshop series is concentrations of dissolved methane in the aqueous output streams (DOE 2015c). This problem is particularly acute at psychrophilic temperatures (~8–15°C), as the solubility of methane in water is substantially higher under such conditions, which could easily occur during winter in temperate regions (Kundu et al. 2012; Smith et al. 2013; Shin et al. 2014). Participants in the March 2015 workshop identified reductions in costs and energy consumption for dissolved methane recovery as a key opportunity. The possibility of enhanced membranes to help retain methane in the primary reactor vessel also arose. The issue is non-trivial, as methane in the digestate represents both a risk of atmospheric discharge, with attendant greenhouse gas consequences, and a lost opportunity for productive use.

4.1.1.3. Arrested Methanogenesis

One of the main objections to AD raised in the November 2014 workshop was that participants strongly questioned the wisdom of producing biogas as an intermediate in the production of biofuels and bioproducts (DOE 2015e). One strategy to avoid the production of biogas is to arrest methanogenesis to the degree feasible and instead produce fatty acids (or other alternatives) as a direct precursor to higher-value biofuel and bioproduct precursors. While research in this area is nascent, a few key challenge and opportunity areas appear to be emerging (Liu et al. 2013; Yun et al. 2013; Otero-Gozalez et al. 2014; Kondaveeti and Min 2015; Zhong et al. 2015):

- Suppression or avoidance of methanogenesis without inhibiting desirable conversion processes. AD consortia are finely co-evolved systems; removal of methanogenesis has the potential to disrupt the entire symbiotic community
- Efficient conversion strategies for the acids common in the early stages of AD (e.g., acetic, butyric, and proprionic) to higher-value intermediates
- Avoidance of targeted process inhibition by "excessive" accumulation of desired intermediates
- Separations of fatty acid/biofuel precursors from fermentation broths may pose a challenge; in particular, selective isolation of target compounds from such a complex organic matrix might prove tricky
- Incorporation of byproduct carbon dioxide and hydrogen into the ultimate product stream
- Utilization of organisms other than traditional wastewater microbial consortia as biological conversion starting points

Generally speaking, this avenue is underrepresented in both the peer-reviewed literature and commercial endeavors. As such, this topic area might be a fruitful avenue for future federal investigation. The data collected to date suggests a productive opportunity for pre-competitive solicitation and collaboration; precisely the sweet spot for federal R&D intervention.

4.1.1.4. Microbial Electrochemical Cells (MxCs)

Microbial electrochemical cells (MxCs), which use various organic wastewaters as feedstock to produce hydrogen and higher hydrocarbons, are another intriguing area of possibility. In principle, they are the opposite of microbial fuel cells, which derive electricity from similar streams. Instead, MxCs supplement the electricity generated from oxidation of organic material at the anode with external sources in order to power reduction reactions at the cathode that yield valuable biofuel and bioproduct precursors (Rabaey and Rozendal 2010; Wang and Ren 2013). While the technologies are at an early stage of technical development, they may have promise, particularly in the kinds of distributed applications that are a theme of this document.

The phenomenon at the core of MxC activity is electron transfer between microbes and electrodes and, in some cases, between microbes. Some species are capable of direct electron transfer to electrodes via cytochromes on the membrane surface; these cytochromes require a specific combination of proteins to manifest effectively (Mohan et al. 2014a). Some organic molecules, such as neutral red, can function as electron shuttles between electrodes and relevant microbes (Lovley and Nevin 2013), and other substances can act as electron donors as well. Additionally, some organisms such as *Geobacter sulfurreducens* produce nanoscale filaments, known as pili, that can act as conducting "nanowires" (Kalathil et al. 2013). Various *Shewanella* species have also been shown to display such exoelectrogenic characteristics, albeit via different mechanisms (Zhi et al. 2014).

The challenge is to harness these phenomena into techno-economically viable systems. Much of the work done to date has focused on microbial fuel cells and the production of hydrogen. These areas represent an opportunity for BETO to collaborate with the Fuel Cells Technology Office, as evidenced by the joint workshop that the two offices sponsored early in 2015 (DOE 2015c). Participants identified the following as key issues: scaling, cost-effective mass production of cathodes, attaining and sustaining economically viable current density, and maintaining biofilm performance over time. The literature raises additional questions about the interactions between biofilms, electrodes, and electrolytes (Mohan et al. 2014b) and about optimization of energy harvesting at a systems level (Wang et al. 2015a), but also expresses some hope regarding prospects for the future (Zhang and Angelidaki 2014). While these technologies have promise, they are clearly at an early stage of development in terms of commercial deployment. Some of the spectroscopic techniques proposed in section 4.1.1.5 may be of assistance in accelerating marketplace success.

One addendum that merits mentioning—one voiced by participants in the March 2015 workshop—is that there may be unique opportunities to combine AnMBRs with various flavors of MxCs. On their own, MxCs tend to face scaling challenges, as noted above. However, the conjunction between MxCs and AnMBRs creates some interesting possibilities that might aid commercial viability (Li et al. 2014; Ren et al. 2014; Tian et al. 2014b). Non-microbial electrochemical systems are also potential candidates (Katuri et al. 2014). More generally, microbial electrochemical processes have connections with the some of the gaseous conversion strategies enumerated in Section 4.2, as well as the possibilities for the distributed/ modular conversion scenarios discussed in Section 4.3.

4.1.1.5. Electrochemical Impedance Spectroscopy

One of the challenges in managing microbial systems is obtaining in real time actionable data suitable for activation of feed-forward controls. Electrochemical impedance spectroscopy (EIS) and related interrogation techniques may offer a novel set of solutions that could serve as an enabling platform for deployment of both waste-to-energy technologies and broader applications. This family of non-invasive approaches has the potential to examine novel details of bioelectrical systems. In combination with existing techniques such as cyclic voltammetry and chronoamperometry (Yu et al. 2013), EIS methods offer substantial promise in enabling future developments in a variety of areas. The simplified discussion here will focus largely on bioelectrochemical systems, such as MxCs, but applicability could be much broader.

EIS applies an alternating current across a range of frequencies and relatively small voltages (e.g., 10 mV) to the system in question. In the case of MxCs, the minimum configuration of the system includes an anode, cathode, some form of separator, and an electrolyte, and more complex configurations are possible. Each of these components has an associated internal resistance, and capacitance also enters into the equation. Analysis of the differences between the applied and received signals in current, voltage, and phase angle can yield information about all the performance of all three basic components, as well as data on microbial processes, including production of extracellular mediators and other mechanisms of electron transfer (He and Mansfeld 2009; Ramasamy et al. 2009; Borole et al. 2010; He et al. 2014).

MxCs are complex phenomena that can include electric double-layer capacitance and substantial heterogeneity within the device. Graphical tools are an important element in interpreting the resulting data, which is a non-trivial exercise. Nyquist plots compare the real and imaginary portions of impedance; Bode plots map phase angle and impedance vs. frequency. Given the non-linear nature of MxCs, caution is necessary in analyzing such results, and corrections may be necessary in some cases (Dominguez-Benetton et al. 2012).

EIS interpretation often relies on the use of equivalent electrical circuit models as a baseline. Dominguez-Benetton et al. criticize the possibility of relying on overly simplistic models for this purpose. The interaction between various elements of resistance and capacitance in bioelectrochemical systems can be complex, and assumptions that fail to take that complexity into account can lead to erroneous conclusions (Dominguez-Benetton et al. 2012). Wang and Pilon make a similar point with respect to electric double-layer capacitance measurements (Wang and Pilon 2012). Zhang et al. present evidence to support their claims that the placement of the reference electrode, when one is needed, can affect the accuracy of EIS readings (Zhang et al. 2014b). While the above literature sample is truncated, it does suggest that substantial methodological questions remain in applying these techniques to microbial systems.

Even with methodological issues, these techniques appear to have considerable promise in other areas as well. For example, one team used a combination of cyclic voltammetry and EIS to characterize the capacitive deionization process, an inorganic method of desalination (Liu et al. 2016). Another explored pH-dependent performance in a microbial fuel cell (Jung et al. 2011). A third group characterized an microbial fuel cell using seawater microorganisms and compared electrode geometries (Hidalgo et al. 2015). A different team employed EIS to examine internal concentration polarization within forward osmosis membranes, a known performance hurdle in such systems (Gao et al. 2013). These techniques appear to have promise for any application in which charge or polarization gradients or resilience in response to an AC current have operational relevance. As such, these approaches merit further investigation.

Stepping back a bit, the discussion to this point has focused on microbial strategies, using existing AD facilities as a starting reference point. While such a focus is appropriate to current practices in managing wet organic waste streams, it may be inordinately restricted by existing realities, particularly given the (understandable) conservatism of the wastewater treatment industry, given their regulatory constraints. As previously noted, wet waste streams have characteristics that differ from terrestrial feedstocks, particularly in terms of moisture content. To that end, the range of options available from a variety of thermochemical strategies might deserve attention.

4.1.2. Thermochemical Processes

Thermochemical processes are widely used in petroleum refining and related industries. They tend to provide high throughput at scales relevant to global volumes of fuel and chemical production. These processes usually require elevated temperatures and pressures, which increase capital costs, and also support economies of scale. Humans have more than 100 years of experience operating such systems—the processes are reasonably well understood, and relevant expertise is well dispersed. At the same time, selectivity, separations, and optimization can present challenges, and require unique tailoring for each process application and conversion.

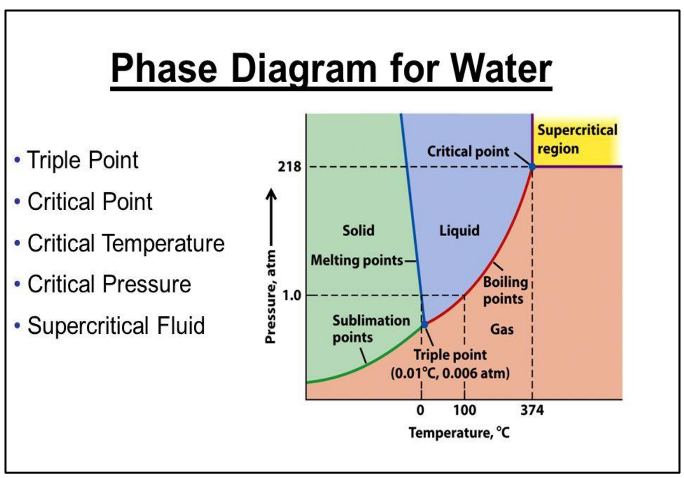

Figure 4-3 Water Phase Diagram

Sub- and supercritical liquefaction is a promising family of conversion technologies for wet waste feedstocks. While a substantial amount of work has been done with algal and woody or herbaceous feedstocks (Biddy 2013; Chen et al. 2014; Jones 2014; Tian et al. 2014a; Zhang et al. 2014a; Chan et al.

2015), the focus of this document is the application of these technologies to biosolids, manure, and related feedstocks as detailed in Chapter 2. These liquefaction processes work well with feedstocks in the 15%–20% solids range, have the potential for high energy and carbon yields, and offer the possibility of producing high-quality bio-crudes at a distributed scale. While much work remains to bring these solutions to widespread commercial success, the market opportunity appears real and relatively near-term.

As depicted in Figure 4-3, the critical point of water is at roughly 374°C and 218 atm (roughly 22.1 MPa). Above that temperature and pressure, it becomes a supercritical fluid, possessing some properties of both liquids and gases. In particular, supercritical water is non-polar, which gives it the ability to dissolve some normally insoluble molecules such as oils.

4.1.2.1. Hydrothermal Liquefaction (HTL)

Hydrothermal liquefaction (HTL) is conducted at temperatures and pressures just below the critical point of water. While not yet a supercritical fluid under these conditions, water does become a much better solvent for non-polar materials such as the organic substances present in wet waste streams of interest (Okajima and Sako 2014). Further, sub- and supercritical water can act as both a catalyst and a reagent in liquefaction reactions (by increasing the concentration of reactive protons and hydronium ions), supplying a source of hydrogen.

Figure 4-4 depicts a laboratory HTL system developed by the Pacific Northwest National Laboratory (PNNL), and there are other actors active in this field. HTL alone produces bio-crude, an aqueous phase

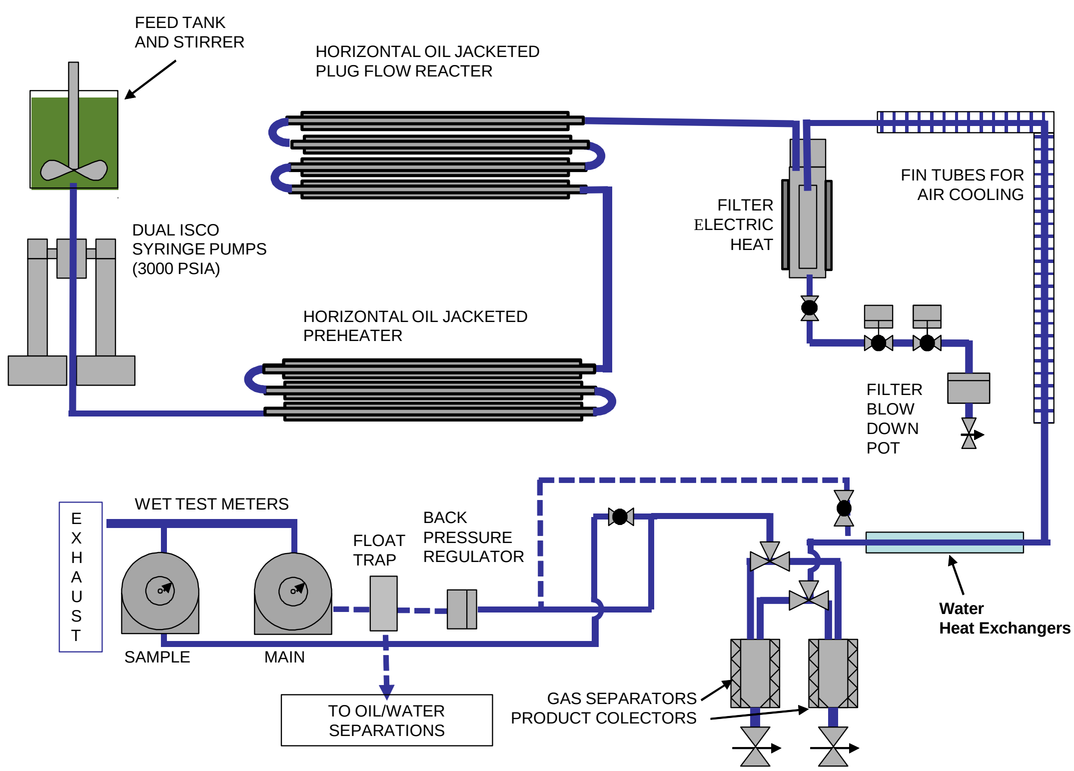

Figure 4-4 PNNL HTL Laboratory Reactor System

Courtesy of Andy Schmidt, PNNL

that still contains organic materials, and both solid and gaseous streams (Tian et al. 2014a). Each of these streams requires further processing or handling in order to maximize economic and environmental outcomes. The bio-crude requires cleanup and hydrotreating to produce a drop-in biofuel, although HTL bio-crudes tend to be more stable, have better energy content, and have lower oxygen concentrations than fast pyrolysis oils (Zhu et al. 2014). Valorizing the remaining organics in the aqueous phase also remains a significant challenge that requires solutions economical in a distributed conversion framework. Additionally, continuous operations at scale, including but not limited to real-time separations and plug-flow reactor parameters, require additional refinement (Elliott et al. 2015).

HTL is also an excellent example of the inextricable interconnections between feedstocks and the operational details of conversion processes. The peer-reviewed literature includes multiple experiments with various feedstocks of interest. Examples include (and are not limited to) sewage sludge (Wang et al. 2013; Leng et al. 2015; Malins et al. 2015), animal manure (Theegala and Midgett 2012), and mixed wet feedstocks (Lemoine et al. 2013). The underlying theme is that all of these (and other) feedstocks vary in terms of moisture content, chemical composition, presence of contaminants, etc. While the notion of a swappable, modular system that can handle these variations at a distributed scale may be achievable, a great deal of work remains to get from here to there. A well-designed HTL system needs to be robust enough to handle composition variations in the different feeds cited because of the inherent variability of these feeds. The kinds of techno-economic analyses (TEA) discussed in Chapter 3 have an incisive role to play. Where are the key opportunity spaces in which technology R&D has a realistic chance to make a substantive difference? How can TEAs and LCAs work together to help frame a constructive intervention space for the federal government in terms of technology R&D?

4.1.2.2. Other Solvent Possibilities

The same solvent property variations that can be obtained with subcritical water are even more pronounced with supercritical water. As Elliott et al. elucidate, increasing temperature and pressure tends to move the primary reaction products from solids, to liquids, to gases (Elliott et al. 2015). Beyond the critical point, water's solvent capabilities become highly tunable with relatively minor variations in temperature and pressure. Supercritical water is effectively non-polar, which opens new ranges of solvent possibilities (Kruusernent et al. 2014). While the DOD has explored the potential of supercritical water for the destruction of potent chemical weapons (Marrone et al. 2005), their focus is on elimination of dangerous wastes. Literature on bioenergy-relevant applications seem mostly limited to laboratory/bench scales (Yakaboylu et al. 2013; Akizuki et al. 2014; Hung Thanh et al. 2014). Though useful work has been published In this regard, as noted above, there is still more to be done, particularly in terms of techno-economic analyses and energy balances, not to mention scaling, and safety questions for high pressure operations.

4.1.2.3. Alternative Solvents

Water has many advantages, but CO_2 is also a candidate as a supercritical solvent. Its critical point is much lower than water's, in the 31°C and 7.4 MPa range (versus 374°C and 22.4 MPa), so less heating and pressurization energy is required to make CO_2 supercritical. It has been used for relevant pretreatments (Duy The and Tan 2014), extraction of fatty acids and other valuable components from salient waste streams (Morais et al. 2014; Adeoti and Hawboldt 2015; Schievano et al. 2015), and fuel upgrading and cleanup (Earley et al. 2015; Escorsim et al. 2015). Though not necessarily a top priority, there seem to be enough possibilities to merit further exploration. While the milder conditions of supercritical CO_2 are an advantage, it is somewhat constrained as a medium—mainly used for extractions as opposed to reforming or transformative reactions, which typically require more energy or extreme conditions. Additionally, the source of the CO_2, whether it is derived from a biogenic source or not, would always be an important question, which suggests possibilities for collaboration between the Office of Fossil Energy and Bioenergy Technologies Office.

Finally, methanol and ethanol have also been explored as possible solvents for liquefaction (Huang et al. 2014), but their potential contribution to production of renewable biofuels is uncertain. It might be possible if the sources of ethanol or methanol were biogenic, but it is not clear how moving through those alcohols as intermediates would result in an economical process. Both TEAs and LCAs would be essential in considering such pathways.

4.1.2.4. Hydrothermal Carbonization

Hydrothermal carbonization (HTC) is another member of this technological family. HTC process temperatures range from 150–250°C, and HTC generally does not require external pressure inputs. The process can be applied to multiple waste feedstocks, including sewage sludge, food wastes, and manure slurries. The main product of HTC is a carbonaceous solid similar to charcoal that can be used as an amendment to improve both soil fertility and leachate quality (Ro et al. 2016). This solid, known as hydrochar, can also be burned to produce electricity. Energy balances and appropriate process conditions still require further investigation (Danso-Boateng et al. 2015a; Danso-Boateng et al. 2015b), as do life cycle implications (Berge et al. 2015). The USDA has contributed to some of the above references; HTC might represent a good opportunity for interagency collaboration.

Stepping back, the emphasis so far has been on wet waste feedstocks. As noted in Chapters 2 and 3, such streams constitute substantial potential. At the same time, gaseous feedstocks are also a large resource, particularly CO_2, and mitigation of emissions of both CO_2 and CH_4 represents an additional GHG reduction opportunity.

4.2. Gaseous Feedstock Conversions

The discussion so far has focused on wet feedstocks. Gaseous waste streams are also of interest to BETO, and most biogas sources are derived from wet organic waste streams. While the obvious holy grail in this area is the conversion of both the CO_2 and CH_4 in biogas to biofuels and bioproducts, there are also subtler possibilities that again involve potential collaboration with other DOE offices. There are multiple waste CO_2 streams available, e.g., from biorefineries, breweries, wineries, and cement plants, not to mention flue gases from power plants. BETO has clear authority to work with biogenic sources, but constructive utilization of fossil-based streams will require collaboration. The same is true of stranded natural gas, which is clearly a fossil resource. **The key point is that solutions that work for biogas might be applicable to other gaseous resources, so there are opportunities for BETO to collaborate with other DOE offices in these arenas.**

4.2.1. Conventional Biogas Applications

Chapter 3 discussed the market challenges for traditional biogas applications. In summary, the best opportunities for biogas generation and utilization are when:

- There are onsite utilization opportunities for both heat and electricity.
- A captive fleet of vehicles can make productive use of either gas or electricity.
- Policy incentives provide favorable gas and/or electric interconnection possibilities.

All of these options have been well reviewed elsewhere (EPA 2011; EPA 2013; Murray et al. 2014). The DOE Fuel Cell Technologies Office conducted a very useful workshop on gas cleanup technologies, and the problems of H_2S and siloxane removal are **reasonably** well understood (DOE 2013; DOE 2014). In short, the R&D opportunities in the realm of traditional biogas applications seem limited, as relevant solutions are largely commercial and constrained more by market conditions than technical limitations. The opportunity space for federal investment seems to lie in solutions to more radical problems, though the proper delineation of boundaries between public and private sectors is a topic that will arise in Chapter 5.

4.2.1.1. Utilizing Both CO_2 and CH_4

Most traditional biogas applications view CO_2 as either a diluting material for direct combustion or an impurity requiring removal for RNG/CNG applications. However, the CO_2 in biogas, which generally ranges between 35% and 50% of the total composition, is in fact a biogenic carbon carrier. Therefore, conversion strategies that utilize both the CO_2 and the CH_4 in biogas offer the potential for significant improvement in overall carbon balances. At the same time, the relatively poor solubility of CO_2 in aqueous solutions at standard temperature and pressure presents both a conversion challenge and potentially an R&D opportunity.

4.2.1.2. Unconventional Reforming of Methane

The commercial state of the art for converting natural gas into hydrogen, syngas, or other product intermediates is steam methane reforming (SMR). The process works well and is commercially viable for fossil natural gas (after removal of natural gas liquids and other impurities). However, SMR is highly endothermic and thus does not take advantage of the CO_2 in biogas, which suggests that alternatives might be explored.

4.2.1.3. Tri-Reforming and Subsidiaries

The most obvious path to utilize both the CO_2 and the CH_4 in biogas is dry reforming of methane (DRM), which utilizes CO_2 instead of steam to activate the methane molecules. The combination of dry and wet (steam) reforming (also known as bi-reforming) has been shown to produce better results than either process alone (Gangadharan et al. 2012; Olah et al. 2013; Jafarbegloo et al. 2015; Sheu et al. 2015); however, it still requires substantial external energy inputs. Coupling other exothermic processes, such as the partial oxidation of methane, with the bi-reforming process (a combination known as tri-reforming) might improve energy balances, but work remains to prove successful operations at practical scales. Dry, bi-, and tri-reforming are not the only options. Some groups are pursuing the oxidative coupling of methane via non-biological mechanisms (Ferreira et al. 2013; Yunarti et al. 2014).

The key area of research for all of these strategies seems to be catalysts. Coking resistance and overall catalyst lifetime under harsh conditions have emerged as critical issues. There are any number of recent peer-reviewed articles that address such questions (Baktash et al. 2015; Chen and Lin 2015; Ding et al. 2015; Mustu et al. 2015; Usman et al. 2015; Zhang et al. 2015; Zheng et al. 2015). What is not clear is how to evaluate one catalytic solution versus another. It is possible that more synergistic and results-oriented approaches are necessary to move these catalysts out of the peer-reviewed literature and into practical applications.

4.2.1.4. Plasma Techniques

Another prominent theme in the DRM literature is the application of variously induced plasmas to the conversion process. The focus is on “non-thermal” plasmas, which rely on particle excitement, rather than overall heating, to induce desired reactions. Plasma stimulation methods include glided-arc discharge (Bo et al. 2008; Abd Allah and Whitehead 2015), dielectric barrier discharge (Hoang Hai and Kim 2015), corona discharge (Hoang Hai et al. 2015), and a number of other options (Iwarere et al. 2015; Kameshima et al. 2015; Zheng et al. 2015; Li et al. 2016). A key question for all of these approaches is energy balance (Ravasio and Cavallotti 2012), i.e., whether the energy input needed to create the plasmas pays off in terms of the energy content of the final products. Similar to findings in the previous section, the challenge for BETO may lie in translating such science-based approaches into tangible solutions that have a real chance at market success.

4.2.1.5. Fischer–Tropsch Conversions at Distributed Scales

The conventional wisdom is that Fischer–Tropsch (and related gas-to-liquids [GTL] processes) makes sense only at petroleum refinery scales of tens or hundreds of thousands of barrels of oil equivalent per day, and almost all of the existing commercial facilities are of that size (Ail and Dasappa 2016). Downscaling issues include the absence of economies of scale for supporting infrastructure, as well as the need for large volumes of co-products such as higher carbon waxes to justify cracking and separation investments. While several commercial ventures are challenging this paradigm with notable success, the dominant discourse remains that refinery-scale operations are necessary for GTL processes to be profitable.

At the same time, a Web of Science search on Fischer–Tropsch with the publication year limited to 2016 yielded 216 hits.[1] This dichotomy may be instructive. One primary focus of the academic literature is catalyst development. There are plenty of articles about, for example, the interaction between active catalysts and supports (Okeson et al. 2016; Xu et al. 2016) and the effects of promoter substances (den Otter et al. 2016; Ma et al. 2016; Xu et al. 2016). There are also a number of proposals regarding reactor design and process conditions (Okeson et al. 2016; Savchenko et al. 2016; Todic et al. 2016). Catalyst morphology, including nanoparticles, pore sizes, and effective surface area, seems to be another active area of research (Gallagher et al. 2016; Ligthart et al. 2016; Nikparsa et al. 2016). The bottom line is that there seems to be a great deal of interesting work on catalyst development, but it is not clear how the peer-reviewed literature is advancing the cause of making Fischer–Tropsch economically feasible at distributed scales.

It is possible that some of these catalyst pathways hold forth the possibility of real breakthroughs for a problem that seems to have stymied progress for some time. While there is some commercial progress with downscaling Fischer–Tropsch processes, there is still work to do to make them economically viable at the scales called for in the modular sections of Chapter 3. Perhaps there is room to focus on identifying and solving specific problems in order to reduce capital costs on a produced-unit basis in distributed operations. This may be a key area in which stakeholder feedback could beneficially inform future documents.

4.2.2. Biological Strategies

Biological conversion approaches have traditionally been known for high selectivity but low yields. The fermentation of corn ethanol provides an obvious counterexample and perhaps points towards possibilities of overcoming traditional mindsets in terms of biological conversion. In terms of gaseous streams, echoing Chapter 2, there are four feedstocks of interest:

[1] Search conducted April 8, 2016, with Fischer-Tropsch as the topic and 2016 as the year of publication.

- Biogas: ~50%–70% CH4, ~30%–50% CO2, with significant contaminants, notably H2S and siloxanes
- Syngas from biogenic sources: Mostly CO and H2, with some CO2, H2O, and other trace constituents
- Stranded methane from various sources, with varying degrees of contaminants
- Both biogenic and fossil-based CO2 streams

Of the four gaseous feedstocks listed above, biogas lies most clearly within BETO's wheelhouse. Given its composition, the fundamental conversion challenges are the activation of CH_4 and the reduction of CO_2, with cleanup of impurities as a side topic. Solutions applicable to biogas may well apply to other relevant gaseous feedstocks, at least in part. Some of the core questions that this document would propose are:

1. What are some of the most promising strategies to activate methane? How might biological, thermal, and electrochemical approaches be productively combined?
2. More generally, how could combinations of thermochemical, biochemical, and electrochemical conversion processes synergistically advance the state of the art in producing biofuels and bioproducts from relevant waste streams?
3. What is the range of biological strategies that could feasibly produce higher hydrocarbons from CO_2? Which pathways might offer the best opportunities?
4. What intermediates might make the most sense to produce from relevant feedstocks in a distributed conversion environment?

Even though the article is primarily focused on methane, a recent publication from Advanced Research Projects Agency – Energy (ARPA-E) personnel provides a very useful starting point for a brief literature review (Haynes and Gonzalez 2014). The paper first notes that biological processes might offer solutions to the downscaling challenges faced by Fischer–Tropsch and similar processes. The authors propose the notion that while biological systems are not as productive as chemical processes volumetrically (the traditional economies of scale), on a yield/hectare/hour basis, corn ethanol plants are competitive with much larger Fischer–Tropsch and GTL installations. This "areal"[1] productivity is an important component of the modular manufacturing discussion in Section 4.3, as technologies that scale areally may lend themselves better to the paradigm of economies of mass production of smaller units.

Haynes and Gonzalez also delve into the technological challenges of the biological activation of methane in some detail. In keeping with the rest of the literature, the authors discuss the importance of methane monooxygenases (MMOs) in native methanotrophs and differentiate between p-MMO and s-MMO. Haynes and Gonzalez note some of the advantages and disadvantages of aerobic and aerobic methanotrophs, and they emphasize the thermodynamic importance of minimizing the demand for donated electrons. They also highlight the need to couple exergonic and endergonic reactions to drive the conversions to completion, another theme that pervades the literature.

Haynes and Gonzalez' paper proposes a new research direction for methane bioconversion to butanol. The design depends on:

1. High-efficiency biological methane activation

[1] Haynes and Gonzalez spell it "aerial."

2. High-efficiency biological synthesis of liquid fuel from an intermediate derived from methane activation
3. Process intensification to address kinetic limitations related to gas transfer and bioconversion rates

The article includes a TEA that projects a minimum fuel (butanol) selling price of $1.52/GGE, a value that aligns well with BETO targets (DOE 2015a). Haynes and Gonzalez also point out that achieving this target will require overcoming numerous technical challenges, such as substantially improved biocatalysts, including the possibility of adapting benzene dioxygenase enzymes, engineering systems based on ammonia-oxidizing bacterial pathways, and advanced bioreactor designs, among others. While the hurdles are substantial, it is a very useful sketch to help frame future R&D possibilities in this area.

Ge et al. also recently published a review article that is useful in scoping the relevant R&D challenges and opportunities (Ge et al. 2014). The authors emphasize the possibilities of three classes of organisms: methanotrophs, ammonia-oxidizing bacteria, and acetogens. The article notes progress in converting methane to methanol with high efficiency and observe the challenges in producing liquid fuel precursors other than methanol with unmodified native organisms. It further highlights the differences between p-MMO and s-MMO as potential sources for metabolic engineering, and reiterates the importance of electron donors. Taher et al. report compatible findings concerning autotrophic conversion of methane to methanol using ammonia-oxidizing bacteria (Taher and Chandran 2013).

Park and Lee also address the biological conversion of methane to methanol (Park and Lee 2013). They call attention to the fact that methanol is currently produced from petroleum resources and that existing production processes are environmentally suboptimal. The authors discuss the differences between s-MMO and p-MMO in some detail, and they conclude that p-MMO is more promising as a source of genetic/proteomic resources for metabolic engineering. However, while their article is impressive in its detailed exploration of specific enzymatic structures, it does not provide clear recommendations as to a path forward. This may be a strong signal that these technologies are currently in the TRL 1–2 range, which is a valuable data point in designing future R&D strategies.

Rasigraf et al. take the conversation in a slightly different direction, in that they focus on alternative carbon utilization pathways in methanotrophic organisms. In particular, they explore CO_2 fixation in "Denitrifying Methanotroph Candidatus Methylomirabilis oxyfera" (Rasigraf et al. 2014). They argue for the importance of the Calvin–Benson–Bassham cycle as an alternative pathway for carbon fixation in methanotrophs, and hint that this phenomenon might be more widespread than previously expected. While again at an early level of development, the Rasigraf et al. publication suggests that biological pathways towards the simultaneous utilization of both the CO_2 and CH_4 might have some traction.

Koepke et al. published a 2014 article that builds upon diverse strands of prior work (Koepke et al. 2014). In this case, the publication focused on the production of 2,3-butanediol from syngas utilizing *Clostridia,* falling into the general category of productive applications for acetogens. While acetogens by definition primarily produce acetate, there are natural outliers of interest that synthesize higher-value biofuel and bioproduct precursors. The authors identify three strains of particular interest:

1. *Clostridium authoethanogenum*
2. *Clostridium ljungdahlii*
3. *Clostridum ragsdalei*

According to this article*, C. authoethanogenum* is already in pilot-scale trials, and *C. ljungdahlii* has clearly attracted interest from other parties (Lan and Liao 2013; Ueki et al. 2014).

While the above article-based case studies represent a very truncated selection of the detail available in both the peer-reviewed literature and existing pre-commercial experiments, including some funded by the DOE, they do serve to identify some emerging trends in terms of challenges and opportunities:

- Relevant wild-type organisms as genetic and metabolic feedstocks. One theme that seems to run through the cited literature is that wild types are unlikely to achieve the titers necessary for economic viability in the absence of metabolic engineering. Both enhancement of existing wild types and synthetic biology approaches to transfer key pathways into industrial platforms such as E. coli may merit attention, as evidenced by recent work from the National Renewable Energy Laboratory (Henard et al. 2016).
- A diverse set of organisms may be of interest. Methanotrophs and acetogenic bacteria seem like obvious choices, as do methane-oxidizing bacteria (van der Ha et al. 2012), and ammonium-oxidizing bacteria also receive multiple mentions. At least one article also mentions carboxidotrophic organisms (Duerre and Eikmanns 2015), and various yeasts and fungi may also have potential. R. eutrophia also seems to crop up with some frequency.
- The choice of viable intermediates is also a key question, particularly as it intersects with the distributed conversion/modular manufacturing concepts. In particular, many literature articles discuss methanol, but it is not clear whether methanol is actually a good idea as a transportable intermediate (Yang et al. 2014).
- While the Wood–Ljungdahl and Calvin–Benson–Bassham pathways/cycles seem to be attracting substantial academic interest, other options may exist, particularly in the realm of combining biochemical, thermochemical, and electrochemical processes. At the same time, pyruvate and acetyl-CoA seem to be emerging as promising intermediates.
- Notions of areal vs. volumetric productivity tie in nicely with Section 4.3 on modular manufacturing/distributed conversions and may be productive areas for further investigation.
- Reducing the need for external electron donors seems to be a critical issue (Hu et al. 2011; Chattanathan et al. 2014). Combining exergonic and endergonic reactions into a coherent whole seems to be one strategy, and getting the energy balances right is a key challenge. While there is interest in incorporating sunlight into the equation, cost-effective photobioreactors remain a challenge (Duerre and Eikmanns 2015).
- Microbial electrosynthesis appears intriguing in terms of both the production of syngas-like feedstocks from waste streams of interest and the conversion of such “syngases” into higher-value hydrocarbons (Logan and Rabaey 2012; Lovley and Nevin 2013; Wang and Ren 2013; Wang et al. 2015b). This ties back to the conversation in Section 4.1.1.4 and forward to Section 4.2.3.
- CO_2 streams present their own set of challenges, most notably the need to secure renewable sources of hydrogen for the production of useful hydrocarbons. Within this realm, novel autotrophic and heterotrophic mechanisms for CO2 fixation that do not require sunlight may be of particular interest (Schiel-Bengelsdorf and Duerre 2012).

In summary, biological pathways for the conversion of gaseous feedstocks offer a number of promising possibilities and probably merit more focused attention.

4.2.2.1. Engineered Methanotrophs

ARPA-E's REMOTE program specifically targeted biological conversion of methane to liquid fuels (ARPA-E 2014). While the modification of methanotrophic organisms was only one among many possible pathways, it is an area of continued interest. As noted above, both dry reforming of methane and modified Fischer–Tropsch processes have yet to be proven economical at distributed scales. So biological approaches remain interesting, and there seem to be several promising possibilities under development (Schiel-Bengelsdorf and Duerre 2012; Haroon et al. 2013; Lan and Liao 2013; Ge et al. 2014; Kalyuzhnaya et al. 2015; Sirajuddin and Rosenzweig 2015; Henard et al. 2016). Additionally, the recent discovery of canonical Embden-Meyerhof-Parnas (EMP) pathways in Type I methanotrophs opens the door for an array of strain-engineering strategies similar to those demonstrated in model microbes (*E. coli/S. cerevisiae*). It is also true that some of the strategies being pursued to enhance biogas production from or to cope with inorganic inhibition in AD could potentially be modified to facilitate the direct production of liquid fuels from waste feedstocks of interest (Christy et al. 2014; Fei et al. 2014; Otero-Gozalez et al. 2014), and hybrid approaches might also offer value (Hamad et al. 2014).

4.2.2.2. CO_2 Consumers

There are also organisms that consume CO_2 and produce valuable hydrocarbon products; not all of them are algae, nor do they all require sunlight. While there are a few relevant references in the peer-reviewed literature (Yang et al. 2012; Fernandez et al. 2014), this may be an area for further exploration. CO_2 is relatively plentiful in the ambient environment; it is likely that there are understudied biological species that can produce valuable biofuel and bioproduct precursors from this gaseous feedstock.

4.2.3 Electrochemical Processes

While debates between thermochemical and biochemical approaches have been part of BETO's history, electrochemistry may represent a new set of strategies particularly well suited to distributed conversion. This is particularly relevant in combination with surplus renewable electrons due to intermittency, such as is already occurring with respect to wind at night in Texas, hydro in the spring in the Northwest, and solar in California. While the frequency of this phenomenon is likely to increase, it is important not to assume the availability of renewable electrons in TEA and LCA analysis efforts. With such caveats firmly in mind, this section sketches a preliminary exploration of the potential of electrochemical conversion strategies for gaseous feedstocks.

The primary focus of this section is the electrochemical reduction of CO_2 to valuable biofuel and bioproduct precursors, although the activation of CH_4 is an ancillary area of interest (Baltrusaitis et al. 2014). The literature seems roughly divided between novel catalysts, process conditions, and product alternatives, with nods to microbial systems as discussed in previous sections (Jhong et al. 2013; ElMekawy et al. 2016; Wu and Zhou 2016). Challenges remain due to the low solubility of CO_2 (and CH_4) in aqueous solutions (Durst et al. 2015), product selectivity, and current density for higher hydrocarbons (Kumar et al. 2016). Additionally, the degree to which the academic literature is focused on solutions with real market potential is unclear and may represent an opportunity for further investigation.

Electrochemical conversion strategies offer the potential for precise control of reaction conditions, and thus theoretical product outputs. However, catalysts are key in minimizing overpotential and in minimizing competition with the hydrogen evolution reaction to maximize efficiency. Many different catalysts, both homogeneous and heterogeneous, have been evaluated, and there are known families of materials with different selectivities and efficiencies (Gao et al. 2016). Cost is also a critical factor, and copper may stand out in this regard (Kumar et al. 2016). Choice of primary material is only the first step. Different deposition techniques, which can themselves be electrochemical (Ruiz et al. 2013), variations in electrode construction (Kim et al. 2016), electrode mesostructuring (Hall et al. 2015), and other options (Kim et al. 2015b; Ganesh 2016) are all possible alternatives. All aspects of catalyst development and deployment appear to be rich areas for additional research.

The interaction of process conditions with various catalysts, electrolytes, and cell structures is also an area of active exploration. Organic solvents have been proposed to addressed the CO_2 solubility issue, in conjunction with copper and cobalt oxides for cathodes and anodes, respectively (Yadav and Purkait 2015). Formic acid is one promising intermediate, and pressurizing the input CO_2 streams is one option to improve conversion efficiency (Scialdone et al. 2016). Another team has explored the possibility of a microfluidic design to support dual electrolytes to take advantage of pH differentials at the cathode and anode to promote the respective reactions (Lu et al. 2016). In a variation on this theme, a different group looked at the combination of pH and varying CO_2 concentrations, which could be applicable to, for example, flue gases from power plants (Kim et al. 2015a). While this cursory review only scratches the surface, it seems clear that there are many intriguing avenues of research available for further development.

Echoing Section 4.1.1.4, microbial electrochemical strategies may have some viability for gaseous feedstocks. While the literature in this area seems less well developed, there are some intriguing possibilities, including the potential to use wastewater as an electrolyte for CO_2 recovery (Lu et al. 2015). There are other options (Villano et al. 2010; ElMekawy et al. 2016; Ganesh 2016) that play into the general theme of this subsection, which is that both inorganic and microbial strategies for electrochemical conversion of CO_2, and perhaps CH_4, include a rich set of possibilities for future work.

In summary, electrochemical strategies for conversion of gaseous feedstocks, particularly CO_2, seem to offer a diverse set of future opportunities. Such approaches are particularly germane in terms of distributed conversion, to which traditional notions of economies of scale may not apply.

4.3. Challenges/Opportunities of Distributed Conversion

Chapters 2 and 3 were very clear that the nature of the feedstocks and markets in question are very different from traditional herbaceous, woody, and algal feedstocks as articulated in BETO's series of Billion-Ton assessments (DOE 2011; DOE 2016). The distributed nature of the wet and gaseous waste feedstocks within the scope for this report force an inversion of the traditional petroleum refinery paradigm, as aggregation is difficult, given that the feedstocks in question are not compatible with existing pipeline infrastructures and have low energy density. The feedstocks are simply not practically available to convert at the scale of hundreds of thousands of barrels of oil/day equivalent, which has been the generally accepted scale for economic feasibility of fuels production. Rather, conversion needs to occur near the feedstock source.

Put more succinctly, the inherently distributed nature of these feedstocks requires a decentralized approach. In one example, there are no U.S. wastewater treatment plants that produce 2,000 dry tons/day of feedstock. Therefore, wet and gaseous feedstocks will require tailored strategies to make economic sense. The key challenge is precisely that: how to make techno-economic sense out of producing biofuels and bioproducts from these distributed feedstocks. Distributed conversion strategies seek to replace traditional economies of scale on the basis of five economic drivers:

1. Economies of mass production
2. Economies of modular manufacturing
3. Technologies that do not necessarily benefit from economies of scale
4. Investor risk reduction due to reduced capital requirements for smaller systems
5. Minimized transportation costs due to matching conversion volumes to feedstock availability

4.3.1. Economies of Mass Production

Mass production takes advantage of standardized, even automated, manufacturing, which reduces fixed costs on a per-unit basis. It also exploits learning by doing; each order-of-magnitude increase in production volumes reduces costs through applied experience. The literature includes reports that learning curves for mass production are three times greater (18% versus 6%) than those for one-off plants (Daugaard et al. 2015). Modularization multiplies this effect by employing standardized subcomponents that are produced in greater volumes than finished systems. It can also reduce risk by allowing factory pre-testing of completed modules that are then disassembled and reassembled on-site in accordance with well-defined procedures (DOE 2015d; Jenks 2015).

4.3.2. Economies of Modular Manufacturing

A modular approach also requires a standardized scheme for interconnections between disparate modules, much as "plug-and-play" in personal computers required well-defined hardware and communications protocols. Novel controls and sensing interlocks are required for temperature, pressure, viscosity, and composition of the materials to ensure the safe operations of the module assembly. Remote monitoring and control of distributed systems is also an important part of the equation, as minimizing requirements for on-site expertise will be a key factor. All of these factors contribute to the development of systems where modular components interact as a coherent whole. These challenges are both analytical design questions and straight technology R&D problems.

4.3.3. Technologies that do not necessarily benefit from economies of scale

One element of the economies of scale is that larger vessels require less container material for a given reactor volume than smaller ones. This is part, albeit by no means all, of the reason capital costs do not increase linearly with scale for systems in which volume is an important part of the equation. Instead, the relationship roughly follows a X^n power model, where X is the scale of the facility and n is approximately 0.6. The question for distributed conversion is whether there are systems that do not obey this rule and, if so, what their characteristics might be.

Systems that rely on active surface areas for their effectiveness may meet this criterion. Photovoltaic cells may be an example, although electron transport is a complicating factor. LEDs may be another, though phonon and structural interference with photon delivery does include some volumetric and materials characteristics (Bochkareva et al. 2010; Chow 2011; Akyol et al. 2012). Certain AnMBR designs that rely on the surface area of both introduced particles and membranes may also qualify (Andalib et al. 2014; Aslam et al. 2014; DOE 2015b). As discussed in earlier sections, both microbial and inorganic electrochemical conversion strategies might also be of relevance, as their productivity is directly related to partial current density and Faradaic efficiency per square centimeter of electrode surface area (Hall et al. 2015; ElMekawy et al. 2016; Lu and Ren 2016). In short, while the general idea of systems that do not scale volumetrically is very attractive for distributed conversion applications, the details of operation at critical surface interfaces are complex and require case-by-case investigation. While achieving a scaling factor of n = 1 in the X^n power model may not be possible, there are examples in which a scaling factor of 0.9 is achieved. This difference has a large impact on capital cost when small-scale operation is required. This may well be a productive challenge–opportunity intersection for future efforts.

Further, heat management is likely to be an issue in distributed systems. Heat exchangers, particular those that do not rely on the evaporation of water, tend to require large surface areas and air circulation. Thus, conversion processes that take place at near-ambient temperatures are likely to be favored in distributed environments. A similar argument can be made for pressure, as compression requires energy. Designing catalysts, reactors, and complete systems that operate economically at close-to-standard temperature and pressure (25°C, 1 atm) conditions is a challenge. Again, this may comprise an R&D opportunity, although much of the work is likely to be at early TRLs, at least initially. In this sense, distributed conversion/modular manufacturing is a very useful strategic concept, as it could help to focus future research directions.

4.3.4. Reducing capital risk

Building on the preceding sections, a key element of success is determining how to bring all of these elements together to facilitate the development of techno-economically viable systems at relevant scales. To begin addressing questions of this nature, the DOE national laboratories held a workshop on the "Fundamental Science Needs for Waste to Chemical Conversion" (Jenks 2016). Presentations covered topics such as the challenges of working with complex mixtures, waste-to-chemical conversion from a biological perspective, low-temperature activation, separations, and catalyst design. The latter topic raised the question of operating in liquid environments, which are implied by conditions relatively close to ambient temperature and pressure. Themes that pervaded the workshop included the need to understand thermodynamics of multi-component liquids and catalytic reactions within liquid media. The role of liquid–solid and liquid–gas interfaces is not well understood compared to solid-gaseous interfaces. More active catalysts will be needed if reactions will be conducted at lower temperatures required to avoid adverse thermal reactions. While smaller systems have inherently lower capital requirements, they have to work at appropriate scales to provide a reasonable return on investment.

4.3.5. Matching conversion volumes to feedstock availability

There are at least two possible variations of distributed approaches to wet and gaseous feedstocks. The first is to convert the feedstock into a fuel usable on-site. This is exactly the model used at the Fair Oaks dairy in Indiana, which converts manure into CNG that fuels its fleet of milk trucks (USDA 2014; USDA 2015). The second is to produce a readily transportable, energy-dense intermediate and move it to a centralized final processing facility, thus marrying the advantages and flexibility of distributed production with the current infrastructure that confers both economies and quality on the final product. Obviously, a number of factors determine which of these strategies is favored and whether there might be other alternatives. The sensitivity component of TEA is one tool that can be used to assess areas where research could help to reduce costs, and other options are also available.

The notion of distributed conversion of wet and gaseous feedstocks raises a number of constructive questions in the scientific, engineering, and analytical domains. Examples include, but are not limited to, the following:

1. What are the necessary characteristics of novel catalysts that deliver high conversion efficiency, selectivity, and long lifetime under realistic conditions?
2. Which key questions need answering to evaluate the potential for technologies to evade the volumetric scaling law?

3. What is the potential value-add for additive manufacturing/3-D printing in the distributed conversion arena?
4. To what degree does the projected future availability of surplus renewable electrons affect the value proposition for distributed conversion?
5. What kinds of fundamental science investigations would best advance our understanding of the role of complex liquid/gas/electrode interfaces in the techno-economics of distributed conversion and modular manufacturing strategies?
6. What nature of federal/state/local policy analyses could best aid the development of a coherent grasp of the relevant marketplaces of the future?

In short, the notion of distributed conversion of wet and gaseous feedstocks focuses attention on a rich set of challenges/opportunities. This document does not purport to answer such questions but does seek to raise them in a targeted way. Chapter 5 will touch on possible next steps, but even it does not pretend to provide all of the answers. This effort is explicitly intended as a first step in a larger conversation.

4.4. Transitioning to the Bioeconomy of the Future

Chapters 2 through 4 are primarily about the state of the art, with a certain eye toward the future. They also take somewhat of a “siloed” approach to feedstocks, markets, and technologies. While such segmentation is perhaps necessary for clarity of presentation, it might not represent an optimal basis for future planning. Chapter 5 attempts to correct for this bias by relying primarily, albeit not exclusively, on feedback from stakeholders throughout the multiyear engagement process embodied in this document. In particular, Chapter 5 seeks to incorporate specific stakeholder comments into the larger framework of the Bioeconomy of the Future.

4.5. Chapter 4 References

Abd Allah, Z. and J. C. Whitehead (2015). "Plasma-catalytic dry reforming of methane in an atmospheric pressure AC gliding arc discharge." Catalysis Today **256**: 76-79.

Abelleira, J., S. I. Perez-Elvira, et al. (2012). "Advanced Thermal Hydrolysis: Optimization of a Novel Thermochemical Process to Aid Sewage Sludge Treatment." Environmental Science & Technology **46**(11): 6158-6166.

Adeoti, I. A. and K. Hawboldt (2015). "Comparison of biofuel quality of waste derived oils as a function of oil extraction methods." Fuel **158**: 183-190.

Ail, S. S. and S. Dasappa (2016). "Biomass to liquid transportation fuel via Fischer Tropsch synthesis - Technology review and current scenario." Renewable & Sustainable Energy Reviews **58**: 267-286.

Akizuki, M., T. Fujii, et al. (2014). "Effects of water on reactions for waste treatment, organic synthesis, and bio-refinery in sub- and supercritical water." Journal of Bioscience and Bioengineering **117**(1): 10-18.

Akyol, F., D. N. Nath, et al. (2012). "Suppression of electron overflow and efficiency droop in N-polar GaN green light emitting diodes." Applied Physics Letters **100**(11).

Alibardi, L., R. Cossu, et al. (2014). "Development and permeability of a dynamic membrane for anaerobic wastewater treatment." Bioresource Technology **161**: 236-244.

Andalib, M., E. Elbeshbishy, et al. (2014). "Performance of an anaerobic fluidized bed bioreactor (AnFBR) for digestion of primary municipal wastewater treatment biosolids and bioethanol thin stillage." Renewable Energy **71**: 276-285.

ARPA-E (2014). "Reducing Emissions using Methanotrophic Organisms for Transportation Energy." ARPA-E. Accessed November 28, 2014, http://arpa-e.energy.gov/?q=arpa-e-programs/remote.

Aslam, M., P. L. McCarty, et al. (2014). "The effect of fluidized media characteristics on membrane fouling and energy consumption in anaerobic fluidized membrane bioreactors." Separation and Purification Technology **132**: 10-15.

Baktash, E., P. Littlewood, et al. (2015). "Alumina coated nickel nanoparticles as a highly active catalyst for dry reforming of methane." Applied Catalysis B-Environmental **179**: 122-127.

Baltrusaitis, J., I. Jansen, et al. (2014). "Renewable energy based catalytic CH4 conversion to fuels." Catalysis Science & Technology **4**(8): 2397-2411.

Batstone, D. J. and B. Virdis (2014). "The role of anaerobic digestion in the emerging energy economy." Current Opinion in Biotechnology **27**: 142-149.

Berge, N. D., L. Li, et al. (2015). "Assessing the environmental impact of energy production from hydrochar generated via hydrothermal carbonization of food wastes." Waste Management **43**: 203-217.

Biddy, M. J., Ryan Davis, Susanne Jones, Yunhua Zhu (2013). Whole Algae Hydrothermal Liquefaction Technology Pathway. Golden, CO, NREL**:** 10.

Bo, Z., J. Yan, et al. (2008). "Plasma assisted dry methane reforming using gliding arc gas discharge: Effect of feed gases proportion." International Journal of Hydrogen Energy **33**(20): 5545-5553.

Bochkareva, N. I., V. V. Voronenkov, et al. (2010). "Defect-related tunneling mechanism of efficiency droop in III-nitride light-emitting diodes." Applied Physics Letters **96**(13).

Borole, A. P., D. Aaron, et al. (2010). "Understanding Long-Term Changes in Microbial Fuel Cell Performance Using Electrochemical Impedance Spectroscopy." Environmental Science & Technology **44**(7): 2740-2744.

Cano, R., S. I. Perez-Elvira, et al. (2015). "Energy feasibility study of sludge pretreatments: A review." Applied Energy **149**: 176-185.

Chan, Y. H., S. Yusup, et al. (2015). "Effect of process parameters on hydrothermal liquefaction of oil palm. biomass for bio-oil production and its life cycle assessment." Energy Conversion and Management **104**: 180-188.

Chattanathan, S. A., S. Adhikari, et al. (2014). "Hydrogen production from biogas reforming and the effect of H2S on CH4 conversion." International Journal of Hydrogen Energy **39**(35): 19905-19911.

Chen, W.-H. and S.-C. Lin (2015). "Reaction phenomena of catalytic partial oxidation of methane under the impact of carbon dioxide addition and heat recirculation." Energy **82**: 206-217.

Chen, W.-T., Y. Zhang, et al. (2014). "Co-liquefaction of swine manure and mixed-culture algal biomass from a wastewater treatment system to produce bio-crude oil." Applied Energy **128**: 209-216.

Chow, W. W. (2011). "Modeling excitation-dependent bandstructure effects on InGaN light-emitting diode efficiency." Optics Express **19**(22): 21818-21831.

Christy, P. M., L. R. Gopinath, et al. (2014). "A review on anaerobic decomposition and enhancement of biogas production through enzymes and microorganisms." Renewable & Sustainable Energy Reviews **34**: 167-173.

Danso-Boateng, E., R. G. Holdich, et al. (2015a). "Process energetics for the hydrothermal carbonisation of human faecal wastes." Energy Conversion and Management **105**: 1115-1124.

Danso-Boateng, E., G. Shama, et al. (2015b). "Hydrothermal carbonisation of sewage sludge: Effect of process conditions on product characteristics and methane production." Bioresource Technology **177**: 318-327.

Daugaard, T., L. A. Mutti, et al. (2015). "Learning rates and their impacts on the optimal capacities and production costs of biorefineries." Biofuels, Bioproducts and Biorefining **9**(1): 82-94.

den Otter, J. H., S. R. Nijveld, et al. (2016). "Synergistic Promotion of Co/SiO2 Fischer-Tropsch Catalysts by Niobia and Platinum." Acs Catalysis **6**(3): 1616-1623.

Ding, C., G. Ai, et al. (2015). "Coking resistant Ni/ZrO2@SiO2 catalyst for the partial oxidation of methane to synthesis gas." International Journal of Hydrogen Energy **40**(21): 6835-6843.

DOE (2011). Billion Ton Update. Oak Ridge, TN, Oak Ridge National Laboratory**:** 227.

DOE (2013). Biological Hydrogen Production Workshop Summary Report. Washington, DC, Department of Energy**:** 49.

DOE (2014). GAS CLEAN-UP FOR FUEL CELL APPLICATIONS WORKSHOP. Washington, DC, DOE**:** 32.

DOE (2015a). Bioenergy Technologies Office Multi-Year Program Plan. Washington, DC, Department of Energy**:** 244.

DOE (2015b). Energy Positive Water Resource Recovery Workshop Report. Washington, DC, Department of Energy**:** 58.

DOE (2015c). "Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters Workshop." DOE. Accessed May 27, 2015, http://energy.gov/eere/fuelcells/hydrogen-hydrocarbons-and-bioproduct-precursors-wastewaters-workshop.

DOE (2015d). Process Intensification Workshop. Washington, DC**:** 67.

DOE (2015e). Waste-to-Energy Workshop Summary. Washington, DC, Department of Energy**:** 53.

DOE (2016). 2016 Billon-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. Washington, DC, Department of Energy**:** 448.

Dominguez-Benetton, X., S. Sevda, et al. (2012). "The accurate use of impedance analysis for the study of microbial electrochemical systems." Chemical Society Reviews **41**(21): 7228-7246.

Duerre, P. and B. J. Eikmanns (2015). "C1-carbon sources for chemical and fuel production by microbial gas fermentation." Current Opinion in Biotechnology **35**: 63-72.

Durst, J., A. Rudnev, et al. (2015). "Electrochemical CO2 Reduction - A Critical View on Fundamentals, Materials and Applications." Chimia **69**(12): 769-776.

Duy The, P. and C.-S. Tan (2014). "Innovative pretreatment of sugarcane bagasse using supercritical CO2 followed by alkaline hydrogen peroxide." Bioresource Technology **167**: 192-197.

Earley, J. H., R. A. Bourne, et al. (2015). "Continuous catalytic upgrading of ethanol to n-butanol and >C-4 products over Cu/CeO2 catalysts in supercritical CO2." Green Chemistry **17**(5): 3018-3025.

Elliott, D. C., P. Biller, et al. (2015). "Hydrothermal liquefaction of biomass: Developments from batch to continuous process." Bioresource Technology **178**: 147-156.

ElMekawy, A., H. M. Hegab, et al. (2016). "Technological advances in CO2 conversion electro-biorefinery: A step toward commercialization." Bioresource Technology **215**: 357-370.

EPA (2011). Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field Washington, DC, EPA**:** 57.

EPA (2013). "An Overview of Landfill Gas Energy in the United States." EPA. Accessed 11/26, 2014, http://www.epa.gov/lmop/documents/pdfs/overview.pdf.

Escorsim, A. M., C. S. Cordeiro, et al. (2015). "Assessment of biodiesel purification using CO2 at high pressures." Journal of Supercritical Fluids **96**: 68-76.

Fei, Q., M. T. Guarnieri, et al. (2014). "Bioconversion of natural gas to liquid fuel: Opportunities and challenges." Biotechnology Advances **32**(3): 596-614.

Fernandez, Y. B., A. Soares, et al. (2014). "Carbon capture and biogas enhancement by carbon dioxide enrichment of anaerobic digesters treating sewage sludge or food waste." Bioresource Technology **159**: 1-7.

Ferreira, V. J., P. Tavares, et al. (2013). "Ce-Doped La2O3 based catalyst for the oxidative coupling of methane." Catalysis Communications **42**: 50-53.

Fotidis, I. A., H. Wang, et al. (2014). "Bioaugmentation as a Solution To Increase Methane Production from an Ammonia-Rich Substrate." Environmental Science & Technology **48**(13): 7669-7676.

Gallagher, J. R., P. Boldrin, et al. (2016). "The effect of Mg location on Co-Mg-Ru/gamma-Al2O3 Fischer-Tropsch catalysts." Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences **374**(2061).

Ganesh, I. (2016). "Electrochemical conversion of carbon dioxide into renewable fuel chemicals - The role of nanomaterials and the commercialization." Renewable & Sustainable Energy Reviews **59**: 1269-1297.

Gangadharan, P., K. C. Kanchi, et al. (2012). "Evaluation of the economic and environmental impact of combining dry reforming with steam reforming of methane." Chemical Engineering Research and Design **90**(11): 1956-1968.

Gao, S., Y. Lin, et al. (2016). "Partially oxidized atomic cobalt layers for carbon dioxide electroreduction to liquid fuel." Nature **529**(7584): 68-+.

Gao, Y., W. Li, et al. (2013). "Characterization of forward osmosis membranes by electrochemical impedance spectroscopy." Desalination **312**: 45-51.

Garcia, I. M., M. Mokosch, et al. (2013). "Impact on reactor configuration on the performance of anaerobic MBRs: Treatment of settled sewage in temperate climates." Water Research **47**(14): 4853-4860.

Ge, X., L. Yang, et al. (2014). "Biological conversion of methane to liquid fuels: Status and opportunities." Biotechnology Advances **32**(8): 1460-1475.

Hall, A. S., Y. Yoon, et al. (2015). "Mesostructure-Induced Selectivity in CO2 Reduction Catalysis." Journal of the American Chemical Society **137**(47): 14834-14837.

Hamad, T. A., A. A. Agll, et al. (2014). "Study of combined heat, hydrogen and power system based on a molten carbonate fuel cell fed by biogas produced by anaerobic digestion." Energy Conversion and Management **81**: 184-191.

Haroon, M. F., S. Hu, et al. (2013). "Anaerobic oxidation of methane coupled to nitrate reduction in a novel archaeal lineage." Nature **500**(7464): 567-+.

Haynes, C. A. and R. Gonzalez (2014). "Rethinking biologocal activation of methane and conversion to liquid fuels." Nature Chemical Biology **10**(5): 331-339.

He, H., S.-J. Yuan, et al. (2014). "Characterization of a new electrochemically active bacterium, Lysinibacillus sphaericus D-8, isolated with a WO3 nanocluster probe." Process Biochemistry **49**(2): 290-294.

He, Y., D. M. Bagley, et al. (2012). "Recent advances in membrane technologies for biorefining and bioenergy production." Biotechnology Advances **30**(4): 817-858.

He, Z. and F. Mansfeld (2009). "Exploring the use of electrochemical impedance spectroscopy (EIS) in microbial fuel cell studies." Energy & Environmental Science **2**(2): 215-219.

Henard, C. A., H. Smith, et al. (2016). "Bioconversion of methane to lactate by an obligate methanotrophic bacterium." Scientific Reports **6**.

Hidalgo, D., A. Sacco, et al. (2015). "Electrochemical and impedance characterization of Microbial Fuel Cells based on 2D and 3D anodic electrodes working with seawater microorganisms under continuous operation." Bioresource Technology **195**: 139-146.

Hoang Hai, N. and K.-S. Kim (2015). "Combination of plasmas and catalytic reactions for CO2 reforming of CH4 by dielectric barrier discharge process." Catalysis Today **256**: 88-95.

Hoang Hai, N., A. Nasonova, et al. (2015). "Analysis on CO2 reforming of CH4 by corona discharge process for various process variables." Journal of Industrial and Engineering Chemistry **32**: 58-62.

Hu, J.-J., L. Wang, et al. (2011). "Enhanced CO2 fixation by a non-photosynthetic microbial community under anaerobic conditions: Optimization of electron donors." Bioresource Technology **102**(3): 3220-3226.

Huang, H.-j., X.-z. Yuan, et al. (2014). "Thermochemical liquefaction characteristics of sewage sludge in different organic solvents." Journal of Analytical and Applied Pyrolysis **109**: 176-184.

Hung Thanh, N., E. Yoda, et al. (2014). "Catalytic supercritical water gasification of proteinaceous biomass: Catalyst performances in gasification of ethanol fermentation stillage with batch and flow reactors." Chemical Engineering Science **109**: 197-203.

Iwarere, S. A., V.-J. Rohani, et al. (2015). "Dry reforming of methane in a tip-tip arc discharge reactor at very high pressure." International Journal of Hydrogen Energy **40**(8): 3388-3401.

Jafarbegloo, M., A. Tarlani, et al. (2015). "Thermodynamic analysis of carbon dioxide reforming of methane and its practical relevance." International Journal of Hydrogen Energy **40**(6): 2445-2451.

Jenks, C. (2015). "Chemical Conversion via Modular Manufacturing: Distributed, Stranded, and Waste Feedstocks." Ames National Laboratory. Accessed April 25, 2016, https://www.ameslab.gov/workshops/chemical-conversion-modular-manufacturing.

Jenks, C. (2016). "Workshop on Fundamental Science Needs for Waste to Chemical Conversion." Ames National Laboratory. Accessed April 25, 2016, https://www.ameslab.gov/workshops/fundamental-science-W2C.

Jhong, H. R., S. C. Ma, et al. (2013). "Electrochemical conversion of CO2 to useful chemicals: current status, remaining challenges, and future opportunities." Current Opinion in Chemical Engineering **2**(2): 191-199.

Jones, S. R. D. Y. Z. C. K. D. A. R. H. D. E. A. S. K. A. T. H. M. (2014). Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading Richland, WA, PNNL**:** 69.

Jung, S., M. M. Mench, et al. (2011). "Impedance Characteristics and Polarization Behavior of a Microbial Fuel Cell in Response to Short-Term Changes in Medium pH." Environmental Science & Technology **45**(20): 9069-9074.

Kalathil, S., M. M. Khan, et al. (2013). "Production of bioelectricity, bio-hydrogen, high value chemicals and bioinspired nanomaterials by electrochemically active biofilms." Biotechnology Advances **31**(6): 915-924.

Kalyuzhnaya, M. G., A. W. Puri, et al. (2015). "Metabolic engineering in methanotrophic bacteria." Metabolic Engineering **29**: 142-152.

Kameshima, S., K. Tamura, et al. (2015). "Pulsed dry methane reforming in plasma-enhanced catalytic reaction." Catalysis Today **256**: 67-75.

Katuri, K. P., C. M. Werner, et al. (2014). "A Novel Anaerobic Electrochemical Membrane Bioreactor (AnEMBR) with Conductive Hollow-fiber Membrane for Treatment of Low-Organic Strength Solutions." Environmental Science & Technology **48**(21): 12833-12841.

Kim, B., F. Hillman, et al. (2016). "Effects of composition of the micro porous layer and the substrate on performance in the electrochemical reduction of CO2 to CO." Journal of Power Sources **312**: 192-198.

Kim, B., S. Ma, et al. (2015a). "Influence of dilute feed and pH on electrochemical reduction of CO2 to CO on Ag in a continuous flow electrolyzer." Electrochimica Acta **166**: 271-276.

Kim, C., H. S. Jeon, et al. (2015b). "Achieving Selective and Efficient Electrocatalytic Activity for CO2 Reduction Using Immobilized Silver Nanoparticles." Journal of the American Chemical Society **137**(43): 13844-13850.

Koepke, M., M. L. Gerth, et al. (2014). "Reconstruction of an Acetogenic 2,3-Butanediol Pathway Involving a Novel NADPH-Dependent Primary-Secondary Alcohol Dehydrogenase." Applied and Environmental Microbiology **80**(11): 3394-3403.

Kondaveeti, S. and B. Min (2015). "Bioelectrochemical reduction of volatile fatty acids in anaerobic digestion effluent for the production of biofuels." Water Research **87**: 137-144.

Kruusernent, K., H. Luik, et al. (2014). "Gasification and liquefaction of solid fuels by hydrothermal conversion methods." Journal of Analytical and Applied Pyrolysis **108**: 265-273.

Kumar, B., J. P. Brian, et al. (2016). "New trends in the development of heterogeneous catalysts for electrochemical CO2 reduction." Catalysis Today **270**: 19-30.

Kundu, K., S. Sharma, et al. (2012). "Effect of operating temperatures on the microbial community profiles in a high cell density hybrid anaerobic bioreactor." Bioresource Technology **118**: 502-511.

Lan, E. I. and J. C. Liao (2013). "Microbial synthesis of n-butanol, isobutanol, and other higher alcohols from diverse resources." Bioresource Technology **135**: 339-349.

Lee, W. S., A. S. M. Chua, et al. (2014). "A review of the production and applications of waste-derived volatile fatty acids." Chemical Engineering Journal **235**: 83-99.

Lemoine, F., I. Maupin, et al. (2013). "Alternative fuel production by catalytic hydroliquefaction of solid municipal wastes, primary sludges and microalgae." Bioresource Technology **142**: 1-8.

Leng, L., X. Yuan, et al. (2015). "Characterization of liquefaction bio-oil from sewage sludge and its solubilization in diesel microemulsion." Energy **82**: 218-228.

Li, J., Z. Ge, et al. (2014). "A fluidized bed membrane bioelectrochemical reactor for energy-efficient wastewater treatment." Bioresource Technology **167**: 310-315.

Li, K., J.-L. Liu, et al. (2016). "Warm plasma catalytic reforming of biogas in a heat-insulated reactor: Dramatic energy efficiency and catalyst auto-reduction." Chemical Engineering Journal **288**: 671-679.

Ligthart, D. A. J. M., I. A. W. Filot, et al. (2016). "Identification of step-edge sites on Rh nanoparticles for facile CO dissociation." Catalysis Communications **77**: 5-8.

Lin, H. J., W. Peng, et al. (2013). "A review on anaerobic membrane bioreactors: Applications, membrane fouling and future perspectives." Desalination **314**: 169-188.

Liu, P.-I., L.-C. Chung, et al. (2016). "Comparative insight into the capacitive deionization behavior of the activated carbon electrodes by two electrochemical techniques." Desalination **379**: 34-41.

Liu, Z., Z. Ruan, et al. (2013). "Integration of sewage sludge digestion with advanced biofuel synthesis." Bioresource Technology **132**: 166-170.

Logan, B. E. and K. Rabaey (2012). "Conversion of Wastes into Bioelectricity and Chemicals by Using Microbial Electrochemical Technologies." Science **337**(6095): 686-690.

Lovley, D. R. and K. P. Nevin (2013). "Electrobiocommodities: powering microbial production of fuels and commodity chemicals from carbon dioxide with electricity." Current Opinion in Biotechnology **24**(3): 385-390.

Lu, L., Z. Huang, et al. (2015). "Microbial Electrolytic Carbon Capture for Carbon Negative and Energy Positive Wastewater Treatment." Environmental Science & Technology **49**(13): 8193-8201.

Lu, L. and Z. J. Ren (2016). "Microbial electrolysis cells for waste biorefinery: A state of the art review." Bioresource Technology **215**: 254-264.

Lu, X., D. Y. C. Leung, et al. (2016). "A pH-differential dual-electrolyte microfluidic electrochemical cells for CO2 utilization." Renewable Energy **95**: 277-285.

Ma, Y., B. Liu, et al. (2016). "Promoted potassium salts based Ru/AC catalysts for water gas shift reaction." Chemical Engineering Journal **287**: 155-161.

Malins, K., V. Kampars, et al. (2015). "Bio-oil from thermo-chemical hydro-liquefaction of wet sewage sludge." Bioresource Technology **187**: 23-29.

Marrone, P. A., S. D. Cantwell, et al. (2005). "SCWO system designs for waste treatment: Application to chemical weapons destruction." Industrial & Engineering Chemistry Research **44**(24): 9030-9039.

Meabe, E., S. Deleris, et al. (2013). "Performance of anaerobic membrane bioreactor for sewage sludge treatment: Mesophilic and thermophilic processes." Journal of Membrane Science **446**: 26-33.

Mohan, S. V., G. Velvizhi, et al. (2014a). "Microbial catalyzed electrochemical systems: A bio-factory with multi-facet applications." Bioresource Technology **165**: 355-364.

Mohan, S. V., G. Velvizhi, et al. (2014b). "Microbial fuel cell: Critical factors regulating bio-catalyzed electrochemical process and recent advancements." Renewable & Sustainable Energy Reviews **40**: 779-797.

Morais, A. R. C., A. M. da Costa Lopes, et al. (2014). "Cattle fat valorisation through biofuel production by hydrogenation in supercritical carbon dioxide." Rsc Advances **4**(61): 32081-32091.

Mota, V. T., F. S. Santos, et al. (2013). "Two-stage anaerobic membrane bioreactor for the treatment of sugarcane vinasse: Assessment on biological activity and filtration performance." Bioresource Technology **146**: 494-503.

Murray, B. C., C. S. Galik, et al. (2014). Biogas in the United States: An Assessment of Market Potential in a Carbon-Constrained Future. Durham, N.C., Duke University.

Mustu, H., S. Yasyerli, et al. (2015). "Effect of synthesis route of mesoporous zirconia based Ni catalysts on coke minimization in conversion of biogas to synthesis gas." International Journal of Hydrogen Energy **40**(8): 3217-3228.

Nasr, N., E. Elbeshbishy, et al. (2012). "Comparative assessment of single-stage and two-stage anaerobic digestion for the treatment of thin stillage." Bioresource Technology **111**: 122-126.

Nikparsa, P., A. A. Mirzaei, et al. (2016). "Modification of Co/Al2O3 Fischer-Tropsch Nanocatalysts by Adding Ni: A Kinetic Approach." International Journal of Chemical Kinetics **48**(3): 131-143.

Oh, S. T. and A. D. Martin (2014). "Glucose contents in anaerobic ethanol stillage digestion manipulate thermodynamic driving force in between hydrogenophilic and acetoclastic methanogens." Chemical Engineering Journal **243**: 526-536.

Okajima, I. and T. Sako (2014). "Energy conversion of biomass with supercritical and subcritical water using large-scale plants." Journal of Bioscience and Bioengineering **117**(1): 1-9.

Okeson, T. J., K. Keyvanloo, et al. (2016). "On the kinetics and mechanism of Fischer Tropsch synthesis on a highly active iron catalyst supported on silica-stabilized alumina." Catalysis Today **261**: 67-74.

Olah, G. A., A. Goeppert, et al. (2013). "Bi-reforming of Methane from Any Source with Steam and Carbon Dioxide Exclusively to Metgas (CO-2H(2)) for Methanol and Hydrocarbon Synthesis." Journal of the American Chemical Society **135**(2): 648-650.

Otero-Gozalez, L., J. A. Field, et al. (2014). "Inhibition of anaerobic wastewater treatment after long-term exposure to low levels of CuO nanoparticles." Water Research **58**: 160-168.

Park, D. and J. Lee (2013). "Biological conversion of methane to methanol." Korean Journal of Chemical Engineering **30**(5): 977-987.

Rabaey, K. and R. A. Rozendal (2010). "Microbial electrosynthesis - revisiting the electrical route for microbial production." Nature Reviews Microbiology **8**(10): 706-716.

Ramasamy, R. P., V. Gadhamshetty, et al. (2009). "Impedance spectroscopy as a tool for non-intrusive detection of extracellular mediators in microbial fuel cells." Biotechnology and Bioengineering **104**(5): 882-891.

Ramos, C., F. Zecchino, et al. (2014). "Chemical cleaning of membranes from an anaerobic membrane bioreactor treating food industry wastewater." Journal of Membrane Science **458**: 179-188.

Rasigraf, O., D. M. Kool, et al. (2014). "Autotrophic Carbon Dioxide Fixation via the Calvin-Benson-Bassham Cycle by the Denitrifying Methanotroph "Candidatus Methylomirabilis oxyfera"." Applied and Environmental Microbiology **80**(8): 2451-2460.

Ravasio, S. and C. Cavallotti (2012). "Analysis of reactivity and energy efficiency of methane conversion through non thermal plasmas." Chemical Engineering Science **84**: 580-590.

Ren, L., Y. Ahn, et al. (2014). "A Two-Stage Microbial Fuel Cell and Anaerobic Fluidized Bed Membrane Bioreactor (MFC-AFMBR) System for Effective Domestic Wastewater Treatment." Environmental Science & Technology **48**(7): 4199-4206.

Ro, K. S., J. M. Novak, et al. (2016). "Leachate water quality of soils amended with different swine manure-based amendments." Chemosphere **142**: 92-99.

Ruiz, E., D. Cillero, et al. (2013). "Bench scale study of electrochemically promoted catalytic CO2 hydrogenation to renewable fuels." Catalysis Today **210**: 55-66.

Savchenko, V. I., V. G. Dorokhov, et al. (2016). "Slurry reactor system with inertial separation for Fischer-Tropsch synthesis and other three-phase hydrogenation processes." Canadian Journal of Chemical Engineering **94**(3): 518-523.

Schiel-Bengelsdorf, B. and P. Duerre (2012). "Pathway engineering and synthetic biology using acetogens." Febs Letters **586**(15): 2191-2198.

Schievano, A., F. Adani, et al. (2015). "An integrated biorefinery concept for olive mill waste management: supercritical CO2 extraction and energy recovery." Green Chemistry **17**(5): 2874-2887.

Scialdone, O., A. Galia, et al. (2016). "Electrochemical reduction of carbon dioxide to formic acid at a tin cathode in divided and undivided cells: effect of carbon dioxide pressure and other operating parameters." Electrochimica Acta **199**: 332-341.

Shen, Y., J. L. Linville, et al. (2015). "An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs." Renewable & Sustainable Energy Reviews **50**: 346-362.

Sheu, E. J., E. M. A. Mokheimer, et al. (2015). "Dry redox reforming hybrid power cycle: Performance analysis and comparison to steam redox reforming." International Journal of Hydrogen Energy **40**(7): 2939-2949.

Shin, C., P. L. McCarty, et al. (2014). "Pilot-scale temperate-climate treatment of domestic wastewater with a staged anaerobic fluidized membrane bioreactor (SAF-MBR)." Bioresource Technology **159**: 95-103.

Sirajuddin, S. and A. C. Rosenzweig (2015). "Enzymatic Oxidation of Methane." Biochemistry **54**(14): 2283-2294.

Skouteris, G., D. Hermosilla, et al. (2012). "Anaerobic membrane bioreactors for wastewater treatment: A review." Chemical Engineering Journal **198**: 138-148.

Smith, A. L., S. J. Skerlos, et al. (2013). "Psychrophilic anaerobic membrane bioreactor treatment of domestic wastewater." Water Research **47**(4): 1655-1665.

Taher, E. and K. Chandran (2013). "High-Rate, High-Yield Production of Methanol by Ammonia-Oxidizing Bacteria." Environmental Science & Technology **47**(7): 3167-3173.

Theegala, C. S. and J. S. Midgett (2012). "Hydrothermal liquefaction of separated dairy manure for production of bio-oils with simultaneous waste treatment." Bioresource Technology **107**: 456-463.

Tian, C., B. Li, et al. (2014a). "Hydrothermal liquefaction for algal biorefinery: A critical review." Renewable & Sustainable Energy Reviews **38**: 933-950.

Tian, Y., C. Ji, et al. (2014b). "Assessment of an anaerobic membrane bio-electrochemical reactor (AnMBER) for wastewater treatment and energy recovery." Journal of Membrane Science **450**: 242-248.

Todic, B., L. Nowicki, et al. (2016). "Fischer-Tropsch synthesis product selectivity over an industrial iron-based catalyst: Effect of process conditions." Catalysis Today **261**: 28-39.

Ueki, T., K. P. Nevin, et al. (2014). "Converting Carbon Dioxide to Butyrate with an Engineered Strain of Clostridium ljungdahlii." Mbio **5**(5).

USDA (2014). Biogas Opportunities Roadmap: Voluntary Actions to Reduce Methane Emissions and Increase Energy Independence Washington, DC, USDA**:** 28.

USDA (2015). Biogas Opportunities Roadmap: Progress Report. Washington, DC**:** 20.

Usman, M., W. M. A. W. Daud, et al. (2015). "Dry reforming of methane: Influence of process parameters-A review." Renewable & Sustainable Energy Reviews **45**: 710-744.

van der Ha, D., L. Nachtergaele, et al. (2012). "Conversion of Biogas to Bioproducts by Algae and Methane Oxidizing Bacteria." Environmental Science & Technology **46**(24): 13425-13431.

Villano, M., F. Aulenta, et al. (2010). "Bioelectrochemical reduction of CO2 to CH4 via direct and indirect extracellular electron transfer by a hydrogenophilic methanogenic culture." Bioresource Technology **101**(9): 3085-3090.

Wang, H. and L. Pilon (2012). "Intrinsic limitations of impedance measurements in determining electric double layer capacitances." Electrochimica Acta **63**: 55-63.

Wang, H. and Z. J. Ren (2013). "A comprehensive review of microbial electrochemical systems as a platform technology." Biotechnology Advances **31**(8): 1796-1807.
Wang, H. M., J. D. Park, et al. (2015a). "Practical Energy Harvesting for Microbial Fuel Cells: A Review." Environmental Science & Technology **49**(6): 3267-3277.
Wang, Y., G. Chen, et al. (2013). "Experimental study of the bio-oil production from sewage sludge by supercritical conversion process." Waste Management **33**(11): 2408-2415.
Wang, Z., D. H. Leary, et al. (2015b). "A Previously Uncharacterized, Nonphotosynthetic Member of the Chromatiaceae Is the Primary CO2-Fixing Constituent in a Self-Regenerating Biocathode." Applied and Environmental Microbiology **81**(2): 699-712.
WEF (2012). Driving Water and Wastewater Utilities to More Sustainable Energy Management. Alexandria, VA, Water Environment Federation**:** 16.
WERF (2011). Energy Production and Efficiency Research - The Roadmap to Net-Zero Energy. Alexandria, VA, Water Environment Reserch Foundation**:** 8.
WERF (2014). Utilities of the Future Energy Findings. Alexandria, VA, Water Environment Research Federation**:** 86.
Westerholm, M., M. Hansson, et al. (2012). "Improved biogas production from whole stillage by co-digestion with cattle manure." Bioresource Technology **114**: 314-319.
Willis, J., N. Andrews, et al. (2015). Assessment of Technology Advancements for Future Energy Reduction. London, WERF**:** 200.
Wu, J. J. and X. D. Zhou (2016). "Catalytic conversion of CO2 to value added fuels: Current status, challenges, and future directions." Chinese Journal of Catalysis **37**(7): 999-1015.
Xie, Z., Z. Wang, et al. (2014). "An anaerobic dynamic membrane bioreactor (AnDMBR) for landfill leachate treatment: Performance and microbial community identification." Bioresource Technology **161**: 29-39.
Xu, J.-D., Z.-Y. Chang, et al. (2016). "Effect of sulfur on alpha-Al2O3-supported iron catalyst for Fischer-Tropsch synthesis." Applied Catalysis a-General **514**: 103-113.
Yadav, V. S. K. and M. K. Purkait (2015). "Electrochemical Studies for CO2 Reduction Using Synthesized Co3O4 (Anode) and Cu2O (Cathode) as Electrocatalysts." Energy & Fuels **29**(10): 6670-6677.
Yakaboylu, O., J. Harinck, et al. (2013). "Supercritical water gasification of manure: A thermodynamic equilibrium modeling approach." Biomass & Bioenergy **59**: 253-263.
Yang, L., X. Ge, et al. (2014). "Progress and perspectives in converting biogas to transportation fuels." Renewable & Sustainable Energy Reviews **40**: 1133-1152.
Yang, Z.-Y., V. R. Moure, et al. (2012). "Carbon dioxide reduction to methane and coupling with acetylene to form propylene catalyzed by remodeled nitrogenase." Proceedings of the National Academy of Sciences of the United States of America **109**(48): 19644-19648.
Yu, L., J. Duan, et al. (2013). "Accelerated anaerobic corrosion of electroactive sulfate-reducing bacteria by electrochemical impedance spectroscopy and chronoamperometry." Electrochemistry Communications **26**: 101-104.
Yun, J. H., S. S. Sawant, et al. (2013). "Production of polyhydroxyalkanoates by Ralstonia eutropha from volatile fatty acids." Korean Journal of Chemical Engineering **30**(12): 2223-2227.
Yunarti, R. T., M. Lee, et al. (2014). "Transition metal-doped TiO2 nanowire catalysts for the oxidative coupling of methane." Catalysis Communications **50**: 54-58.
Zhang, C., P. Duan, et al. (2014a). "Catalytic upgrading of duckweed biocrude in subcritical water." Bioresource Technology **166**: 37-44.
Zhang, F., J. Liu, et al. (2014b). "Reference and Counter Electrode Positions Affect Electrochemical Characterization of Bioanodes in Different Bioelectrochemical Systems." Biotechnology and Bioengineering **111**(10): 1931-1939.
Zhang, G., L. Hao, et al. (2015). "CO2 reforming of CH4 over efficient bimetallic Co-Zr/AC catalyst for H-2 production." International Journal of Hydrogen Energy **40**(37): 12868-12879.
Zhang, Y. and I. Angelidaki (2014). "Microbial electrolysis cells turning to be versatile technology: Recent advances and future challenges." Water Research **56**: 11-25.
Zheng, X., S. Tan, et al. (2015). "Plasma-assisted catalytic dry reforming of methane: Highly catalytic performance of nickel ferrite nanoparticles embedded in silica." Journal of Power Sources **274**: 286-294.
Zhi, W., Z. Ge, et al. (2014). "Methods for understanding microbial community structures and functions in microbial fuel cells: A review." Bioresource Technology **171**: 461-468.
Zhong, Y., Z. Ruan, et al. (2015). "A self-sustaining advanced lignocellulosic biofuel production by integration of anaerobic digestion and aerobic fungal fermentation." Bioresource Technology **179**: 173-179.
Zhu, Y., M. J. Biddy, et al. (2014). "Techno-economic analysis of liquid fuel production from woody biomass via hydrothermal liquefaction (HTL) and upgrading." Applied Energy **129**: 384-394.

5. Feedback and Remaining Challenges

The previous chapters set the stage for this chapter. Chapter 1 sketches the overall landscape and suggests why the U.S. Department of Energy (DOE) might be able to establish a unique value proposition in terms of the conversion of wet and gaseous waste feedstocks to biofuels and bioproducts, with biopower as a potential ancillary benefit. Chapter 2 explores the volumes, distributions, and composition of many of the feedstocks in question, and it also foreshadows the need to connect feedstocks with specific conversion technologies and parameters. Chapter 3 begins the exploration of the complex intersections among feedstocks, current practices, and the expected markets of the future. Although it poses more questions than it provides answers, it offers some guidance for possible future analysis. Chapter 4 explores specific technological challenges and opportunities within the context of the previous three chapters. It seeks to outline possibilities for the future and to inform future research and development (R&D) efforts in these areas.

Chapter 5 is based partly on feedback received from a workshop held June 22–23, 2016, at the National Renewable Energy Laboratory in Golden, Colorado. Participants were provided an earlier draft of this document in advance of the meeting, and the breakout sessions were highly targeted to elicit specific feedback. The feedback was derived from thoughts shared in person at the event and written comments provided afterwards. Further, the feedback also draws on input received at previous workshops sponsored by the DOE in partnership with the U.S. Environmental Protection Agency (EPA) and the National Science Foundation (NSF) over the last 18 months (DOE 2015b; DOE 2015c; DOE 2015a).

While many specific elements have already been incorporated into previous chapters, there were enough separate themes to justify a chapter of their own. Notions of transcending boundaries of all kinds pervaded the comments, as did the need to integrate ideas of sustainability throughout the DOE's efforts. That latter theme ties nicely into section 5.5, which deals with next steps in incorporating wet and gaseous feedstocks into the Bioeconomy of the Future. However, one of the strongest messages that participants sent was the need for the DOE to integrate its activities, which is the subject of the next section.

5.1. Need for Problem-Solving Approaches

A clear message that emerged was that wet and gaseous waste streams are existing problems that need solutions. For example, in certain jurisdictions the combination of increasingly stringent regulations and transportation costs renders disposal of wastewater sludges a high-priority problem (Moss et al. 2013). When sludge disposal starts to comprise a significant percentage of overall wastewater treatment operating costs, alternative approaches, such as the on-site production of biofuels and bioproducts, might have an opportunity to construct an attractive value proposition. One useful framing question was "What problems are we trying to solve by eliminating waste that people are willing to pay for?" Participants called out situations like this as an example that might constitute potential for early market adoption.

Another strong theme was the need to couple a diversity of possible bioproduct outputs with biofuels in order to enable marketplace success. Participants specifically called out the desirability of including liquid products other than biofuels in the possible suite of acceptable outputs. The participants thoughts were in keeping with the notion of "replacing the whole barrel" that DOE's Bioenergy Technologies

Office (BETO) has advocated in the past (DOE 2013). Participants also expressed concern that current energy prices are too low to support many biofuel projects in the absence of supplemental revenue streams.

Commenters also drew attention to the state of existing infrastructure, particularly in the municipal wastewater treatment sector. Many of the existing facilities, including large-scale anaerobic digesters, were built in response to the passage of the Clean Water Act and are now nearing the end of their useful life. Participants saw this aging infrastructure as an opportunity for innovation. Alternatives to anaerobic digestion, such as hydrothermal liquefaction and supercritical water oxidation, were mentioned as possibilities. The main point may have been that the expiration of existing facilities might present an opportunity to break through to what is traditionally a risk-adverse industry. Although not directly germane to the DOE, the notion of regulatory flexibility also arose in this context, which might provide an opportunity for future analyses in collaboration with the EPA. The Clean Air Act in particular might offer interesting possibilities for constructive action.

Constraints imposed by existing infrastructure also produced a more nuanced body of feedback, which ties back to questions raised in Chapter 4. Notions related to relatively short-term (~10 year) solutions to infrastructure replacement questions surfaced as a possible way to avoid technological lock-in. Bolt-on possibilities such as thermal hydrolysis pretreatment for anaerobic digestion also arose. The fact that at least some of these technologies are beginning to achieve commercial success raises the question of where the DOE can or should add value.

Following on that point, some difficult issues in this space seem to be about appropriate boundaries—a theme that pervades this chapter. What are the proper roles of the various agencies of the federal government, the private sector, municipalities, and non-governmental organizations (NGOs) in these arenas? In federal terms, the NSF is primarily oriented toward basic research and education while the DOE is about science and technology research, development, and demonstration (RD&D), and the EPA straddles both regulatory responsibilities and supports constructive innovation. NGOs such as the Water Environment and Reuse Foundation (WE&RF) and the Water Environment Federation (WEF) also have valuable roles to play, as do state and local agencies and the private sector. Participants offered more questions than answers about the proper roles of the various agencies, but the questions are clearly important moving forward.

The need for approaches that integrate feedstocks, markets, and technologies was another strong theme. There was strong sentiment that the distributed nature of the feedstocks in question demands a networked approach in line with the arguments advanced in section 4.3, as opposed to standalone refineries. The notion of transportable intermediates as a “flow” within such networks received attention, as did the tenet of handling waste problems as close to the source as possible. Tight coupling between “waste” production and value-added conversion also found voice, even to the point of thinking in terms of “eco-parks” and industrial ecology.

In a similar vein, the concept of sustainability was discussed throughout the June 2016 workshop. There was a strong emphasis on triple bottom line approaches, including the importance of both techno-economic and lifecycle analyses. One commenter highlighted the possibility of using such studies as tangible prioritization strategies for future BETO work—an idea that might merit further investigation. Finally, the idea of “green-driven” early adopters emerged prominently. While product economics are clearly critical for widespread adoption, participants emphasized the need to identify and support early niche markets as a first step.

5.2. Feedstocks

While fully recognizing the call for integrated approaches and the themes of sustainability and overcoming boundaries, a substantial portion of the comments still fit within the feedstocks/markets/technologies framing of Chapters 2 through 4. Feedback specific to particular sentences or factual claims has been addressed in the relevant chapters. Sections 5.2 through 5.4 are about more general comments that are not quite universal to the document but are still at a high enough level of abstraction to merit separate treatment. Many of the general comments do seek to transcend the somewhat artificial boundaries between feedstocks, markets, and technologies, but they follow the overarching themes of integration, sustainability, and boundaries.

One of the chief notes that participants expressed in June was that while the current resource assessments of wet and gaseous feedstocks have value, they are only a first step. These markets will change going forward. In particular, the assumption of negative feedstock costs (avoided tipping fees) should not be taken as a given in the future. Participants felt that the analytical emphasis should move from static characterizations of what has been to analyses of what might be. For example, future assessments should consider under what conditions various wet and gaseous feedstocks would become valuable commodities and how those price differences might affect putative techno-economic analyses. These might be productive areas for future investigations and would build on existing modeling efforts.

Another theme was the need to fully characterize both feedstock composition and temporal variability. Broadly speaking, waste feedstock characterization is identified as an area where literature data is limited. One commenter stressed the value of early identification of contaminants and the potential importance of sensor development. Others emphasized the importance of representative sampling of actual waste streams to capture the variability present in the real world. The characterization of these feedstocks extends further to blends thereof (e.g., food waste and sludge, and wet feedstocks with drier, such as agricultural wastes). The issue of differential parameter targeting between the fermentation and wastewater industries also arose. Fermentation operations tend to focus on sugars, proteins, and lignins, while wastewater treatment is more focused on chemical oxygen demand (COD), biological oxygen demand, and solids content. These use similar feedstocks but have different analytical emphases. BETO might have a convening role to play.

An additional major topic that arose in terms of feedstocks is the notion of blending. Several commenters questioned the lack of emphasis on feedstock blending, particularly the lack of attention to wet versus dry. Others noted the seasonal variability issue, with respect to algae in particular. Participants also called for further analysis of content variability and, in particular, its effect on biocrude quality. Although not directly included in comments to previous drafts of this document, there is also the notion of economically and sustainably viable processing networks, based on regionally specific feedstock analyses. In short, Chapters 2 and 3 constitute only a first step, and feedstock blending represents a significant area for future exploration.

There was also an emphasis on the fact that many wet and gaseous “waste” feedstocks are already being collected, and in some cases sorted. Furthermore, many of these streams are already available at any time throughout the year and currently represent a clear disposal problem, as noted in section 5.1.

Participants also observed that co-digestion of various kinds of food wastes, including chicken processing byproducts and yogurt wastes, and aggressive collection programs for fats, oils, and greases (FOG) are already paying substantial dividends in terms of progress toward energy-positive water resource recovery facilities (DOE 2015a).

Perhaps one of the most significant findings from the June 2016 workshop—although it also came up in previous events, and was also noted in 5.1—is the degree to which participants challenged the DOE's implicit divisions of labor. There were a number of earnest questions about separations between BETO and other parts of the DOE, the DOE and other federal agencies, and the DOE and the private sector. One particular example in this section was that there was a lack of clarity on the appropriate dividing lines among the DOE, EPA, perhaps the U.S. Department of Agriculture (USDA) and NSF, and the private and municipal sectors on the topic of co-digestion. Who within the federal government, if anyone, should take primary responsibility for this area, and why? What kinds of federal/state/local/municipal/ private coalitions might be best suited to address problems of this nature? These questions are by no means limited to feedstocks and apply equally to markets, technologies, and the overall whole.

5.3. Markets

The previous section has made it clear that feedstocks and markets are inextricably interconnected in the contexts at hand. This section strives to bring out the participant responses and ideas regarding markets that either did not quite fit into either Chapter 3 or Section 5.2 or may be potential targets for expanded future attention.

Echoing the March 2015 Bioenergy/Fuel Cells event, there was a strong emphasis on the need to focus on early adopters and niche markets. High-strength industrial wastewaters figured prominently in the conversation. First, the energy potential (as measured by COD) of wastewaters is high; the resource is rich. Second, industries such as breweries, wineries, and various food processors may have more appetite for risk-taking than entities such as municipal wastewater facilities. Third, the expense of either treating these waters or paying fees to discharge them creates a potential contribution to net return above any revenues from bioproducts and/or biofuels. Finally, in some cases, there may be a green marketing advantage associated with converting organic wastes to useable products. Together, all of these factors make these kinds of industries good early adopter targets, and there may be others.

Another topic that resounded with previous workshops was the idea that aging wastewater infrastructure represents a critical opportunity in the United States. Many of the existing anaerobic digesters and other wastewater treatment facilities were built in the years following the passage of the Clean Water Act in 1972. Many of these facilities are thus over 40 years old and nearing the end of their useful lives. Participants observed that this wave of obsolescence represents both an opportunity and a risk. The opportunity is obvious; there is a clear need to replace existing structures, offering the chance to do things entirely differently. The risk is subtler, and it stems from the inherent conservatism of the industry. The danger lies in missing the opportunity for radical constructive change and locking in the status quo for the next 40–50 years. Thus, RD&D to de-risk novel technologies might provide tangible benefits in the near- and medium-term.

There were also a number of comments about the techno-economics of distributed processing. Examples included questions about minimum size for feasible transportation, possibilities of blending feedstocks explicitly for transportation purposes, and finding the optimum balance between technology, resource, and transportation economics. There was also curiosity about how many units it takes to achieve economies of mass production, and whether that count applies at the entire system or component levels. Willingness of refineries to accept raw biocrude as a feedstock also came up, as did the whole notion of transportable intermediates. In summary, there were a lot of questions about the techno-economic feasibility of distributed processing of wet and gaseous waste feedstocks, and there may be fertile grounds for future investigation.

Similarly at participatory BETO-sponsored events, the notion of the economic importance of bioproducts as a potential enabler for biofuels was also prominent. Participants noted current oil and natural gas prices are key drivers and challenges. They observed that profit margins for bioproduct precursors can be substantially larger than those for biofuels under existing market conditions. In such a price environment, waste feedstocks were seen as a bit of a silver lining. One commenter noted that this is particularly relevant given the substantive contribution of feedstock prices to minimum fuel selling price in several existing analyses (Davis et al. 2013; Davis et al. 2014; Jones 2014). Currently, in many localities these streams are available at a negative cost; however, it is recognized that this may not persist. What is persistent, however, is that these waste streams represent operational and disposal cost liabilities to municipalities. Thus, existing municipal organic waste streams may represent another class of early adopters/niche markets, particularly in conjunction with the opportunities presented by expiring infrastructure.

At the same time, the discussion on bioproducts as an enabler for biofuels focuses attention on prospective future valuations of these feedstocks. While this point was raised in section 5.2, there may be value available in expanded techno-economic analysis/scenario modeling to answer several important questions. For example, under what conditions would tipping fees for various kinds of waste feedstocks go negative, i.e., have cash value? How might these conditions vary geographically and seasonally? What are the potential implications of possible future regulatory actions, including renewable identification number (RIN) allocations, at the local, state, and federal levels? One particularly interesting example for exploration would be the possibility for the EPA to approve pathways for electricity generated from biogas and used in electric vehicles as eligible for D3 RINs, and others likely exist. All of these questions seem to be ripe possibilities for future modeling efforts.

Sections 5.1 through 5.3 implicitly come together in raising the question of where technology RD&D can make a meaningful difference in terms of future progress on the ground. The intersecting web of feedstocks, markets, technologies, and policies does not always lend itself to obvious answers. Put differently, technological innovation never takes place in a vacuum; it always occurs within larger socioeconomic and environmental contexts. DOE needs to determine how best to contribute to technological development in a way that makes constructive sense in these larger contexts.

5.4. Technologies

Participants at the June 2016 workshop were generally supportive of the technological families included in Chapter 4, and that sentiment was also prevalent in the earlier workshops. The overall sentiment was that the DOE is on the right tracks technologically and should continue to forge ahead, and participants expressed relief that the DOE was “finally” taking wet and gaseous feedstocks seriously. There was also recognition that the technologies in question diverge widely in terms of their technological readiness level and pathways to widespread deployment. Future activities will need to take this diversity into account.

5.4.1. General Support for Existing Technological R&D Directions

In general, the comments regarding the major themes of Chapter 4 were supportive. Hydrothermal processes received an enthusiastic reception, and microbial electrochemical strategies also drew positive attention. Conversion of both the CO2 and CH4 from biogas garnered support, as did biological conversion approaches in general. Distributed processing of wet and gaseous waste streams was also viewed favorably. In short, most of the technological families proposed for consideration were well received.

One notable exception was the idea of arrested methanogenesis in anaerobic digestion, which garnered mixed reviews. Some of the participants were enthusiastic and advocated for additional emphasis on ketonization and oligmerization. Others were more skeptical about disturbing the balance of co-evolved microbial communities and emphasized the separations challenges in working with such complex biological broths. This suggests a need for careful targeting of future R&D efforts and perhaps making overcoming the identified barriers an explicit part of the requirements for future solicitations.

Anaerobic Membrane Bioreactors (AnMBRs) also drew some attention, most of it positive. A noteworthy point is that the line between wastewater treatment and energy recovery/biofuels and bioproduct production is unclear. It merits mention because it raises questions of appropriate boundaries/possibilities for collaboration both within the DOE and among the DOE and sister agencies such as the EPA, USDA, and NSF, as well as the private and NGO sectors. In one example, Bioenergy by itself does not have the congressionally-derived authority to tackle energy efficiency in wastewater treatment as an isolated target. The DOE's Advanced Manufacturing and Fuel Cells offices probably do, and the EPA certainly does. AnMBRs treat wastewater and produce energy, and AnMBRs are good candidates for distributed deployment—another area of interorganizational interest. As such, they are a good example of a technology (MxCs are another) that raise political questions that may merit further intra- and interagency collaboration in the future.

Implicit in the recognition that the technologies in question are at different levels of development is the value of responses targeted to specific stages of deployment readiness. In this vein, Bioenergy recently released a solicitation focused on pilot- and demonstration-scale facilities, and biosolids and related feedstocks were the explicit target of one of the three topics (DOE 2016c). The DOE has recently collaborated with the WE&RF in a pilot-scale project that successfully produced renewable diesel from municipal wastewater sludge (Marrone 2016). In 2014, Bioenergy funded two projects that seek to produce valuable bioproduct precursors from biogas, and one of the projects strives to utilize both CO_2 and CH_4 as feedstocks (DOE 2014).

In contrast, some of the early-stage technologies require more of an "all-of-the-above" strategy, as it is not yet clear which approaches are likely to pan out. To this end, Bioenergy has been aggressively utilizing the Small Business Innovation Research (SBIR) program over the last 18 months and hopes to continue doing so. Congress has mandated that a certain percentage of federal extramural R&D funds be set aside for small businesses and industry collaborations. There are at least two sequential phases. For Bioenergy, phase I involves awards of $150,000 over nine months. Successful phase I awardees are allowed to compete for phase II awards, which can amount up to $1 million over two years. Subsequent phases are also possible.

The SBIR program offers a relatively low-risk way for federal agencies to develop a tangible sense of the "state-of-the-market" in areas of interest. It seems like an excellent fit for the nascent waste-to-energy program within Bioenergy. To this end, 11 awards have been made in the last two rounds, and another solicitation is currently open as of this writing (August 2016). Awards have included technologies to produce bioproduct precursors from biogas, higher hydrocarbons from volatile fatty acids resulting from arrested methanogenesis, and hydrothermal liquefaction of food waste (DOE 2016a). The current topics seek to delve more deeply into possible combinations of anaerobic membrane bioreactors and microbial electrochemical cells, as well as further work with arrested methanogenesis (DOE 2016b). All of the technologies discussed in Chapter 4 are fair game for future topics.

Returning to an ongoing theme, a number of the live and written comments harped on the desire for BETO to play a greater role with technologies that are either already commercial or represent incremental improvements over the state of the art. These criticisms were focused on the area of municipal wastewater treatment in which the market conditions are different because they are in domains dominated by the private sector. The notion of investing in commercial or incremental technologies is anathema to the dominant philosophies within the DOE Office of Energy Efficiency and Renewable Energy, of which Bioenergy is a part. This might suggest a need for additional partnerships both within and outside of the federal government. While it may not be Bioenergy's role to subsidize existing technologies, there may be room to work with those entities that are in such a position, such as state agencies, to provide maximum value to the taxpayer.

5.4.2. Requests for Technological Expansion/Modification

Several requests for technological expansion, most notably inorganic and organic electrochemical conversion, have already been incorporated into this version of the document. Another group of requests raised a different and equally valuable set of boundary issues. The notion of value in an improved understanding of complex anaerobic microbial communities has been a consistent theme throughout the workshop series. There are clearly many promising scientific approaches in this area that could yield valuable results, particularly in the combination of systems biology with various -omics. These problems are close enough to basic research that they clearly fall within the federal wheelhouse. However, an open question remains: which departments of which agencies should take on these problems? Within the DOE, Bioenergy, the Advanced Research Projects Agency-Energy, and the Office of Science all have interest. Such questions also matter to the NSF, the EPA, and probably the USDA. How to best divide the labor and develop appropriate interagency collaboration strategies has not been determined, but it might provide productive grounds for future consultations.

Nutrient recovery from waste streams provides another example. The EPA, USDA, and DOE are already collaborating on a Nutrient Recovery Challenge led by the EPA (EPA 2015). WE&RF and others have previously done valuable work in this area (Latimer et al. 2015; Nancharaiah et al. 2016; Zou and Wang 2016). Nutrient recovery is another area of boundary inquiry; sales of nutrient-related materials could clearly qualify as part of an integrated biorefinery approach (Carey et al. 2016). The question remains, what is the appropriate role for the BETO in these spaces? This could be another area where techno-economic and lifecycle analyses could help to shape future priorities.

5.4.3. Wastewater Test Bed Network

Participants also recommended establishing a network of test beds for wastewater treatment and energy recovery technologies. This idea also emerged strongly in the April 2015 session, and the June 2016 workshop was held immediately on the heels of an NSF-sponsored event on structural considerations for such a network. There was some participant overlap among the two efforts, so the prominence of this subject is perhaps unsurprising. However, it is another example of a challenging boundary question: Which organization should have primary responsibility for running such a network? Is a federal agency appropriate as a lead, or is this a better fit for the private/NGO sector with support from the NSF, EPA, DOE, and possibly the USDA? There is an ongoing collaboration between the NSF, EPA, DOE, WE&RF, and now WEF, with participation from the USDA and other organizations that is striving to address these questions. Therefore, this document attempts to provide no particular answers, but does refer interested readers to that parallel track.

5.5. Integrating Wet and Gaseous Feedstocks into the Bioeconomy of the Future

Workshop participants also expressed a strong desire to see the DOE's efforts in these areas integrated within larger contexts. Triple bottom line considerations came up throughout, as did the importance of sustainability arguments as a competitive advantage for these waste feedstocks. These streams represent immediate problems to be solved, with potential for cost savings in many cases. Further, participants voiced the opinion that these feedstocks could serve as a leading edge of the Bioeconomy of the Future.

5.5.1. Sustainability/Prioritization

There were several calls for closer integration of sustainability metrics and lifecycle analyses into BETO's R&D prioritization. One commenter explicitly wanted closer connections with sustainability analyses of the larger energy–water nexus, which is an overarching priority across the DOE. The connections between this effort and BETO's Multi-Year Program Plan also engendered questions, and the connections also created possible intersections with broader DOE documents, such as the Quadrennial Technology Review and Quadrennial Energy Reviews. There was also a suggestion to include more discussion about analytical methodologies and prioritization criteria for future R&D investments. All of these suggestions will be taken into consideration as BETO moves on to additional steps beyond this document.

5.5.2. Further Technical Analysis and Precision

Another general theme of recommendations for better integration of these topics with larger contexts was the criticism that this document does not go far enough. While this document does discuss challenges and opportunities for a number of feedstocks, markets, and technologies, it does not set specific targets. This thought was particularly directed toward technologies, and there was a desire for the DOE to nail down precise performance and cost targets by given dates, with a clear understanding of the technological advances needed to meet such objectives. Again, BETO views these kind of comments as very useful feedback to inform future activities.

5.5.3. Boundaries

Building on discussions sprinkled throughout this chapter, the notion of boundaries emerged with sufficient prominence that it merits re-summarization. The types of boundaries in question include the following:

1. Relationships between BETO and its sister offices within the DOE
2. Intersections among BETO and other federal agencies
3. Interaction between the DOE and various state, local, and NGO entities and associations
4. The proper role of the federal government vis-à-vis the private sector

The fundamental categories of questions raised with respect to these boundaries seemed to coalesce into a relatively limited number of areas:

1. What is the appropriate role of BETO in all of these contexts?
2. How can BETO and its federal partners better communicate the constraints of respective legislative authorities to non-governmental audiences?
3. Where are creative opportunities for constructive collaboration?

In keeping with overall themes, all of these are valuable inputs for future deliberations and actions.

5.5.4. Summarizing Challenges and Opportunities

This document is not intended as a definitive set of answers. Instead, it is meant as an invitation for constructive conversation moving forward. Chapter 2 establishes that the wet and gaseous feedstocks in question do in fact constitute a significant resource. It strives to do so with meaningful rigor, which is particularly important given the range of uncertainty that has surrounded previous estimates. Chapter 3 raises the question of potential competing uses of the resources in question and points a way for further analysis. Yes, these resources exist in the millions of dry tons per year within the United States, but it is not clear how much of that is truly available for biofuel and bioproduct production and under what economic assumptions. This is clearly a priority for near-term techno-economic and lifecycle analyses.

In terms of technological possibilities, Chapter 4 outlines several areas of potentially productive R&D. Various technological families are at different levels of market readiness, and supportive strategies need to be tailored accordingly. No single "silver bullet" solutions emerge, but thermochemical, biochemical, and electrochemical strategies all show promise. Perhaps a "pewter buckshot" strategy is more appropriate and in keeping with Bioenergy's current trajectories in terms of larger extramural solicitations, SBIRs, and projects with the national laboratories.

Perhaps more intriguingly, wet and gaseous feedstocks might have a role to play in jump-starting the Bioeconomy of the Future. These resources represent clear and existing problems with immediate cost implications and could therefore present a short-to-medium-term opportunity. For example, municipalities "in extremis" with respect to current waste transportation and tipping fee costs might be well positioned to overcome the traditional risk aversion of their industry. Similarly, producers of high-quality organic waste streams with direct consumer connections, such as microbreweries and wineries, might see a green premium in turning their waste streams into higher value products. Finally, although the possibility of systems of distributed processing of these feedstocks has yet to materialize in practice, that notion could provide useful guidance for R&D strategies in the future.

In summary, this document argues that the combination of feedstocks, markets, and technologies covered represent valuable resources that merit further investigation. Comments are welcomed as part of a conversation that is helping make the integration of wet and gaseous waste feedstocks into the Bioeconomy of the Future happen.

5.6. References

Carey, D. E., Y. Yang, et al. (2016). "Recovery of agricultural nutrients from biorefineries." Bioresource Technology **215**: 186-198.

Davis, R., L. Tao, et al. (2013). Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons. Golden, CO, NREL: 147.

Davis, R. E., D. B. Fishman, et al. (2014). "Integrated Evaluation of Cost, Emissions, and Resource Potential for Algal Biofuels at the National Scale." Environmental Science & Technology **48**(10): 6035-6042.

DOE (2013). Replacing the Whole Barrel to Reduce U.S. Dependence on Oil. Washington, DC, DOE**:** 24.

DOE (2014). "Energy Department Announces $13.4 Million to Develop Advanced Biofuels and Bioproducts " DOE. Accessed August 21, 2016, http://energy.gov/eere/articles/energy-department-announces-134-million-develop-advanced-biofuels-and-bioproducts.

DOE (2015a). Energy Positive Water Resource Recovery Workshop Report. Washington, DC, Department of Energy**:** 58.

DOE (2015b). "Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters Workshop." DOE. Accessed May 27, 2015, http://energy.gov/eere/fuelcells/hydrogen-hydrocarbons-and-bioproduct-precursors-wastewaters-workshop.

DOE (2015c). Waste-to-Energy Workshop Summary. Washington, DC, Department of Energy**:** 53.

DOE (2016a). "2016 SBIR awards." DOE. Accessed August 21, 2016, http://science.energy.gov/sbir/awards/.

DOE (2016b). "FY 2017 DOE SBIR Funding Opportunities." DOE. Accessed August 21, 2016, http://science.energy.gov/~/media/sbir/pdf/TechnicalTopics/FY2017_Phase_1_Release_1_Topics_Combined.pdf.

DOE (2016c). "Project Development for Pilot and Demonstration Scale Manufacturing of Biofuels, Bioproducts and Biopower (PD2B3)." DOE. Accessed August 21, 2016, https://eere-exchange.energy.gov/#FoaId751733aa-d067-485a-aeb6-6927147d81f7.

EPA (2015). "Nutrient Recyling Challenge." EPA. Accessed August 10, 2016, https://www.epa.gov/sites/production/files/2015-11/documents/epa_nutrient_recycling_challenge_factsheet_oct2015_draft_0.pdf.

Jones, S. R. D. Y. Z. C. K. D. A. R. H. D. E. A. S. K. A. T. H. M. (2014). Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading Richland, WA, PNNL**:** 69.

Latimer, R., J. Rohrbacher, et al. (2015). Towards a Renewable Future: Assessing Resource Recovery as a Viable Treatment Alternative. Case Studies of Facilities Employing Extractive Nutrient Recovery Technologies. Arlington, VA, WERF**:** 140.

Marrone, P. A. (2016). Genifuel Hydrothermal Processing Bench-Scale Technology Evaluation Project. Alexandria, VA, WE&RF**:** 202.

Moss, L. H., J. F. Donovan, et al. (2013). Enabling the Future: Advancing Resource Recovery from Biosolids. Arlington, VA, WEF**:** 89.

Nancharaiah, Y. V., S. V. Mohan, et al. (2016). "Recent advances in nutrient removal and recovery in biological and bioelectrochemical systems." Bioresource Technology **215**: 173-185.

Zou, H. M. and Y. Wang (2016). "Phosphorus removal and recovery from domestic wastewater in a novel process of enhanced biological phosphorus removal coupled with crystallization." Bioresource Technology **211**: 87-92.

6. Appendix: Peer Review Meeting Summary (June 22-23, 2016)

Peer Review Meeting: Converting Wet and Gaseous Waste Streams to Biofuels and Bioproducts: Challenges and Opportunities

Date: June 22–23, 2016
Location: National Renewable Energy Laboratory, Golden, CO

BETO invited stakeholders form industry, academia, government, and the national laboratories to review a preliminary draft of this report. This review, hosted by the National Renewable Energy Laboratory in Golden, CO on June 22-23, 2016, presented an opportunity for key stakeholders to provide focused input on future challenges, opportunities, and possible strategies regarding the conversion of wet and gaseous waste streams into drop-in biofuels and bioproducts.

Participants at the review meeting were asked to read and analyze a draft of this report containing early versions of Chapters 1 through 4. This feedback helped identify the correct scope for the report in addition to errors and gaps in the material. Additionally, participant feedback was essential to informing Chapter 5, Wet and Gaseous Feedstocks in the Future Bioeconomy. Suggestions were incorporated into this document when and where appropriate.

Three parallel breakout groups identified important innovations and technological advances, promising technology pathways, and DOE actions to enable wet and gaseous waste utilization in the future bioeconomy. During the course of the review meeting, several key factors and metrics of promising technology pathways emerged that could influence technology research, development, demonstration, and deployment (Table 6-1).

Table 6-1. Participant Identified Influential Factors and Metrics for Resource Recovery RD&D

Key Factors with Potential to Influence Wet and Gaseous Resource Recovery	
Economic	The technology must provide a return on investment.
Environmental	The technology must perform greater than or equal to current waste treatment processes.
Technological	Mature technologies are more likely to benefit from incremental gains. The participants recommended that DOE focus on disruptive new technologies.
Inter-governmental Cooperation	The nature of these resources present opportunities for shared support between different government agencies on single pathways.
Metrics of Promising Technology Pathways	
Socio-economic value: • Product value • Waste disposal cost aversion • Related public health and environmental benefits	Lessened environmental impacts including: • Waste reduction • Excess carbon utilization • GHG emission reduction

Note: Participant recommendations could be biased.

6.1. List of Report Review Participants

Name	Organization	Name	Organization
Aaron Fisher	Water Environment & Reuse Foundation	**Karen Goeders**	Kimberly-Clark Corporation
Anelia Milbrandt	National Renewable Energy Laboratory	**Kent Swisher**	National Renderers Association
Barry Liner	Water Environment Federation	**Leanne Miller**	Water Research Foundation
Brandi Schottel	National Science Foundation	**Marc von Keitz**	ARPA-E (DOE)
Brandon Hoffman	Allegheny Science & Technology	**Mark Elles**	BETO
Brendan Scott	Allegheny Science & Technology	**Mark Fischer**	New Belgium Brewing Company
Chad Miller	Clearas Water Recovery	**Mark Philbrick**	Allegheny Science & Technology
Christopher Koczaja	PHG Energy	**Mark Stoermann**	Newtrient
Cindy Gerk	National Renewable Energy Laboratory	**Meltem Urgun-Demirtas**	Argonne National Laboratory
Corinne Drennan	Pacific Northwest National Laboratory	**Michael Guarnieri**	National Renewable Energy Laboratory
Craig Criddle	Stanford University	**Michael Washer**	Merrick & Company
Cynthia Jenks	Ames Laboratory	**Nancy Andrews**	Brown and Caldwell
Daniel Fishman	BETO	**Nii Ofei Mante**	RTI International
Daniel Inman	National Renewable Energy Laboratory	**Paget Donnelly**	Energetics, Inc.
David Babson	BETO	**Paul Kadota**	Metro Vancouver
Derek Griffin	LanzaTech, Inc.	**Philip Marrone**	Leidos
James McQuarrie	Metro Wastewater Reclamation District	**Philip Pienkos**	National Renewable Energy Laboratory
James Oyler	Genifuel Corporation	**Philipp Stratmann**	Velocys Inc.
James Webb	Smithfield	**Rafael Nieves**	Allegheny Science & Technology
Jason Turgeon	U.S. Environmental Protection Agency	**Rick Skaggs**	Pacific Northwest National Laboratory
Jeff Cumin	GE Power	**Robert Hallenbeck**	Waste Management
Jeff Moeller	Water Environment & Reuse Foundation	**Shawna McQueen**	Energetics, Inc.
Jeremiah Wilson	DOE—EPSA	**Ted Kniesche**	Fulcrum BioEnergy
Joe Zuback	Kore Infrastructure	**Zachary Peterson**	BCS Incorporated
John Holladay	Pacific Northwest National Laboratory	**Zhiyong (Jason) Ren**	University of Colorado
Jonathan Rogers	Energetics, Inc.		

6.2. Innovations and Technological Advances

The participants identified key innovations and technological advances in the short-, mid-, and long-term (the timelines for these categories were changed by group).

Table 6-2. Participant Identified Innovations and Technological Advances

Group 1	Group 2	Group 3
Short-Term (< 7 yrs)	**Short-Term (< 3 yrs)**	**Short-Term (< 3 yrs)**
• AD-related – Biogas clean-up – Enhanced AD – AD tail gas utilization – Improved nutrient recovery and products (post-AD) – Advanced hydrolysis for AD – Codigestion – Improve gas recovery • Membranes • Methane to proteins • HTL skid for small facilities (<1 mgd) • Lower cost heat exchangers • Standardization of PNG • Improve logistics • Feedstock characterization tools	• Enhanced operations at existing facilities • Guidance documents providing economics/options for waste carbon operations (e.g., value of product per pound of carbon) • Feedstock test bed network • Compositional analysis protocol – Convertibility & blending strategies • Regular working group/consortium including end users • Targeted pull into LabCorps • HTL demo	• I.D. contamination in inbound stream • Systems bio models for AD consortia • Separations – Technologies – Social behavior changes • Education initiatives • Wells-to-wheels GHG modeling and standardized methodology • Waste stream forecasting • Incremental changes in existing technologies • Establish pilot location(s) • TEA/LCA w/ industry inputs
Mid-Term (7-15 yrs)	**Mid-Term (3-5 yrs)**	**Mid-Term (3-5 yrs)**
• HTL • Hydrothermal processes • Direct conversion of methane to chemicals (metabolic engineering) • Arrested methanogenesis • Integrated HTL upgrading • Enhanced methanotrophs • Development of Anaerobic Membrane Bioreactors • FT at smaller scales • Improved nutrient recovery	• Methane production from MxCs • Defend & challenge review panels overseen by DOE • Identify typical WTE technology & connection needs (modular solutions) • Biogas (including CO2 and CH4) to value-added chemicals • Upgrading industrial gas streams • Syngas from biogas	• Separations improved – Technology focused • Streams (pulp & paper must remove) – Water, Inorganic, Cellulose • Direct CH4 fermentation at small/intermediate scale • HTL – Biocrude refinement capacity • Process intensification – Integrated processes – Reduced capex
Long-Term (15+ years)	**Long-Term (5+ years)**	**Long-Term (5+ years)**
• Membrane separations to replace high energy separations • Microbial batteries • Thermochemical processing • MxC development – Genetic engineering of MxC's • Integrated systems for watershed management • Interrupted methanogenesis	• SynBio tools	• Wash stream forecasting – Forecast contaminants – Sensing/forward looking • Eco-Park Concept – Process integration to improve economics

6.3. Promising Feedstock-Technology-Market Pathways

In recognition of the interconnected nature of wet and gaseous waste feedstocks, technologies, and markets, participants were asked to suggest viable pathways following the progression of feedstocks to markets. These suggestions, presented in the table below, fell into three categories: short-term (<5 years), mid-term (5-10 years), and long term (10+ years).

Table 6-3. Partner Identified Short-, Mid-, and Long-Term Feedstock-Technology-Market Pathways

Feedstock →	Technology →	Market/ End User
Short-Term (< 5 years)		
Biogas/Stranded Natural Gas	-	Animal Feed and Specialty Chemicals
Co-digestion of FOG, Food Waste, and Biosolids	HTP	Liquid or Gaseous Fuels
Biosolids	AD	Biogas → Electricity (to power the resource recovery facility itself)
FOG	Hydrotreating/hydrocracking	Refinery Upgrading (UOP technology)
Wet Waste	HTL	Biocrude → Refinery Upgrading
Regional Food Waste	Small-scale Solid Fermentation	Higher Value Products
Gases	Biological Processes	Liquid Fuels
Residual Organic Streams from Crop Bioprocessing	-	Fertilizer
Mid-Term (5-10 years)		
Stranded Natural Gas	Alternative Upgrading Processes/Fischer-Tropsch	Refinery Upgrading
Biosolids and Food Waste	HTL	Refinery Upgrading
Biosolids	Arrested Methanogenesis	Bioproducts
Animal Manure Utilization	(Stripper well analogy taking advantage of co-location)	-
Stranded Natural Gas and CO2	Dry Reforming → Syngas → Fischer-Tropsch	Fuel
FOGs	Biochemical Conversion	Value Added Chemicals
Wastewater	Membrane → Direct NH3 Removal	Fertilizer
-	HTL	Biocrude --> Distributed Hydrotreating
Blended Feedstocks	Improved AD	Gas Products
Wet Feedstocks	Drying → Pyrolysis/Gasification	Syngas Upgrading
Long-Term (10+ years)		
Carbon Rich Aqueous Streams	Electrochemical Upgrading	Biocrude → Local Upgrading
All Components of Wastewater (Organic MSW, WW Solids)	AD	Chemicals, Proteins, and Liquid Fuel

6.4. Suggested Actions to Progress Wet and Gaseous Resource Recovery

Participants suggested actions the DOE, other federal agencies, state and local governments, industry, the general public, and other stakeholders could take to progress wet and gaseous feedstock conversions. The recommended actions fell into categories relating to research and development, analysis and knowledge advancement, policy and regulatory, and partnership opportunities.

Table 6-4. Participant Suggested Actions to Progress Wet and Gaseous Resource Recovery

Participant Suggested Actions to Progress Wet and Gaseous Resource Recovery	
Research and Development Actions	
Pilot Testing and Technology Development	Utilize real feed streams
	Accelerate time to pilot
	Test co-digestion
	Increase funding for pilot facilities and long-term demonstrations at small scales
	Identify existing testbed facilities and infrastructures
	Coordinate a testbed network and information resources on these facilities
	Quick test different feedstocks and technologies
	Concept well pad conversions for stranded natural gas
Process Integration	Evaluate and enable refinery acceptance of end products
	Reduce nitrogen and sulfur in biocrude and refinery acceptance.
	Use renewable electricity to feed chemical production
	Define boundary layer conditions and issue funding opportunities for alternative schemes to convert NG to liquids
Resource Collection	Reduce cost of waste collection (accounts for 60-80% of total cost in residential and commercial wastes)
	Logistical and separations – which technologies offer the best approach to utilize the most feedstocks
	Identify feedstock blending opportunities.
	Sensing technologies to shape consumer behavior for waste sorting
Analysis and Knowledge Advancement	
Resource Assessment/ Understanding	Expand “waste” definition
	Sample sludge streams for performance comparisons
	Identify feedstock blending opportunities.
	Develop technology and feedstock inventory
	Develop databases for different feedstock streams (location, quantity, composition)
	Develop better understanding of existing distribution infrastructure
	Consider availability, accessibility, and scalability of resources
Triple Bottom Line Analyses	Evaluate trade-off between different feedstocks and processes
	Comparative analyses of the socio-economic costs of current treatment processes (or lack thereof) vs new technology pathways
Techno-economic analyses	Do not rely on incentives as a sign of longer term economic viability
	Consider the cost of resource collection in analyses
	Consider the increasing valorization of “waste” as value-added pathways are developed

	Determine the maximum value you can recover from particular resources (e.g., wastewater to clean water, organics to methane, etc)
	Evaluate end product market readiness
Policy Drivers and Regulatory Actions	
Drivers	Organics diversion from landfills
	Drive social behavior to encourage increased sorting of waste materials
	Incentives to reduce waste treatment energy consumption and production
	Accounting for socio-economic cost benefits in the price of products from waste resources
Standards	Feedstock quality and characterization
Partnership Opportunities	
Interagency Collaboration	Engage with other federal agencies such as the Advanced Manufacturing Office, Fossil Energy Office, EPA, and more
	Align analyses and assumptions (EPA Office of Solid Waste, USDA, and NREL each offer resource assessments with different assumptions)
International Collaboration	Look for learning opportunities from experiences abroad (e.g., Europe)
Testbed Facilities	Local wastewater treatement plants with resources for piloting available
Public-Private Partnerships	Look for partnership opportunities with environmentally conscious private sector partners (e.g., those with zero-waste landfill targets)