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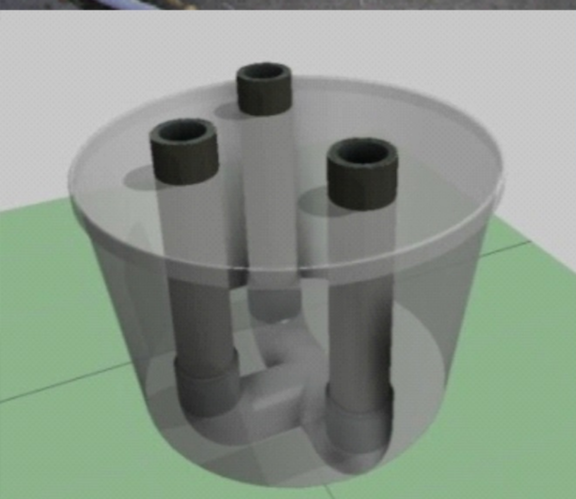

Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters Workshop

Sponsored by the
Bioenergy Technologies Office
Fuel Cell Technologies Office

Prepared by
Energetics Incorporated

January 2016

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Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters Workshop Summary

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Workshop and report sponsored by the

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Office of Energy Efficiency and Renewable Energy
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Preface

This report is based on the proceedings of the Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters (HHBPW) Workshop held by the U.S. Department of Energy's (DOE's) Bioenergy Technologies Office (BETO) and Fuel Cell Technologies Office (FCTO) on March 18–19, 2015. Thirty experts from academia, government, and industry met at the offices of the National Renewable Energy Laboratory in Washington, DC, to share information on biological, biochemical, and other techniques for producing hydrogen and higher hydrocarbons (containing three or more carbon molecules) from wastewaters. The assembled experts evaluated the status of current production techniques or processes and identified potential research, development, and demonstration activities to improve or advance these technologies. The ideas provided here represent a snapshot of the perspectives and ideas presented by the individuals who attended the workshop.

Acknowledgements

Special thanks are extended to Office Directors Jonathan Male of BETO and Sunita Satyapal of FCTO for delivering the opening remarks that inspired and helped frame this workshop.

The workshop organizers also wish to thank the eight panelists who presented informative briefings on the status of relevant technologies and key challenges: Jason He, Virginia Polytechnic Institute and State University; Bruce Logan, Pennsylvania State University; Derek Lovley, University of Massachusetts Amherst; Perry McCarty, Stanford University; Mark Ramirez, DC Water; Jason Ren, University of Colorado Boulder; Art Umble, MWH Americas; and Meltem Urgun-Demirtas, Argonne National Laboratory.

BETO and FCTO gratefully acknowledge the valuable ideas and insights contributed by all of the stakeholders who participated in the HHBPW Workshop. The willingness of these experts to share their time and knowledge has helped to define current and emerging opportunities to accelerate the development and deployment of innovative technologies for sustainably producing a suite of advanced fuels, products, and power from wastewater. These individuals are listed in Appendix A.

Workshop planning and execution were carried out under the guidance of Daniel Fishman, BETO; Mark Philbrick, BETO Fellow; Katie Randolph, FCTO; and Sarah Studer, FCTO Fellow. Aaron Fisher and Amit Talapatra of Energetics Incorporated and Remy Biron of BCS served as note takers for the workshop. This report was prepared by Aaron Fisher and Amit Talapatra, with help from the workshop organizers, others at Energetics Incorporated, and DOE.

Executive Summary

The U.S. Department of Energy's (DOE's) Bioenergy Technologies Office (BETO) and Fuel Cell Technologies Office (FCTO) jointly sponsored a workshop on Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters (HHBPW) on March 17–18, 2015, in Washington, DC. The workshop focused on the use of biological, biochemical, and other techniques to produce hydrogen and higher hydrocarbons (containing three or more carbon molecules) from wastewaters. Experts participating in the workshop discussed relevant research, development, and demonstration (RD&D) activities, including recent breakthroughs, ongoing work, and potential future directions. The workshop specifically focused on microbial fuel cell-based technologies (MxCs) and anaerobic membrane bioreactors (AnMBRs). This summary complements the published results of two related workshops[1] recently hosted by DOE and its sister agencies to gain a better understanding of the wastewater-to-energy space. The ideas presented herein represent a snapshot of the perspectives and concepts offered by the individuals who attended the HHBPW workshop.

Major Themes

Larger themes

- **Innovation challenges**. Financial, regulatory, and other risks tend to limit the pace of innovation in municipal wastewater treatment, and the focused missions of many organizations may impede efforts to implement integrated solutions.
    - *Financial*: To attract funding for further development, technologies must first be proven viable via scaled-up demonstrations—which also require funding.
    - *Regulatory*: Regulated facilities may hesitate to demonstrate scaled-up treatment systems on site due to concern that the water may fail to meet regulatory requirements.
    - *Interagency mission gaps*: Technologies that can provide clean water while also producing fuels may not fall clearly within the purview of a single funding source. For example, separate federal agencies address water treatment and energy production.
- **Municipal utility challenges**. Municipal water utilities are primarily motivated to perform reliably, provide stable rates, and meet discharge permit requirements—rather than turn a profit—so there is little interest in funding RD&D. Potential solutions include dedicated RD&D surcharges, methods to pool resources, and other strategies to incorporate RD&D into budgets.
- **Collaboration, cooperation, and communication.** Mechanisms are needed to encourage and support collaborative interaction among the groups involved in all aspects of water resource recovery—leading to information sharing and cooperation rather than competition. Industry contributions in the form of information, expertise, and financial support are actively encouraged, as are other forms of public–private partnership.
- **Early markets.** Niche applications may be more receptive to early market entry. A variety of tactics can help to identify promising markets:

[1] BETO Waste-to-Energy Workshop Report: www.energy.gov/eere/bioenergy/waste-energy-workshop
NSF-DOE-EPA Energy Positive Water Resource Recovery Workshop Report: www.energy.gov/eere/bioenergy/energy-positive-water-resource-recovery-workshop-report/

  - Look for wastewater profiles that play to the strengths of the respective treatment technologies, such as high salinity in combination with organic contamination (as at oil and gas operations) or the presence of potentially hazardous contaminants, like pharmaceuticals.
  - Find industries that face high disposal costs and fewer regulatory restrictions (e.g., food and beverage producers that discharge wastewaters to municipal systems).
  - Explore the production of high-value bioproduct precursors (such as succinic acid, lactic acid, 1-4 butanediol, and many others), which initially may be more lucrative than drop-in biofuels for light-duty vehicles and could pave the way for higher-volume fuels.
  - Conduct market-driven, applied RD&D to develop technologies with the needed characteristics to succeed commercially (e.g., cost, quality, volume, performance, etc.). Market assessments can identify specific needs, which generally vary by niche market.

Common technical themes

- **Better analysis**. Improved analytic tools are needed for MxCs and AnMBRs. Areas for improvement include modeling of chemical reactions, microbial interactions, and system integration into existing facilities. Related needs include additional data, validation and calibration, and the ability to integrate models for different aspects of each system. Workshop participants also highlighted the need to conduct techno-economic analyses, particularly those focused on market and industry acceptance of these technologies.
- **Demonstrations**. A range of technologies still need to be demonstrated at relevant scales using actual wastewaters. Demonstrations are essential to confirm the scalability, operation, maintenance requirements, and cost-effectiveness of these technology solutions.
- **Novel adsorptive materials.** Incorporating innovative materials, such as granular activated carbon (GAC), into treatment systems could solve some of the issues associated with MxCs and AnMBRs. Use of novel materials merits further investigation.
- **Microbial communities**. As both MxCs and AnMBRs utilize microbial communities, two areas of RD&D would enhance both technologies: (1) increased understanding of microbial activities and interactions and (2) methods to better control and optimize microbial communities.
- **Nutrient recovery**. Both AnMBRs and MxCs offer possibilities for nutrient recovery, which could augment the value of these technologies in wastewater treatment.

Emerging technologies offer significant potential benefits, such as: reduced energy requirements for water treatment, fuel and chemical production, nutrient recovery, and treatment of recalcitrant wastewaters. Addressing the many remaining challenges associated with these technologies will require further RD&D activities, techno-economic studies, and policy analysis.

Contents

Introduction

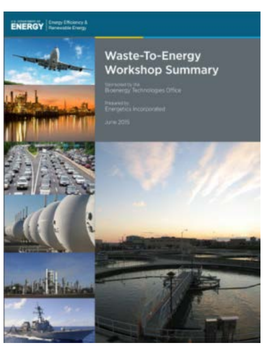
Background

The collection, transportation, and treatment of wastewaters consume 0.8% of U.S. electricity annually,[2] yet viewing wastewater as an encumbrance to be remediated misses its true value. Wastewater contains a number of resources that, if properly handled, can offset this energy demand and yield useful fuels or chemicals. To explore the challenges and opportunities in this field, the Bioenergy Technologies Office (BETO) and the Fuel Cells Technologies Office (FCTO) in the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy convened the Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewater (HHBPW) Workshop.

The HHBPW workshop was held in Washington, DC, on March 18 and 19, 2015. The workshop gathered stakeholders from industry, academia, national laboratories, and government to discuss the issues and potential pathways forward to utilize this waste feedstock. These discussions are helping to define how BETO and FCTO might advance the sustainable utilization of wet waste streams, complement the work of other agencies, and maximize the value of research investment. The workshop focused on two technologies, both of which had been previously identified as promising concepts by the stakeholder community: anaerobic membrane bioreactors (AnMBRs) and microbial electrochemical cells (MxCs).

Workshop Stream

This HHBPW workshop was the second in a series of three workshops on waste and energy issues sponsored by DOE between November 2014 and April 2015. Links to reports from the other two workshops are provided below. DOE is working alongside industry [which is pursuing a number of research efforts[3]] to meet two overarching goals: (1) minimize the amount of energy required to treat organic wastewaters and (2) maximize the energy output from those same waters, whether that energy is produced in the form of combined heat and power (CHP), hydrogen, or higher hydrocarbons (as precursors to biofuels and bioproducts).

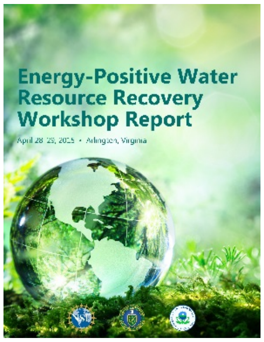


Waste-to-Energy Workshop: November 5–6, 2014

Hosted by BETO, this workshop focused on anaerobic digestion, 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 discussed in this report.

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

[2] Electric Power Research Institute. *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries*, Pabi, Amaranth, Goldstein, and Reekie (2013). www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002001433.
[3] NACWA, Water Environment Federation, and Water Environment Research Foundation. *Water Resource Utility of the Future 2015 Annual Report: A Blueprint for Action* (2015). http://www.nacwa.org/images/stories/public/2015-07-10wruotf-exs.pdf.



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

The National Science Foundation (NSF), DOE, and the U.S. Environmental Protection Agency (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 www.energy.gov/eere/bioenergy/energy-positive-water-resource-recovery-workshop-report/.

This present report summarizes the results of the HHBPW workshop as a resource for BETO, FCTO, and members of the broader stakeholder community in evaluating the research, development, demonstration, and market transformation efforts needed to achieve affordable, scalable, and sustainable production of hydrogen, hydrocarbons, and other bioproduct precursors from wastewater. This report is not designed to cover all relevant issues; it simply summarizes the innovative ideas generated by those in attendance at the workshop. The report presents these results in the two technical areas discussed during the workshop—AnMBRs and MxCs—which are briefly described below. In separate sections, the report then provides summaries of the workshop presentations, a technical discussion of the workshop findings, and closing remarks. Appendices provide a list of workshop attendees, the meeting agenda, and acronyms used in this report.

Anaerobic Membrane Bioreactors (AnMBRs)

Anaerobic digestion (AD) typically requires a large tank in which mixed populations of microbes digest biomass material (e.g., sludge, manure, or agricultural residue). This process generates biogas, which is a mixture consisting predominantly of methane and carbon dioxide, with a few other impurities (e.g., siloxanes). In the operation of AD, the limiting factor is how quickly the microbes can digest the biomass to yield biogas; the longer the biomass stays in the reactor (solid retention time [SRT]), the more biogas can be produced. At some point, however, additional time yields diminishing returns. The biomass must then be replaced and the process restarted. The leftover biomass, referred to as biosolids, is often applied to farmland as fertilizer or sent to landfills. Operating as a batch process, AD throughput is limited by reactor volume, with larger reactors enabling greater throughput.

AnMBRs are a special class of AD that addresses the limitation of traditional AD, i.e., a yield directly proportional to SRT. In AnMBRs, membranes retain the solids in the reactor yet permit water to flow out. These membranes allow the length of time the water is in the reactor, known as the hydraulic retention time (HRT), to be distinct from the SRT, enabling continuous operation. As a result, throughput and yield can increase without a proportional increase in the size of the reactor. Produced biogas is largely collected in the headspace of the reactor. Some biogas though does remain dissolved in the effluent stream; this is an active area of research. A variation of the AnMBR, called the anaerobic fluidized membrane bioreactor (AnFMBR), circulates fluidized particles in the reactor. These particles give the microbes a surface on which to grow and assist in cleaning the membrane. AnMBRs are being piloted at a few locations around the world, including one under construction at Stanford University (see Perry McCarty's presentation in the next section).

Microbial Electrochemical Cells (MxCs)

MxCs integrate microbiology, electrochemistry, materials science, and engineering to generate products from biodegradable materials. The term MxC corresponds to a broad class of technologies that can produce a range of products (see Table 1). This broad functionality permits these systems to play a wide range of key roles, independent of or in conjunction with another technology.

Table 1. Types of MxCs

Type of MxC	Primary Products	
Microbial fuel cell (MFC)	• Electricity	
Microbial electrolysis cell (MEC)	• Hydrogen • Hydrogen peroxide	• Other inorganic molecules
Microbial electrosynthesis (MES)	• Methane • Acetic acid	• Ethanol • Organic molecules
Microbial desalination cell (MDC)	• Desalinated water	

At their most basic level, electrochemical cells are set up with an anode and cathode in an electrolyte solution. The electrolyte solution permits the diffusion only of select ions (often protons), while electrons must go through external wiring that connects the two electrodes. A difference in voltage (either applied or generated) between the anode and cathode drives the movement of ions and electrons and, ultimately, the electrochemical reaction.

The key difference between microbial electrochemical cells and traditional electrochemical cells is the use of microorganisms on the anode, cathode, or both to drive production of the cell's output (e.g., microbes on the anode help to generate electrical current in a microbial fuel cell (MFC)). This use of microbial cultures enables MxCs to use a wide range of inputs and function in the presence of impurities that traditional electrochemical cells could not necessarily tolerate.[4]

Despite these advantages, MxCs have not yet achieved widespread deployment, and challenges remain in the areas of wastewater treatment, energy production, and cost. The two major challenges of all MxCs are (1) ensuring good contact between the electrode and the microbe and (2) ensuring that the microbes work at an industrially relevant rate on a real waste stream. A number of research/pilot efforts have begun to scale up promising technology solutions for some of these issues, though the projects remain smaller than commercial scale (see presentations by Jason Ren and Bruce Logan in the next section).

[4] Logan, B.E. 2008. Microbial Fuel Cells. John Wiley & Sons, New York.

Workshop Presentations

Presentations by diverse experts launched lively discussions at the HHBPW workshop. These presentations are summarized below in four categories: Introductory, Anaerobic Technology, Microbial Electrochemical Cells, and Advanced Facility Perspective. The supporting slides are available on the workshop website at http://energy.gov/eere/fuelcells/hydrogen-hydrocarbons-and-bioproduct-precursors-wastewaters-workshop.

Introductory Presentations

Overview of the Fuel Cell Technologies Office (FCTO)

Dr. Sunita Satyapal, Director, Fuel Cell Technologies Office, U.S. Department of Energy

The Sustainable Transportation Sector of the DOE Office of Energy Efficiency and Renewable Energy supports sustainable transportation technologies such as hydrogen (H_2) and fuel cells, hybrid vehicles, and bioenergy. These efforts support achievement of the national energy goals identified in the *President's Climate Action Plan*, including the 50% reduction in net oil imports by 2020 and 80% reduction in greenhouse gas emissions (GHGs) by 2050. As a propulsion technology, fuel cells offer a strong opportunity to reach these goals, as they can reduce well-to-wheels carbon dioxide (CO_2) emissions by 90%, depending on how the hydrogen fuel is produced.[5]

While internal combustion engines have a conversion efficiency of 15%–40%, fuel cells have a potential conversion efficiency of more than 60% (chemical energy to electricity). Fuel cells can produce more than just electricity. FCTO recently demonstrated the world's first trigeneration system at Orange County's Fountain Valley Wastewater Reclamation Plant. This innovative system used biogas from the wastewater treatment facility in a high-temperature fuel cell to co-produce hydrogen, heat, and power.

The fuel cell industry has grown about 30% annually since 2010. While much of this growth has been in the stationary power market, the transportation sector is also starting to take off. In 2013 FCTO joined leading automakers and other stakeholders to launch H2USA, a public-private partnership to address the need for hydrogen production and distribution infrastructure for fuel cell electric vehicle refueling. In the same year, the Office held a workshop on biological hydrogen production that identified research and development (R&D) needs to overcome MxC barriers from all feedstocks, looking beyond natural gas as a source of hydrogen.[6]

"Wet" Waste-to-Energy in the Bioenergy Technologies Office (BETO)

Dr. Jonathan Male, Director, Bioenergy Technologies Office, U.S. Department of Energy

BETO aims to validate at least one technology pathway that will deliver hydrocarbon biofuel at $3 per gge (gallon of gasoline equivalent)[7] by 2017—with at least a 50% reduction in GHGs. In support of this goal, the Office is working throughout the supply chain—from feedstock to market—to enable the cost-competitive production of advanced biofuels and bioproducts.

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[5] Argonne National Laboratory. *Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles,* Elgowainy, Burnham, Want, Molburg, and Rousseau, (2009) www.transportation.anl.gov/pdfs/TA/559.pdf
[6] The full workshop report is available at http://energy.gov/eere/fuelcells/biological-hydrogen-production-workshop.
[7] Mature modeled price at pilot scale

Recently, the Office has expanded its scope beyond terrestrial feedstocks to include wet waste feedstocks. This category includes underutilized biomass in municipal sludge, biosolids, animal manure, industrial organic wastewaters, and the non-recyclable organic fraction of municipal solid waste. Recovery of the energy contained in WRRFs; animal manure; and industrial, institutional, and commercial sources such as biogas could alone yield 274 trillion British thermal units (TBtu) in 2014, equivalent to nearly 2% of U.S. motor gasoline consumption each year.[8] This effort would complement the work on cellulosic feedstocks that is already well underway in the Office.

Several high-profile projects highlight BETO's expanded feedstock focus. A recent funding opportunity announcement (FOA) for biochemical upgrading has resulted in the selection of two biogas projects totaling $5 million: (1) Natureworks is researching the fermentation of biogas to lactic acid, and (2) the National Renewable Energy Laboratory is working to convert biogas into muconic acid and then to bioproducts. BETO has also funded several pioneer or commercial-scale facilities: INEOS converts wood and vegetative waste to cellulosic ethanol, Fulcrum Bioenergy converts municipal solid waste to drop-in biofuels, and Red Rock Biofuels converts woody biomass to drop-in biofuels. In addition, the Office has been working with the National Alliance for Advanced Biofuels and Bioproducts Consortium and the Pacific Northwest National Laboratory on whole-algae hydrothermal liquefaction, which is projected to produce hydrocarbon fuel from a biomass slurry at $4.49 per gge by 2022.[9]

This HHBPW workshop is part of a broader, more concerted effort on the topic and will help to inform Office policy and direction.

Anaerobic Technology

Anaerobic MBR: Challenges and Opportunities

Dr. Art Umble, MWH Americas

AnMBRs hold considerable promise in municipal wastewater treatment, yet the technical challenges remain significant. Dr. Umble noted that only limited development has been achieved since the early 2000s, particularly with regard to municipal applications with lower chemical oxygen demand (COD).

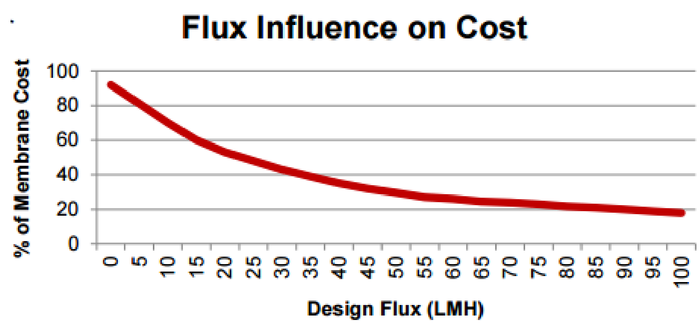

Figure 1. Flux influence on AnMBR cost (a sustainable flux rate is <15 liters/m^2/hour [LMH])

Key challenges for the deployment of AnMBRs in municipal wastewater treatment include problems with membrane fouling, methanogen sensitivity, ambient temperature operation, and low flux (see Figure 1). Membranes are the biggest challenge, accounting for 72% of capital costs and requiring 47% of operational costs for scouring. Potential solutions to address membrane fouling include biogas sparging; backflushing; periodic membrane relaxation; and the addition of powdered activated carbon (PAC), granulated activated carbon (GAC), or some combination of the two. AnMBRs remain attractive for their ability to remove more than

[8] Saur, G. and Milbrandt, A. *Renewable Hydrogen Potential from Biogas in the United States*. National Renewable Energy Laboratory. (2014).

[9] Pacific Northwest National Laboratory. *Process Design and Economics for Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading.* (2014). http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf

85% of COD and better than 99% of total suspended solids (TSS). Continuing research will seek to reduce membrane fouling with low-strength wastewaters, reduce energy consumption, incorporate backend nutrient removal systems, and better understand the relationships among HRT, SRT, performance, and fouling.

Anaerobic Fluidized Bed Membrane Bioreactor (AnFMBR) for Energy-Efficient Wastewater Reuse

Dr. Perry McCarty, Stanford University

The ReNUWIt NSF Engineering Research Center at Stanford University is "Re-inventing the Nation's Urban Water Infrastructure." The research focuses on compact water recycling systems, distributed treatment system planning, energy-positive wastewater treatment, open water unit process wetlands, and ecosystem rehabilitation. In pursuit of these goals, the team is currently installing a three-unit AnFMBR system at the Codiga Resource Recovery Center at Stanford University.

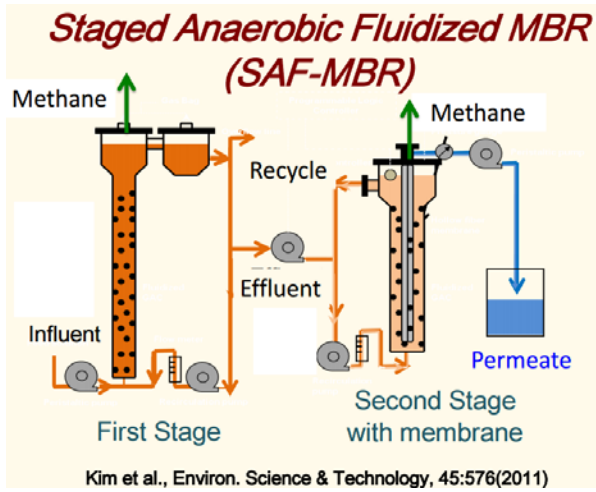

Figure 2. Staged AnFMBR

One research focus is to move toward 100% anaerobic treatment. In conjunction with researchers at Inha University in South Korea, ReNUWIt researchers piloted a staged AnFMBR (see Figure 2). This system is predicated on the use of GAC to reduce membrane fouling through abrasion. Once the system reached steady state, assisted by warm summer temperatures, the facility met biochemical oxygen demand (BOD) emission guidelines, reduced the production of biosolids, and even reduced the concentration of pharmaceuticals in the waste stream (~96% reduction of measured species vs. 76% for traditional aerobic treatment).

Dr. McCarty noted that the Monterey County Water Recycling Project uses traditional anaerobic digestion and leaves nitrogen in the effluent stream for use as fertilized irrigation water. By switching to the AnFMBR technology, that facility would significantly reduce its physical footprint to accommodate critical space constraints on agricultural land.

Enhanced Anaerobic Digestion and Hydrocarbon Precursor Production

Meltem Urgun-Demirtas, Argonne National Laboratory

Argonne National Laboratory is working to transform negative-value biosolids into high-energy density, fungible, hydrocarbon precursors. One process the lab is currently pursuing generates biogas containing greater than 90% CH_4 while sequestering CO_2 and removing H_2S. This biogas effluent stream would require minimal, if any, gas treatment to qualify for D3 (cellulosic biofuel) renewable identification numbers (RINs) under the Renewable Fuels Standard. The team is able to achieve these metrics by adding a layer of biochar on top of the reactor to filter out impurities as the biogas is produced (see Figure 3). The biochar itself is also enriched in the process. To validate the technology, the team plans to deploy a field-scale demonstration unit by 2017.

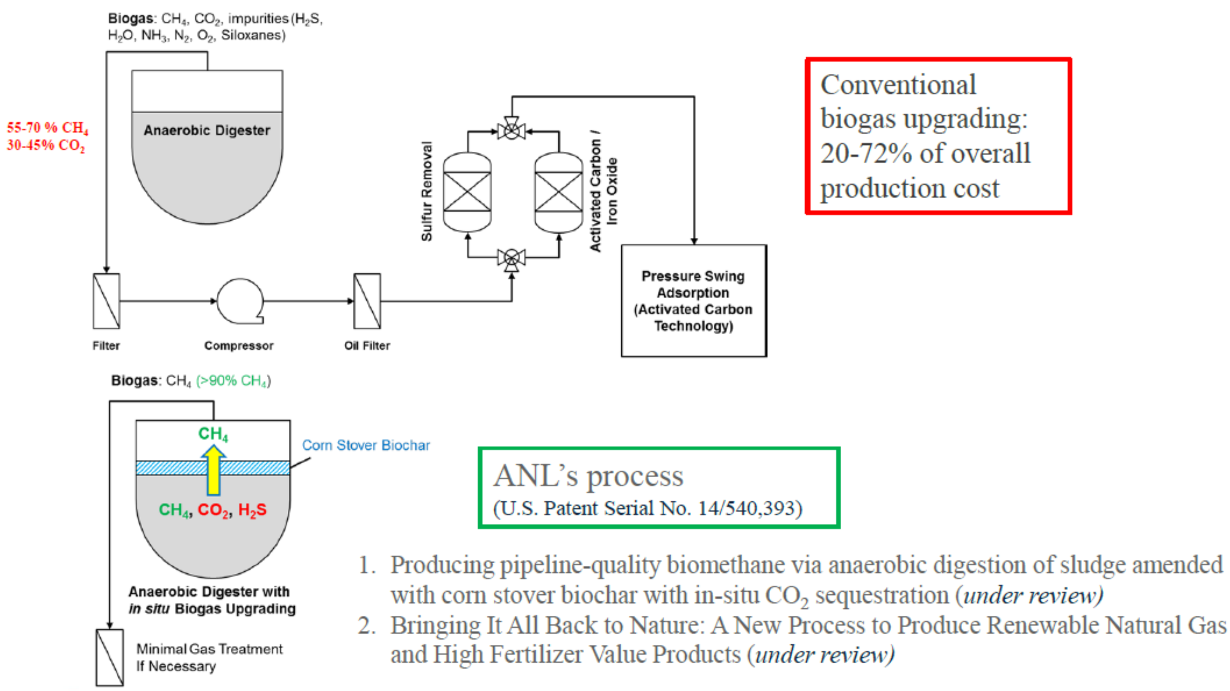

Figure 3. Schematic of Argonne's AD technology that uses biochar as a membrane

The ANL team is also looking at the conversion of biosolids to hydrocarbon precursors. Biosolids and other sludge streams can be treated in a hydrolytic/acidic digester to release sugars. Oleaginous microbes can digest these sugars to produce C_{12}-C_{24} hydrocarbons, which are valuable as diesel or jet fuel alternatives (see Figure 4). Preliminary work has shown promise, and work is beginning on digestate permeate as the feedstock.

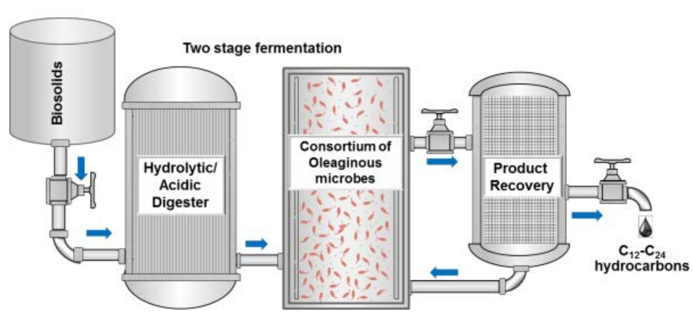

Figure 4. Schematic of Argonne's process that uses oleaginous microbes to produce higher hydrocarbons

Microbial Electrochemical Cells

Microbial Electrochemical Technology (MxCs): Challenges and Opportunities

Dr. Jason Ren, University of Colorado Boulder

MxC systems that use wastewater as a feedstock are challenged by the high degree of variability intrinsic to the stream. System design and operation must account for this feedstock variability or it will adversely impact performance. Researchers at the University of Colorado Boulder reconfigured the reactor to be spirally wound (Figure 5). The advantages of a spiral-wound MxC include: a compact and modular design to support different scales, higher matched surface area for electrodes, less leakage relative to cubic and tubular designs, and easy adaptability into current manufacturing infrastructure. Ongoing pilot testing is evaluating the commercial prospects of this technology for treating oil/gas wastewater; preliminary laboratory testing shows a 230% increase in total power with a 20-minute hydraulic retention time.

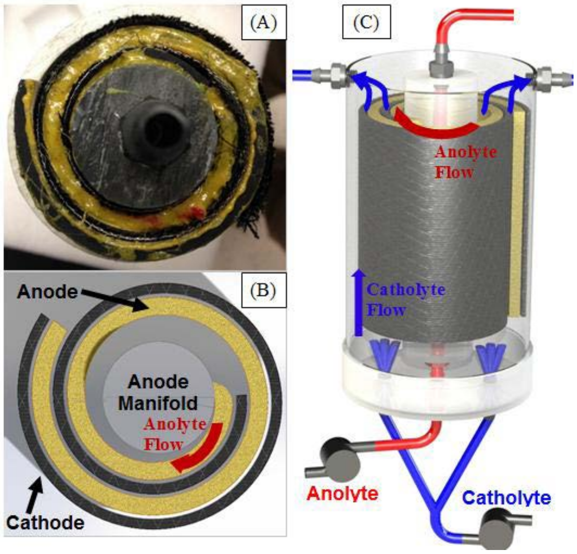

Figure 5. Spiral-wound MxC

Microbial Fuel Cell Technologies—MxCs: Can They Scale?

Dr. Bruce Logan, Pennsylvania State University

Dr. Logan's team at Penn State University is working to scale up MFCs and MECs by reducing the cost of the electrodes. The team has reduced system electrode costs from $2,200/m^2 to $36/m^2 by using high surface area/low-volume graphitic brush anodes, removing platinum catalyst from the cathode, and replacing binder with lower-cost polyvinylidene fluoride. These steps have led to a 1,000-liter MEC reactor capable of producing 16 times more energy than the amount of electricity input.

The difficulty in implementing MxCs to treat wastewater is that COD is not reduced sufficiently to meet discharge quality standards. Current density drops rapidly at low CODs, limiting the effectiveness of MxCs below ~100 mg/L. This shortcoming presents a great opportunity to pair this technology with AnMBRs. Preliminary work has shown success, and ongoing scale-up work is continuing on a single solution that combines the two technologies.

Electrobiocommodities from Carbon Dioxide: Enhancing Microbial Electrosynthesis with Synthetic Electromicrobiology and System Design

Dr. Derek Lovley, University of Massachusetts Amherst

Dr. Lovley's research has focused on upgrading CO_2 to higher-value organic molecules through electrosynthesis. His team has extensively studied direct interspecies electron transfer (DIET), which allows an organism to accept electrons from the external environment to promote organic synthesis reactions. The team's research into *Methanosaeata*, a prodigious methanogen, was particularly enlightening. Dr. Lovley's team overturned the conventional belief that acetate is the only appropriate substrate for methane production by identifying an existing CO_2 reduction pathway in the *Methanosaeata* genome. This pathway was able to accept electrons from co-cultured *Geobacter* to promote methanogenesis.

Dr. Lovely also detailed his work on artificial photosynthesis using the electrons generated by photovoltaic solar cells. The electrons are conducted to microbes that take in CO_2 and water to produce organics and O_2 (see Figure 6). Compared to biological photosynthesis, artificial photosynthesis is 100-fold more efficient in solar energy capture; directly produces fuel, avoiding the need for further processing; and does not require arable land.

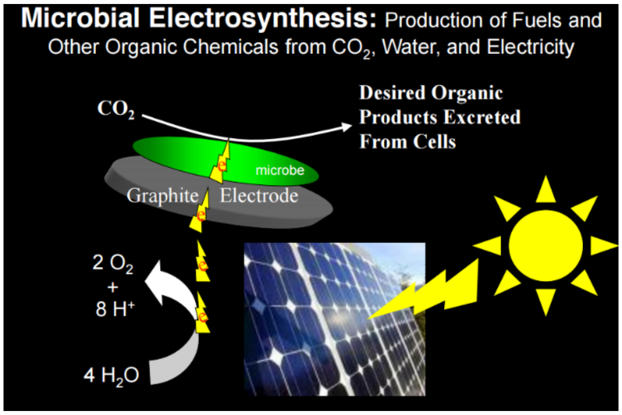

Figure 6. Microbial electrosynthesis using energy generated by photovoltaic cells

Ongoing work by the Lovley group focuses on the organism *Clostridium Ijungdahlii* as the CO_2-fixing microbe. Gene knockout work on this acetogen has limited acetate and ethanol production and increased butanol and acetone production. Research has also looked into modifying *C. Ijungdahlii* strains to enable formation of thick, conductive biofilms that could be grown on electrodes. This work shows promise for the use of microbial electrosynthesis to convert the carbon dioxide produced during anaerobic digestion (or from other sources) into high-value organic commodities.

Synergy between Membranes and Microbial Fuel Cells

Dr. Jason He, Virginia Polytechnic Institute and State University

Dr. He has explored the synergy between membranes and MxCs, specifically the ability to separate biomass to produce high-quality wastewater. Membranes can be internal and external to the MxC. Placing the membrane at the anode in a fluidized GAC system increased the amount of electricity generated. When the membrane was placed at the cathode, the system showed good ammonia removal, but aeration energy requirements increased. Though efforts to look at larger external membranes have been limited by poor temperature control, the system did demonstrate marked reductions in total COD (92.5%), soluble COD (86.2%), and total suspended solids (TSS) (99.6%). Dr. He's team also paired MxCs with forward osmosis (FO) and pressure-retarded osmosis (PRO)—pairing an energy producing process with an energy consuming process (see Figure 7). This technology pairing would either generate clean water or H_2, depending on the system set-up. Overall, the research has shown promising synergy between the membranes and MxCs.

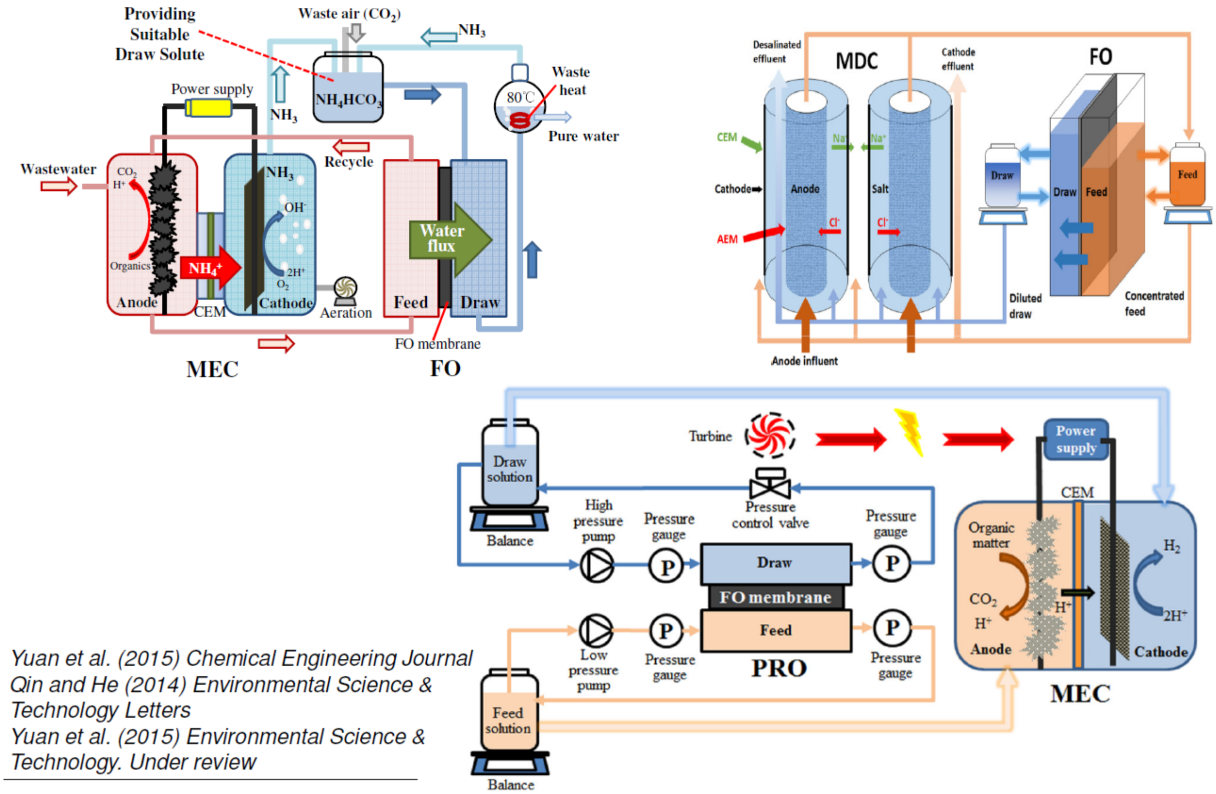

Figure 7. Schematics of MxCs used in conjunction with membrane-based technologies

Advanced Facility Perspective

Report from the Field: Nutrient and Energy Recovery at DC Water

Mark Ramirez, DC Water

The Blue Plains facility in Washington, DC, is the largest advanced recovery system in the world, processing 370 million gallons per day. Blue Plains is also the first facility in the country to deploy the Cambi thermal hydrolysis pretreatment process, which improves the operation of downstream anaerobic digesters. Mr. Ramirez highlighted the future of the water treatment industry from the perspective of the operators, focusing on three issues of preeminent importance for a WRRF: clean water, energy and nutrients.

In total, the Blue Plains plant consumes 27–30 MW of power (see Figure 8), with 34% going to aeration (20% to nitrification and 14% to secondary). To reduce its $1.1 to $1.4 million monthly power bill, Blue Plains installed anaerobic digesters to generate biogas and generate 10 MW of electricity in turbine generators.[10] The facility also plans to install as much as 11 MW of solar panels and is considering additional turbines, depending on biogas production. In addition, the plant is exploring the use of

[10] DC Water. *Blue Plains Advanced Wastewater Treatment Plant.* Accessed December 10, 2015. https://www.dcwater.com/news/publications/Blue_Plains_Plant_brochure.pdf

anaerobic ammonia oxidation (anammox) to reduce the energy needs of aeration. Beyond the ideas that DC Water is actively pursuing in its capital improvement plan, its long-term vision includes MxCs and the sustainable use of food nutrients and energy resources. DC Water actively funds some of this work through rebated biosolids contracts, with funds specifically earmarked for research.

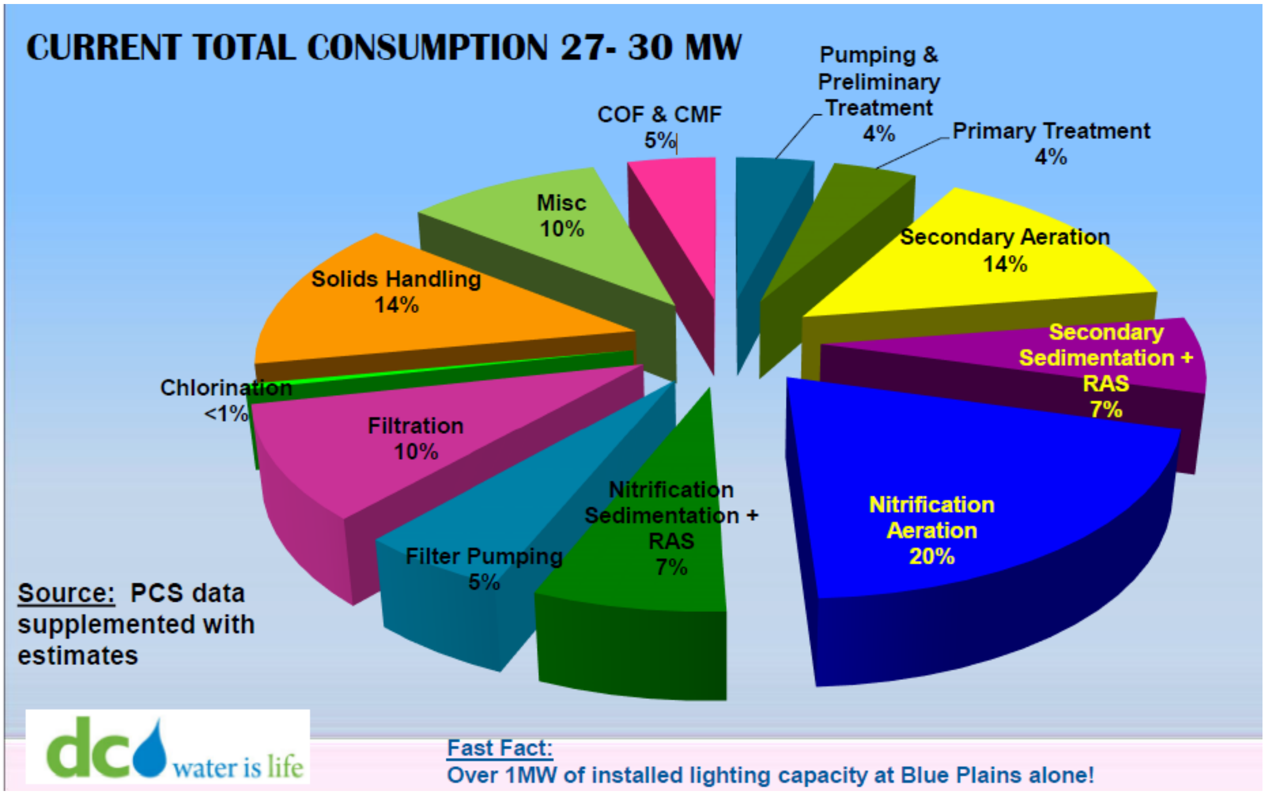

Figure 8. Electricity consumption at Blue Plains

Technical Discussion

In separate breakout sessions, workshop participants were guided through a series of facilitated discussions that captured the diverse opinions of stakeholders. To enable a deeper level of technical discussion on the first day, participants could join either a session focused on anaerobic membrane bioreactors or one on microbial electrochemical cells. For the second day of discussions, two parallel sessions focused on what is would take to deploy wastewater energy recovery technologies.

Anaerobic Membrane Bioreactors

AnMBRs potentially offer a dramatic improvement over existing AD systems by separating HRT from SRT. The technology is also being driven by distributed resource availability and pricing, a host of policy factors, and the widespread push toward sustainability. Participant discussions on the technical barriers often centered on the membranes—as they are the key enabling technology and the main difference between AnMBRs and traditional ADs. Participants also identified additional areas of needed research, including improved methane recovery and means to assure effluent quality.

Participants identified the commercialization of AnMBR technology as a realistic prospect for the near future, given continued work on the underlying technology. However, obstacles remain in the areas of financing, regulation, and infrastructure. Participants also discussed overcoming inertia in the industry to deploy new technologies, the focus on treatment instead of resource recovery, and the lack of broad public support. Addressing these obstacles will require a sustained effort to demonstrate the clear value of AnMBR technology. The group underscored the critical need for support from both industry and the government to fund these efforts and demonstrate the technology.

Characteristics

Participants identified the key technical and non-technical characteristics of AnMBR systems that will ultimately determine the commercial potential of the technology. As shown in Table 2, the ideas fell into a range of categories. Wastewater characteristics, particularly nitrogen and phosphorous concentrations, are critical factors in the use of AnMBRs. To advance the technology, the group emphasized the importance of clarifying specific characteristics of the bioreactor, the membrane, and the biofilms that form on them. The participants also identified characteristics of output streams, including gas productivity and collection, produced and remaining solids, and the permeate. From a broader system perspective, financial and energy metrics were identified as key characteristics to measure, given their direct relevance to the end customer. The ability to monitor and improve upon these identified characteristics will enable the deployment of AnMBRs over other wastewater treatment technologies.

Table 2. Participant-identified AnMBR characteristics

Category	Identified Characteristics
Wastewater Characteristics	• Nitrogen and phosphorous o Removal/recovery o Fate of nitrogen and phosphorous after the process o Effect of nitrogen and phosphorous on organisms • Variability load, temperature, flow, etc. • Robustness of membrane operations for varying wastewater composition or flow rate • Temperature • Contaminants of emerging concern removal

Category	Identified Characteristics
	• pH • COD/BOD • Total Suspended Solids: Volatile and non-volatile • Sulfur
Bioreactor	• Choice of anaerobic microorganisms o Performance o Resilience • Temperature • Solids retention time • Hydraulic retention time • Organic loading rate • Hydrolysis • Scale-up (technical) • Reactor footprint • Treatment efficiency • Shear • Heating • Gas collection • Organism support medium o GAC o Sand o Organic beads
Membrane	• Fouling • Fouling control o Energy intensity o Effectiveness of cleaning methods ▪ Sparging ▪ GAC ▪ Chemical cleaning ▪ Scouring • Transmembrane pressure o Effect of inorganic salts • Operation • Clogging • Type/material • Flux • Cost • Membrane configuration: external versus submerged • Membrane location (internal or separate external reactor) • Membrane cost
Biofilms	• Role of biofilm/fouling layer during treatment o SRT research shows a good portion of the COD removal occurs in biofilm o Ability to design or model the biofilm? • Soluble COD removal mechanisms
Produced and Remaining Solids	• Material recovery from the sludge • Struvite • Biosolids yield

Category	Identified Characteristics
Gas Productivity and Collection	• Thermal value of the produced gas • Possible H_2 production • CH_4 solubility • Dissolved CH_4 that limits CH_4 recovery • Methanogenic activity • Maximum theoretical CH_4 per COD/BOD • Percent methane in biogas • Sulfate interference
Permeate	• Quantity of dissolved methane • Effluent quality • Low BOD in permeate • Effluent/permeate characteristics (sulfide, CH_4, NH_4^+, PO_4^{3-}) • Follow-on treatment of permeate • Downstream processes • Algae cultivation • Fertigation
Energy	• Efficiency of the microturbines (kWh_e/kWh_{th}) • Energy production • Energy consumption
Financial	• CapEx, as a function of organic loading rate • Scale-up (financial) • Cost • OPEX (kWh/m^3 treated) energy consumption of membrane/recirculate (including TMP, cleaning, fouling)

Challenges

As shown in Table 3, specific challenges to advancing the technology and facilitating commercial deployment fall into four broad categories: 1) membranes/fouling, 2) nutrient recovery, 3) effluent, and 4) deployment/scale-up. Identification of these challenges helped to frame the follow-on discussion related to activities and work needed to commercialize AnMBRs.

Table 3. Participant-identified challenges to advancing AnMBR technology and facilitating commercial deployment

Category	Challenges
Membranes/ Fouling	• Develop new fouling control strategies • Measure and control biofilm contribution • Produce membrane materials that are resistant to fouling • Reduce membrane total operational and energy costs • Better concentrate organic nutrients • Improve reaction kinetics and modeling of biofilm formation • Improve fouling control and consistent operation • Connect the definition of solubility with membrane size • Control flow to enable optimal membrane operation at maximum flux • Restore flux after cleaning • Enable higher flux rates with lower fouling: improve understanding of the relationships among HRT, SRT, and performance

Category	Challenges
Nutrient Recovery	• Increase productivity: reduce retention time to increase throughput • Optimize microbiology within the process and between microbial communities • Develop appropriate and efficient N&P removal and/or recovery • Increase hydrolysis rates • Remove or control sulfite
Effluent	• Develop energy-neutral methane recovery to close the energy gap • Reduce cost and energy consumption for dissolved methane recovery • Study the systems to determine the cause of methane solvation/desolvation • Improve permeate quality to meet BOD effluent targets/requirements o Fit-for-purpose o N&P in the permeate—sometimes wanted/sometimes not
Deployment/ Scale-Up	• Simplify—move toward minimal operations and maintenance (O&M) costs • Increase understanding and acceptance by industry • Increase AnMBR use with other technologies o Find best fit for this technology in a WRRF • Identify the sweet spot for the scale of this technology o Cost relationship is closer to (but not totally) linear, relative to traditional AD • Utilizing low-concentration wastewater • Utilizing low-temperature treatment • Find waste heat and improve turbine efficiency • Residential-scale AnMBR

Potential Solutions

The participants outlined solutions they envision as possible within the next 20 years, as summarized in Table 4. Membranes occupied a central role in the discussions, meriting two separate yet related categories: “Improved Membrane Economics” and “Managing Membrane Fouling.” Three of the identified categories significantly overlap with existing efforts on traditional AD; these are “Nutrient Recovery,” “Enhanced Methane Recovery,” and “Optimized Microbial Communities.” Advances in these topics will pay dividends across the full value chain, from research through deployed AD systems. Looking ahead to deployment, participants identified the broad categories of “Increasing Throughput” and “Identifying Appropriate Production Scale” as potential solutions to the previously identified challenges.

Table 4. Participant-identified AnMBR solutions envisioned as possible in the next 20 years

Category	Potential Solution
Improved Membrane Economics	• Improve chemical resistance • Dynamic membranes (technology in which a layer forms that has lower risk of fouling and is easier to clean) • Optimize flux versus cleaning frequency • Devise novel materials and set-ups: ceramic membranes, hollow fiber vs. flat sheet membranes, self-healing membranes, nanomaterial coatings, cloth media, hybrid organometallics, or dynamic membranes • Improve membrane longevity o Standardized (e.g., ASTM) method for characterization o Predictive metrics • Improve structural strength • Reduce membrane total costs • Enhance membrane lifetimes o Effective use of pretreatment • Connect definition of solubility with membrane size • Develop bio-membrane reactor so that they have the correct flux and assist with wastewater treatment o Biomimicry
Managing Membrane Fouling	• Seek outside perspectives on fouling o Collaborate with membrane manufacturers not familiar with AnMBR issues • Optimize fluidized bed reactor o Particle density o Granular activated carbon o Powdered activated carbon • Maintain flux and restore flux after cleaning • Develop membranes for targeted biofilm formation • Embrace fouling—design the membrane for the fouled state o Operation at a fouled state o Membrane fouling control with low energy • Facilitate control and consistent operation • Increase membrane flux • Develop cleaning robots • Measure biofilm contribution • Develop hydrophilic surfaces to improve cleaning capabilities • Develop mechanical membrane modules (ones that shake, vibrate, or spin)
Nutrient Recovery	• Develop appropriate and efficient nitrogen and phosphorous removal and/or recovery—use nitrogen-laden water for irrigation • Integrate anammox • Improve nutrient recovery/control in effluent • Explore ammonia-selective ion exchange • Develop an algae MBR • Improve effectiveness at low concentration • Establish BOD effluent targets/requirements • Devise technology suitable for fit-for-purpose water • Control sulfide

Category	Potential Solution
Enhanced Methane Recovery	• Develop methane recovery to close energy gap • Reduce costs and energy consumption for dissolved methane usage • Increase understanding of methane oversaturation • Develop gas-permeable membrane • Improve vacuum recovery of methane o Increase recovery by coupling with turbulence • Evaluate viability of mechanical systems for gas transfer from the liquid-phase • Beneficial use of dissolved methane • Employ methanotrophs for dissolved methane, yielding higher hydrocarbons • Address fugitive emissions
Optimizing Microbial Communities	• Improve reaction kinetics and modelling—biofilm formation • Improve model calibration with real data • Increase understanding of methanogen growth under varying conditions • Enhance simulation of syntrophic organisms • Identify primary colonizers—which bacteria attach first? • Catalog high-rate hydrolysis organisms • Improve modeling of hydrolysis • Study bioaugmentation of species • Explore bioengineering systems • Devise bio-inspired treatment/hydrolysis • Examine microbial community structure and dynamics

Increasing Throughput	• Improve performance over competing technologies
	• Increase productivity; decrease retention time
	• Simplify process (i.e., move toward minimal O&M)
	• Increase hydrolysis rates
	• Devise selective removal of suspended solids
	• Improve pretreatment
	  o Preheat wastewater to increase hydrolysis—utilizing solar?
	  o Concentrate COD in preprocessing (e.g., forward osmosis)
	  o Use enzymatic pretreatment
	  o Avoid need for pretreatment
	• Adjust process conditions: temperature, flow variability (potentially not under plant's control)
	• Increase SRT with external storage
	• Explore co-digestion
	• Use reduced-lignin toilet paper
	• Reduce HRT
	• Understand HRT-SRT-performance

Identifying Appropriate Production Scale	• Examine small scale; residential • Study distributed treatment of high-strength streams • Examine large scales; large industrial units • Create a system that is cost effective at any and all scales • Integrate/use with other technologies • Improve acceptability to potential customers

Microbial Electrochemical Cells

MxCs present opportunities to add value to wastewater treatment processes by recovering energy from waste streams. Depending on the microbes used and the reactor configuration, MxCs can produce a wide range of energy products, including electricity, hydrogen, and higher hydrocarbons. MxCs also accommodate modular design, which increases system flexibility in scaling to different plant sizes.

Participants identified barriers related to cost, manufacturing, and demonstration of the technology in plant-scale processes. They also identified some characteristics of MxC systems that would expand their applicability to diverse waste streams. Finally, they highlighted energy products that could meet market needs while reducing a facility's carbon footprint.

Characteristics

Participants discussed key technical and non-technical characteristics that will determine the success of MxC systems, as summarized in Table 5. A major point of discussion was the need to standardize the figures of merit for MxC systems throughout the industry. Participants specifically noted the need to define uniform units of energy density for systems, payback from energy products, active surface area, and other specifications. Other key characteristics that need to be better understood include the energy balance of systems, pricing and O&M costs, and the quality of waste streams used as input.

Table 5. Participant-identified MxC characteristics

Category	Identified Characteristics
Relevant System Costs	• Standardize units of measurement o $/lb o $/lb/hr o $/lb COD or payback (IRR, payback period, whatever end users want) o W/m^2 / unit biomass (captures microbial activity, e.g., SRT) o W/m^2 o kWh/lb COD o kWh/m^3 • Calculate H_2 production rate (current density); $ H_2/kg • Identify "High" (good) energy / hydrocarbon / or hydrogen production per dollar • Make technology attractive commercially • Calculate the ratio of surface area to volume (also cost related)
Operations and Maintenance	• Ensure ease of troubleshooting—can a municipal operator fix or know when to call? • Ensure long lifetime • Design for system stability • Ensure reliability • Specify failure mode (e.g., reversible vs. non-reversible) • Minimize system complexity; simple design wins • Ensure low/no electrical generation at low COD

Category	Identified Characteristics
Energy	• Calculate molecular characterization of COD for conversion to energy • Identify useful form of energy • Ensure low current per volume (energy density) • Ensure coulombic efficiency • Ensure coulombic recovery (for products) • Design for energy balance (pumping aeration, etc.) • Examine energy input • Maximize potential efficiency • Include energy efficiency in water treatment
Integration with Wastewater Treatment	• Design for high-COD removal • Integrate MxC with existing wastewater treatment framework; is a new paradigm structure needed? • Improve sludge quality and reduce quantity
Other	• Identify economic drivers • Convince investors in R&D of the real pay-off / standardization of "attractive" pay-offs • Optimize anode/cathode design for each MxC application o Energy production o COD/BOD reduction o H_2 production • Volume or weight of different products • Design to be modular • Build in microbial control • Calculate sustainability "energy return on investment" • Ensure realistic scalability

Challenges

The participants listed specific technical and economic challenges to advancing the technology and facilitating commercial deployment. They then voted on these challenges to identify key focus areas. The most significant challenge identified was a lack of funding for the technology, followed by the mass production of cathodes and the start-up of microbes in large reactors. Key themes were grouped into broad categories of challenges (see Table 6). Among these, the themes that played a major role in the discussion included manufacturing, education to accelerate public acceptance and early adoption, and competition in the industry, which limits sharing of data sets.

Table 6. Participant-identified challenges to advancing MxC technology and facilitating commercial deployment (● = one vote)

Category	Challenges
Manufacturing	• Enable mass production of cathodes ●●●●●●● (7) • Enable mass manufacture of all unique aspects (growing anode-respiring bacteria, cathode, etc.) ●● (2) • Address the challenges of manufacturing and producing systems (e.g., machining or packaging)
Regulations	• Navigate regulation approval process ● (1)
Comparative Data Sets	• Unify comparative data sets for analysis ● (1) • Develop explanations for comparative data sets—metrics, reporting, etc.
Education	• Address lack of information transfer—educate industry ● (1) • Improve public acceptance (education)

Category	Challenges
	• Improve public acceptance (education) of supporting financial, societal, and regulatory policies to speed R&D
Demonstration	• Find suitable locations to demonstrate the technology (e.g., plants with excess capacity, but with existing pipes would require minimal modification) • Build track record of successfully scaling demonstration systems
Other Challenges	• Lack of funds (Avoiding the valley of death; needing $1+ million/pilot) ●●●●●●●● (8) • Start-up of large reactor microbes ●●●●●● (6) • Cost benchmarking concessions, technoeconomic analysis (TEA) ●●●●●● (6) • Current density ●●●●● (5) • Maintain biofilm performance over time – long term ●●●●● (5) • Integrated nutrient removal ●●●● (4) • Properly communicate energy data (energy balance, not just power) ●● (2) • Performance monitoring and control of COD and others ●● (2) • Value of energy products ●● (2) • Energy efficiency ●● (2) • CH_4 inhibition ●● (2) • Product/market fit ●● (2) • Implementation/ technology adoption ● (1) • Early adopters – find and convince ● (1) • Thinking outside the box; evaluating other cathodes that may be attractive ● (1) • Transitional stage at 100–200 L for demonstration at an intermediate scale ● (1) • Cost-effective and efficient storage/transport of MxCs products: energy/H_2/hydrocarbons • Time to upgrade an existing WRRF • R&D → tech development → manufacturing making the leaps • Finding application niches • Establishing public/private partnership: Appropriate roles? Responsibilities? • IP data sharing • Competition for limited resources

Potential Solutions

For the identified high-priority challenges, participants discussed solutions that they envision as possible within the next 20 years. Much like the discussion on key challenges, the ideas presented were grouped into major themes, including manufacturing, cathode development, biofilms, and data sharing (see Table 7). A key solution was the mass production of cathodes through continuous and automated manufacturing processes. Outside of the major challenges identified in the previous discussion, participants focused on maintaining biofilm performance over a period of five to ten years as an important solution and highlighted the need to pursue the required R&D.

Table 7. Participant-identified MxC solutions envisioned as possible in the next 20 years

Category	Potential Solution
Manufacturing	• Use existing manufacturing processes • Deploy mass production of cathodes: industrial continuous process with automated manufacturing
Cathodes	• Develop a better cathode • Fouling-resistant cathode, as measured against current density decreases

Category	Potential Solution
Biofilms	• Improve biofilm performance and electrochemical diagnostics • Maintain biofilm performance/optimize biofilm activity/maintain activity/have operational control defined by R&D
Data Sharing	• Simplify intellectual property (IP) requirements for tech transfer • Develop a standard template non-disclosure agreement • Allow open discussion through IP and data sharing
Other Solutions	• Integrate nutrient or (products) removal • Standardize cost-effective, in-time, sensor and control technologies for reactors, allowing for the integration of emerging products • Focus on high-value or multiple outputs; invest more funds • Optimize synthetic microbial communities • Develop models that can be used to optimize reactor design • Increase current density by developing better materials for the cathode catalyst, oxidizer, and conductive support "system" • Design current density hybrid systems that overcome current power density limitations • Demonstrate scale system for a platform R&D linear scale-up • Maintain 20-25 A/m^2 for 30 days—this should be the target for applications • For power conditioning, regulate and control current • Harvest most energy potential • Accelerate startups through cultivation of robust microbes • Integrate nutrient removal: effectively balance nutrient removal and energy production • Go small initially; modular system at gallons per minute so investors will consider investing • Develop a more concentrated microbe starter

R&D Activities

Participants identified the R&D activities that would be necessary to achieve the solutions listed above within the next 20 years (see Table 8). The greatest share of participant votes went to forming a task force to encourage collaboration rather than competition in the industry. In discussions, this competition was linked to restricted data sharing, which had been highlighted as a challenge. Major themes in needed R&D activities included developing computational models for scaling up and optimizing designs, developing precise sensor technologies for real-time measurement of COD, and taking a systems biology perspective toward system development.

Table 8. Participant-identified R&D activities for MxCs (● = one vote)

Category	**R&D Activities**
Modeling	• Scale-up modeling → understand how to effectively and operationally manage the scale-up process ●●●●●●● (7) • Combine existing models to have a (research) community model. Researchers input parameters of their own systems ●●● (3) • Define parameters • Gather data to improve/feed models • Develop new computational models • Integrate model and experiments to optimize design • Develop a multi-objective, integrated systems model to show how technology works with existing facilities • Develop cost tool for research community (like H2A)

Category	R&D Activities
Sensors	• Improve precision sensing of reactor conditions ●●●● (4) o New sensors that are cost effective o Real-time sensors leverage existing sensors • Develop new, cost-effective sensors or identify sensing technology from other R&D areas for in-situ analysis of nutrients or products to be removed ●● (2) • Use electroactive microbes as sensors
Current Density	• Reduce internal resistance to increase current (buffer capacity) ●●●● (4) • Enhance proton transfer
System Biology	• Outline systems biology perspective approach ●●●●● (5) o Potentially more important for engineered industrial systems o Physiology, -omics, etc. over time
Other Activities	• Form task force to tackle problem together. Have consortia collaborate rather than compete ●●●●●●●●●●● (11) • Conduct technoeconomic analysis (TEA) → enable fair comparison of different approaches to determine ROIs ●●●●● (5) • Understand O_2 reduction in MxC cathodes ●●●●● (5) • Reduce H_2 overpotential in MEC cathodes with new materials ●●●●● (5) • Develop cathode coatings for protection ●●● (4) • Conduct an in-depth study on system integration (i.e., improved pretreatment, post-treatment) outside of tech space to full system ●●● (3) • Improve understanding of biofilm growth and activity relationships for currents ~20 A/m^2 ●● (2) • Use synthetic biology to build better organisms for anode and cathode ●● (2) • Conduct research on materials science: identify and test new or non-standard materials to improve cathode system performance (e.g., conduct a life-cycle analysis) ● (1) • Gather more data ● (1) • Develop a small swatch of material of interest in a bench-scale experiment as a platform for manufacturing design. Design for ease of manufacturing.● (1) • Develop cheap membranes for H_2 and hybrid systems ● (1) • Identify entry points for technology • Identify alternate funding mechanisms → teams propose together • Examine surface modification • Address mass transfer limitations: hybrid processes with separated anode and cathode; leverage materials and integration • Design for manufacturing, especially where parts can be made from plastic • Elucidate methods of electron transfer

Deploying Wastewater Energy Recovery Technologies

The second day of discussions focused on the commercialization of advanced wastewater energy recovery technologies. Given the similar markets in which MxCs and AnMBRs would be deployed, both groups of participants (referred to here as "Session A" and "Session B") discussed commercial applications of both technologies and their hybrids to recover energy products (e.g., electricity, hydrogen, higher hydrocarbons) from wastewater. Each group first identified the key economic drivers and opportunities for using MxCs and AnMBRs to produce energy products. Participant discussions focused on the availability of feedstocks, opportunities in target markets, financial incentives, and policy factors. They then identified the key obstacles to these opportunities, citing the lack of education and technology advocates as well as technical, financial, and policy factors.

Among the diverse commercial markets in which advanced water treatment technologies could be applied, the participants identified the following as some of the most promising: food and beverage manufacturers, military and federal facilities, biorefineries, small WRRFs, and agriculture operations. The participants also specifically called out facilities suffering from aging infrastructure, being pushed toward greater levels of sustainability, or looking to avoid regulatory fines.

Economic Drivers and Opportunities

Identifying and capitalizing on advantageous economic drivers and opportunities can enhance commercial prospects for advanced water treatment technologies. Characterizing the end market can help to prioritize and tailor research activities, which may face resource constraints. In Session A, the identified economic drivers and opportunities fell into four broad categories: 1) the feedstock, 2) target markets, 3) policy, and 4) financial (Table 9). The first three categories represent market pull, wherein the customer stimulates development. The last category addresses market push, wherein direct or indirect governmental policy is the main driver. In Session B, opportunities for high-value coproducts and the environmental benefits stood out as major themes (Table 10). Other identified drivers in Session B echoed the financial or policy drivers highlighted by Session A.

Table 9. Participant-identified economic drivers and opportunities for energy recovery from waste (Session A)

Category	Economic Drivers and Opportunities
Feedstock	• Value and quantity of water input • Quantity, quality, and variety of feedstock available • Fats, oils, and greases

Target Markets	• Transportation fuels: gas; jet fuel; diesel; compressed natural gas (CNG); H_2
	• Co-production of valuable byproduct
	• Distributed systems
	  o H_2 fueling stations at WRRFs
	  o Taking advantage of stranded assets
	  o Minimalized scale, targeted market
	• Algae to potentially yield higher hydrocarbons
	• H_2 and CH_4 together; is there synergistic value?

Financial	• Utilize existing capacity, sunk capital • Avoid infrastructure costs • Stabilize oil prices • Improve performance and throughput, particularly at lower temperatures
Policy	• Act of Congress

Category	Economic Drivers and Opportunities
	• Renewable fuel standards • Government incentive; public utilities do not receive them • Fossil fuel tax • R&D grants • Nutrients as driver for carbon flow • Price on carbon • Reduced water footprint

Table 10. Participant-identified economic drivers and opportunities for energy recovery from waste (Session B)

Category	Economic Drivers and Opportunities
High-Value Co-products	• Digestate • Reduction of handling and costs • Reduction of residuals • Reduction of solid wastes • Tipping fees make feasible
Environmental Sustainability	• Carbon-neutral H_2 • Climate change • Clean air; reduced emissions • Sustainable energy source • Green image • Reduction of reliance on fossil fuel, foreign oil
Other Drivers and Opportunities	• Value of water • Market need • Oil/energy prices • Footprint • ROI • Methane also great motor fuel • Power products • Energy storage: H_2, CH_4, MECs, H_2O splitting, electromethanogenesis • High carbon conversion efficiency • High product titer and yield • Market pain/current practices unacceptable • Benefit:cost ratio • Reduced energy input • Incentives for industry to adopt new technology • Opportunity cost • RINs • Carbon credits

Obstacles

Participants identified key obstacles and a number of non-specific technical issues that stem from an immature technology entering a new market (Tables 11 and 12). [For more details, please see the earlier section on Challenges, which elaborates on many of these topics.] Two of the categories of identified barriers mirror those for opportunities—financial and policy. Closely related to these two categories are education and the need to develop the next generation of scientists and engineers who understand the value of AnMBR and MxC technologies in moving from wastewater treatment to resource recovery. Looking ahead, participants identified the need for a champion to promote these technologies in the marketplace. Because the technologies are likely to impact multiple markets, that champion should be capable of interfacing with diverse groups of stakeholders to overcome this obstacle.

Table 11. Participant-identified obstacles to energy recovery from waste (Session A)

Category	Key Obstacle
Technical	• Separations and purification issues • Conversion technologies • Lack of infrastructure/storage • Economies of scale • Biomass transportation and logistics
Educational	• Need scientists and engineers equally comfortable with energy, water, and economics • Train students to redefine problem • Educate older staff members
Financial	• Sunk cost of current infrastructure • Rationality of renewable markets • More incorporation of renewables, tying into the grid for backups o Fossil fuel costs o Cost of backup power o Grid and pipeline interconnection
Policy	• Carbon management paradigm • Nutrient regulation • State and local transportation laws • Lack of funds for research • Pretreatment program regulations
Finding a Technology Champion	• Federal silos on the topic of wastewater • Public utility ownership • Fossil fuel industry • Institutional inertia • Framing of the problem

Table 12. Participant-identified obstacles to energy recovery from waste (Session B)

Category	Key Obstacle
Technical	• Low production rate and quantity • Source and production location • Lack of R&D • Purity of biogas, biofuels • Multidisciplinary research and development • H_2 purity • Application-specific or unique wastewater characteristics • Whole value chain scalability
Educational	• Education/technology adoption • Lack of skilled labor force • Acceptance of new technology—liability issues for government and support infrastructure • Lack of understanding • Misperception of technology status

Category	Key Obstacle
Financial	• High normalized cost relative to conventional method • Capital and O&M costs • Lack of funds • Cost of components
Policy	• Regulatory change • Regulatory restrictions
Culture	• Conservative nature of utilities • Risk avoidance • Complacency
Finding a Technology Champion	• Not core business • Lack of a system to foster small-scale innovation • Technology readiness for full-scale applications at WRRFs • Converting/marketing equipment to use H_2, etc. • Infrastructure needs for product • H_2 storage and distribution • Industrial communication and collaboration

Target Markets

The commercialization of many technologies is predicated on finding a niche market to adopt and pilot the technology. These markets are in greater need of a solution and willing to pay a premium for one. As the technology is further deployed, costs come down and familiarity increases; the technology is then expected to become more broadly deployed into longer-term markets. Workshop participants identified a number of markets that stand to benefit from advanced water treatment technologies and subsequently categorized them as niche markets or longer-term markets (Tables 13 and 14). Notable niche markets include the food and beverage industry, military applications, and green building opportunities. For the long term, participants identified municipalities, existing wastewater treatment facilities, and biorefineries.

Table 13. Participant-identified markets for energy recovery from waste (Session A)

Target Niche Markets	Longer-Term Markets
• Food and beverage manufacturers • High-strength organic industrial waste • Craft breweries • Military • Green buildings—the U.S. Green Building Council's Leadership in Energy & Environmental Design (LEED) program has a resource recovery credit under wastewater treatment • Animal feeding operations • Potentially funded by garbage taxes/fines: cities tax and fine based on specific types of garbage thrown	• Future biorefineries • Small communities • Existing treatment facilities (large and small)

Table 14. Participant-identified markets for energy recovery from waste (Session B)

Target Niche Markets	Longer-Term Markets

• Caribbean wastewater treatment
• Developing world applications (point-of-use sanitation and water recycling)
• Places where CO_2 is sequestered
• Environments with ideal microbial communities (e.g., benthic fuel cells)
• Distributed wastewater treatment systems (smaller scale)
• Saline wastewater treatment plants [as a target market] for microbial fuel cells (publicly owned treatment works with settling issues)
• Industries that spend most money to treat water: oil/gas, food, agriculture, Industry paper/pulp effluent
• Industrial wastewater treatment
• Food and beverage industry (e.g., beer, wine, sodas)
• Markets with:
  o Less stringent requirements
  o Difficult-to-treat wastewater
  o Economic risk (high capital costs despite ROI)
  o Noncompliance fees/surcharges
• Source separation/decentralized treatment solution
• Integrated nutrient removal at wastewater treatment plant
• Subsidized water reclamation plants
• Hospitals
• Hotels and cruise ships
• Military applications (ships/FOBs)
• Co-location of wastewater treatment plant and power plant
	• Early Adopters
	  o Target one tank at huge plant (for proving)
	  o Forward-thinking municipal wastewater treatment plant
	  o Needs: Status quo has the rate payer complaining
	• Municipalities
	  o Need demonstration of proven performance
	  o Need: cost certainty
	• Those who cannot tolerate risk of experimental technology (when they can have higher ROI options for investment elsewhere)

Needs for Target Markets

Participants identified the actions they deem necessary to strategically match R&D activities to the targeted markets. Participants developed lists of ideas that could help accelerate commercialization efforts (Tables 15 and 16). The major categories of identified needs include the demonstration of these technologies at large scale, effective communication and outreach to educate and engage industries on energy recovery from wastewater, and making financing available to enable technology development.

Table 15. Participant-identified needs to match R&D activities with targeted markets (Session A)

Category	Needs
Technology Demonstration	• Develop high conversion rates in R&D • Demonstrate platforms/mechanisms (e.g., cellulosic ethanol) • Identify high-value product streams

Category	Needs
Communication and Outreach	• Form interagency partnerships • Document and share success stories • Educate all stakeholders • Map innovations from other sectors • Change perceptions of the technology in terms of carbon management • See waste as a feedstock
Financing Activities	• Provide subsidies for getting R&D to the market • Tap into industry cost-share • Offer a challenge prize to encourage competition • Enlist corporate sponsorship

Table 16. Participant-identified needs to match R&D activities with targeted markets (Session B)

Category	Needs
Technology Demonstration	• Conduct larger scale and real-world demonstration • Demonstrate long-term operation to show reliability (time period depends on technology, scale) • Design of monitor and control system • Conduct technology pilots and commercial pilots • Demonstrate technology at pilot scale at reasonable cost • Design for manufacturer • Develop technology for diverse industrial streams • Obtain/make available the data to develop and test models • Improve deficiency of CH_4 conversion to electrical energy (e.g., microturbine) • Better understand model assumptions o Anaerobic wastewater characterization o Hydrolysis kinetics • Assess markets • Adopt system approach
Communication and Outreach	• Form university/industry partnerships • Take the time to cooperate and organize for effective outreach • Leverage sales channels • Involve technology providers • Involve other stakeholders • Publicize project successes • Educate; convey operational knowledge • Form pre-competitive partnerships; set performance targets
Financing Activities	• Obtain more research funding from more sources • Establish 10-year, $50 million MxC grant through Congress • Place all R&D funding under one umbrella

Closing

Participants in the workshop identified specific activities that could help bring AnMBR and MxC technologies closer to commercial success. This exercise led them to conclude that a long-term, concerted effort will be needed. Building from existing, fragmented efforts will require a broad coalition of stakeholders representing academia, government (e.g., DOE, U.S. Department of Agriculture [USDA], EPA), and industry (e.g., WEF, WERF, NACWA, IWA, the International Society for Microbial Electrochemistry and Technology (ISMET), operators, technology providers). A major hurdle to technology deployment is the lack of a single governmental authority over the diverse issues relevant to the technologies and stakeholders. Given the broad interest in advancing these technologies, a consortium consisting of these stakeholders might represent a potential path to formalize action.

While continued R&D funding will be essential to accelerate the deployment of AnMBRs and MxCs, the workshop participants looked beyond financial support to other forces that could accelerate deployment. One potentially enabling factor identified is the establishment of incentives for facilities that pilot the technologies, such as increased flexibility within regulatory requirements (i.e., a "Bubble" policy, which would grant a facility freedom to choose the best way to meet regulations). Alternatively, recoverable resources emitted or wasted could be taxed or regulated, which would change the economics of water treatment and nudge conservative facilities toward more advanced and progressive treatment technologies. Participants also suggested prize competitions to attract a broader array of participants and catalyze follow-on funding and publicity. Efforts to educate facility operators could familiarize conservative industry segments with newer technologies and improved practices.

The workshop participants actively discussed how best to fund the R&D needed to develop the technologies to the point required for broad market acceptance (performance, reliability, economics, etc.) and use in actual facilities. Government agency funding cannot accomplish the desired outcomes alone; industry must be a partner—bringing funds, facilities, and expertise to the table. Participants cited existing R&D enabling programs, such as DC Water's $1 per ton R&D surcharge on biosolids, which provides a reliable research funding mechanism, and WERF's Leaders Innovation Forum for Technology program, which pairs operators with technology providers to pilot novel systems that can potentially serve as models for others. A successful commercialization and deployment effort will also require a strategic orientation of the research toward the most promising and economically viable markets. All stakeholders will need to collaborate and help commit adequate funding and institutional focus to the long-term vision for the WRRF of the Future.

Current community perceptions of wastewater treatment must shift. WRRFs will need to actively engage with their customers, elected officials, the private sector, and the public to create a desire to improve this public utility. Improved water treatment, energy recovery, and resource recovery represent positive returns on investment, among other benefits. AnMBRs and MxCs must be presented as technologies that address these issues and reduce costs. Participants noted that disasters (e.g., drought, power outages) often play a role in finally spurring stakeholders to action, though that is not the preferred approach. Ideally, effective outreach, technology development, education, and collaborative efforts will move the technologies into place to head off disasters. Widespread deployment, though, will depend upon appropriately developing and testing the technology so that it works correctly when first installed and continues to operate reliably and economically over the coming decades. Workshop participants expressed optimism about the future of these two technologies and their beneficial impact on the WRRF of the Future. Their closing thoughts are summarized briefly in Table 17.

Table 17. Participants' concluding thoughts on future directions and needs

Future Directions and Needs	
Who can do it	• Establish a broad consortium of government, industry, and academia • Piggyback on associations/events (e.g., WERF, WEFTEC, WEF, IWA AD, ISMET) • Find a federal champion o NSF Food, Energy, Water o USDA o EPA o ARPA-E o Water – Energy Nexus
What to do	• Fund research • Implement changes to facility permits for pilot testing (i.e., 'bubble permit') • Educate operators about technologies • Improve tracking of pollutants and waste streams (i.e., nitrogen), potentially in support of permit trading • Devise tax incentives for pilot projects • Stimulate discussions among researchers, industry, regulators • Launch challenge competitions • Establish price on carbon or other emissions
How To Do it	• Make long-term commitment to the topic • Conduct stakeholder outreach o Leveraging WEF/WERF/NACWA o Industry • Define realistic commercialization targets • Fund industry R&D o Emulate DC Water, levy a biosolids charge/fee o Work through R&D focused associations
Messaging	• Target messaging at different stakeholders o Industry o Public o Congress o President • Refine potential messages o Outline a future vision on the topic o Wastewater as resource o Creates jobs; keeps jobs where treatment facilities were not sufficient o Elucidate the interconnection between water treatment issues and other measures of sustainability o Reduces water treatment costs o Quantify investment already occurring and needed in the near future to maintain water treatment infrastructure o Educate stakeholders about the technology and its applicability to their work • Leverage the motivating impact of a disaster o Superstorm Sandy o Drought

Appendix A: Workshop Attendees

Last Name	First Name	Organization
Andalib	Mehran	Environmental Operating Solutions (EOSI)
Biron*	Remy	BCS, Incorporated
Borole	Abhijeet	Oak Ridge National Laboratory (ORNL)
Bretschger	Orianna	J. Craig Venter Institute (JCVI)
Call	Douglas	North Carolina State University
Cardenas	Andres	SRI International
Choi	Youngchul	RTI International
Cumin	Jeff	GE Power & Water
Cusick	Roland	University of Illinois at Urbana-Champaign
Dean	William	Cambrian Innovation
Fillmore	Lauren	Water Environment Research Foundation (WERF)
Finley	Cynthia	National Association of Clean Water Agencies (NACWA)
Fisher*	Aaron	Energetics
Fishman+	Dan	Bioenergy Technologies Office, DOE
Haynes	Chad	Booz Allen
He	Zhen (Jason)	Virginia Tech
Liu	Hong	Oregon State University
Logan	Bruce	Penn State
Lovley	Derek	University of Massachusetts
Male	Jonathan	Bioenergy Technologies Office, DOE
McCarty	Perry	Stanford University
McFadden	Lisa	Water Environment Federation (WEF)
Philbrick+	Mark	Fellow, DOE
Ramirez	Mark	DC Water
Randolph+	Katie	Fuel Cell Technologies Office, DOE
Raskin	Lutgarde	University of Michigan
Ren	Zhiyong (Jason)	University of Colorado Boulder
Satyapal	Sunita	Fuel Cell Technologies Office, DOE
Schottel	Brandi	AAAS Fellow, National Science Foundation (NSF)
Solina	Brent	MicroOrganics
Studer+	Sarah	Fellow, DOE
Talapatra*	Amit	Energetics
Umble	Art	MWH Americas
Urgun- Demirtas	Meltem	Argonne National Laboratory (ANL)
Willis	John	Brown & Caldwell
Yang	Jeff	Environmental Protection Agency
Yeh	Daniel	University of South Florida

+ Workshop Organizers * Notetakers

Appendix B: Acronyms

AD	Anaerobic digestion
AnFMBR	Anaerobic fluidized membrane bioreactor
AnMBR	Anaerobic membrane bioreactor
AMO	Advanced Manufacturing Office
ARPA-E	Advanced Research Projects Agency–Energy
BETO	Bioenergy Technologies Office
BOD	Biochemical oxygen demand
Btu	British thermal unit(s)
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DIET	Direct Interspecies Electron Transfer
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FCTO	Fuel Cell Technologies Office
FO	Forward osmosis
FOA	Funding opportunity announcement
GAC	Granulated activated carbon
gge	Gallon of gasoline equivalent
H_2	Hydrogen (diatomic)
HHBPW	Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewater
HRT	Hydraulic retention time
ISMET	International Society for Microbial Electrochemistry and Technology
kg	Kilogram(s)
kWh	Kilowatt hour
LMH	Liters per square meter per hour
m	Meter(s)
MDC	Microbial desalination cell
MEC	Microbial electrolysis cell
MES	Microbial electrosynthesis
MFC	Microbial fuel cell
MW	Megawatt
MxC	Microbial electrochemical cell
NACWA	North American Clean Water Agencies
NSF	National Science Foundation
O&M	Operations and maintenance
PAC	Powdered activated carbon
PRO	Pressure retarded osmosis
R&D	Research and development
RD&D	Research, development, and demonstration
ReNUWIt	Re-inventing the Nation's Urban Water Infrastructure
RIN	Renewable identification number
SRT	Solids retention time
T	Trillion
TSS	Total suspended solids
USDA	U.S. Department of Agriculture
WEF	Water Environment Federation
WERF	Water Environment Research Foundation
WRRF	Water resource recovery facility

Appendix C: Meeting Agenda

Wednesday, March 18, 2015	
8:40 am	**Welcome and Introductions**
9:00 am	**Fuel Cell Technologies Office Hydrogen Production Overview**, Sunita Satyapal, Director, DOE Fuel Cell Technologies Office
9:30 am	**Waste-to-Energy in the Bioenergy Technologies Office**, Jonathan Male, Director, DOE Bioenergy Technologies Office
10:00 am	*Break*
10:15 am	**Presentations: Technological State of the Art** ▸ **MxCs: Challenges and Opportunities,** Jason Ren, University of Colorado, Boulder ▸ **AnMBR: Challenges and Opportunities,** Art Umble, MWH ▸ **MxCs: Can they scale?,** Bruce Logan, Penn State ▸ **Report from the field: Sidestream MFCs at DC Water,** Mark Ramirez, DC Water
12:00 pm	*Lunch*
1:15 pm	Breakout Discussion: Technological State of the Art and Current Challenges ▸ Breakout groups based on technologies (MxCs, AnMBR)
2:45 pm	*Break*
3:15 pm	Breakout Discussion: Technological Next Steps *(Same groups as earlier session)*
4:45 pm	Preliminary Breakout Reports
5:15 pm	*Adjourn*

Thursday, March 19, 2015	
8:30 am	**Presentations: Targeting High-Value Challenges** ▸ **Alleviating fouling in AnMBRs,** Perry McCarty, ReNUWit program at Stanford/UCB ▸ **Electrobiocommodities from CO_2,** Derek Lovley, UMass Amherst ▸ **Integrating AnMBR with MFCs,** Jason He, Virginia Tech ▸ **Anaerobic Digestion, Interrupted: Alternatives to Producing CO_2,** Meltem Urgun-Demirtas, Argonne National Laboratory
10:15 am	*Break*
10:30 am	Breakout Discussions: Integrated Product Delivery to Markets ▸ Two concurrent breakout groups will address the same questions
12:30 pm	*Lunch*
1:30 pm	Breakout Reports from Morning Sessions
2:00 pm	Plenary Discussion: Where Should We Go From Here?
2:45 pm	Summary and Adjourn

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