Energy-Positive Water Resource Recovery Workshop Report

April 28–29, 2015 • Arlington, Virginia

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Arlington, Virginia

Prepared by
Energetics Incorporated

Prepared for an Interagency Working Group
National Science Foundation, U.S. Department of Energy, U.S. Environmental Protection Agency

Preface

This report summarizes the proceedings of the Energy-Positive Water Resource Recovery (EPWRR) Workshop hosted jointly by the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), and the National Science Foundation (NSF) on April 28–29, 2015. The workshop gathered stakeholders from industry, academia, national laboratories, and government at NSF headquarters in Arlington, Virginia, to discuss barriers to the development and deployment of the *water resource recovery facilities (WRRF) of the future*. The goal of this report is to stimulate further dialog and accelerate the wide-scale advent of advanced WRRFs. Concepts reported herein represent a synopsis of the perspectives and ideas generated by the experts who attended the workshop.

Acknowledgements

Special thanks are extended to the workshop plenary speakers: Dr. Diana Bauer, DOE; Dr. Kartik Chandran, Columbia University; Lauren Fillmore, Water Environment Research Foundation (WERF); Dr. Brent Giles, Lux Research; Dr. Mark Kodack, U.S. Department of Defense (DOD); Paul Kohl, Philadelphia Water Department; Jeff Lape, EPA; Dr. JoAnn Lighty, NSF; Dr. Richard G. Luthy, Stanford University; Erika Mancha, Texas Water Development Board; Ed McCormick, the Water Environment Federation (WEF); Kerri Neary, DOE; Ben Shuman, U.S. Department of Agriculture (USDA); and Dr. Suzanne van Drunick, EPA.

Sincere thanks also go to members of the Workshop Steering Committee (listed on page iv), who oversaw the planning and execution of the workshop and the preparation of this report.

The DOE, EPA, and NSF gratefully acknowledge the valuable ideas and insights contributed by all stakeholders who participated in the EPWRR Workshop. The willingness of these experts to share their time and knowledge has helped to define current and emerging opportunities to expedite development and deployment of innovative technologies for the next generation of WRRF. These individuals are listed in Appendix A.

This report was written by Dr. Aaron Fisher; Jonny Rogers; and Paget Donnelly, all of Energetics Incorporated, with support from the Energetics Incorporated graphics and editing teams.

Workshop facilitation was conducted under the direction of Molly Mayo of Meridian Institute. Facilitators included Gary Decker, Meridian; Selena Elmer, Meridian; Bryan Pai, SRA; and Brad Spangler, Meridian. Note-taking services were provided under the direction of Dr. Aaron Fisher of Energetics Incorporated with support by Becca Price, Paget Donnelly, and Caroline Kramer, all of Energetics Incorporated.

Contents

Workshop Steering Committee

Tamara Battle, Engineering and Science Analyst, Division of Chemical, Bioengineering, Environmental, and Transport Systems (CBET), NSF

Dr. Diana Bauer, Director, Office of Energy Systems Analysis and Integration, Office of Energy Policy and Systems Analysis (EPSA), DOE

Dr. William J. Cooper, Program Director, CBET, NSF

Dr. Aaron Fisher, Senior Engineer and Program Lead, Energetics Incorporated

Dr. Bruce Hamilton, Program Director, CBET and Office of Emerging Frontiers and Multidisciplinary Activities, NSF

Scott Hutchins, Technology Manager, Advanced Manufacturing Office, Office of Energy Efficiency and Renewable Energy (EERE), DOE

Jeff Lape, Deputy Director, Office of Science and Technology (OST), Office of Water (OW), EPA

Ardra Morgan, Senior Advisor, Office of Research and Development, EPA

Dr. Mark Philbrick, Oak Ridge Institute for Science and Education (ORISE) Science and Technology Fellow, Bioenergy Technologies Office, EERE, EPSA, DOE

Grace Richardson, ORISE Research Fellow, OW, EPA, now with Alexandria Renew Enterprises

Bob Rose, OW, EPA

Dr. Brandi Schottel, American Association for the Advancement of Science, Science and Technology Fellow, CBET, NSF

Dr. Tom Speth, Director, Water Supply and Water Resources Division, National Risk Management Research Laboratory, EPA

Dr. Sarah Studer, EERE Postdoctoral Fellow, Fuel Cell Technologies Office, EERE, DOE

Jason Turgeon, Environmental Scientist, Region 1, Energy and Climate Unit, EPA

Dr. Jeff Yang, Scientist, EPA

Executive Summary: Transitioning from water treatment to resource recovery

The aging U.S. water infrastructure will require an investment of about $600 billion over the next 20 years if it is to continue reliably transporting and treating wastewater and delivering clean drinking water.[1] This massive investment marks an opportunity to apply new knowledge and technology and rethink the design and functionality of the water management infrastructure. Building on industry's pioneering efforts to reduce energy usage and increase the recovery of valuable resources from wastewater, the United States can seize this opportunity to create a world-class water infrastructure, while reducing the costs to run it. Aside from the critical financial benefits, society would benefit from cleaner water, reduced landfilling, increased resilience to climate change, and more sustainable utilization of resources. In pursuit of this vision, stakeholders have outlined potential federal activities to support industry in advancing the state of the art for water resource recovery facilities (WRRFs) while reducing or even eliminating the nearly 1% of U.S. electricity currently used to collect, transport, and treat wastewater.[2]

Water Resource Recovery Facility

The term "water resource recovery facility" (WRRF) is used throughout this document at the behest of the water treatment community to reflect a shift in self-identification; it replaces the term "wastewater treatment plant."

The National Science Foundation (NSF), the U.S. Environmental Protection Agency (EPA), and the U.S. Department of Energy (DOE) jointly hosted the *Energy-Positive Water Resource Recovery* (EPWRR) *Workshop* to envision a transition from the wastewater treatment facilities of today to a new generation of WRRFs nationwide and identify specific opportunities to stimulate and support this transition. The U.S. Department of Agriculture (USDA) and the Department of the Army also participated in this workshop at the NSF headquarters in Arlington, Virginia, on April 28–29, 2015. Participants provided information to federal stakeholders about ongoing industry efforts[3] and how federal activities could best amplify and help realize the industry vision for the *WRRF of the Future*.

WRRF of the Future

As used in this document, "WRRF of the Future" refers to the workshop participants' vision of the facilities that are expected to recover water and other resources by 2035 or before.

Envisioning the Utility of the Future

As envisioned by the workshop participants, the *WRRF of the Future* should continue to assign top priority to wastewater treatment for the protection of human health and the environment but should also expand its slate of services and products in support of healthy, economically vibrant communities.[4] For example, the future WRRF could effectively manage more diverse waste streams, generate fuel, produce water and fertilizer, and help communities recover other valuable resources. To achieve this

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1 U.S. Environmental Protection Agency. "Water Infrastructure and Resiliency Finance Center." Accessed July 27, 2015. http://water.epa.gov/infrastructure/waterfinancecenter.cfm.

2 30.2 billion kilowatt hours: Pabi, B., A. Amaranth, R. Goldstein, and L. Reekie. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Electric Power Research Institute and Water Research Foundation, 2013. www.waterrf.org/PublicReportLibrary/4454.pdf.

3 For more information, please see: National Association of Clean Water Agencies (NACWA), Water Environment Federation, and Water Environment Research Foundation. Water Resource Utility of the Future 2015, Executive Summary. Washington, DC: NACWA, 2015. www.nacwa.org/images/stories/public/2015-07-10wruotf-exs.pdf.

4 This section identifies the idealized characteristics of a future WRRF.

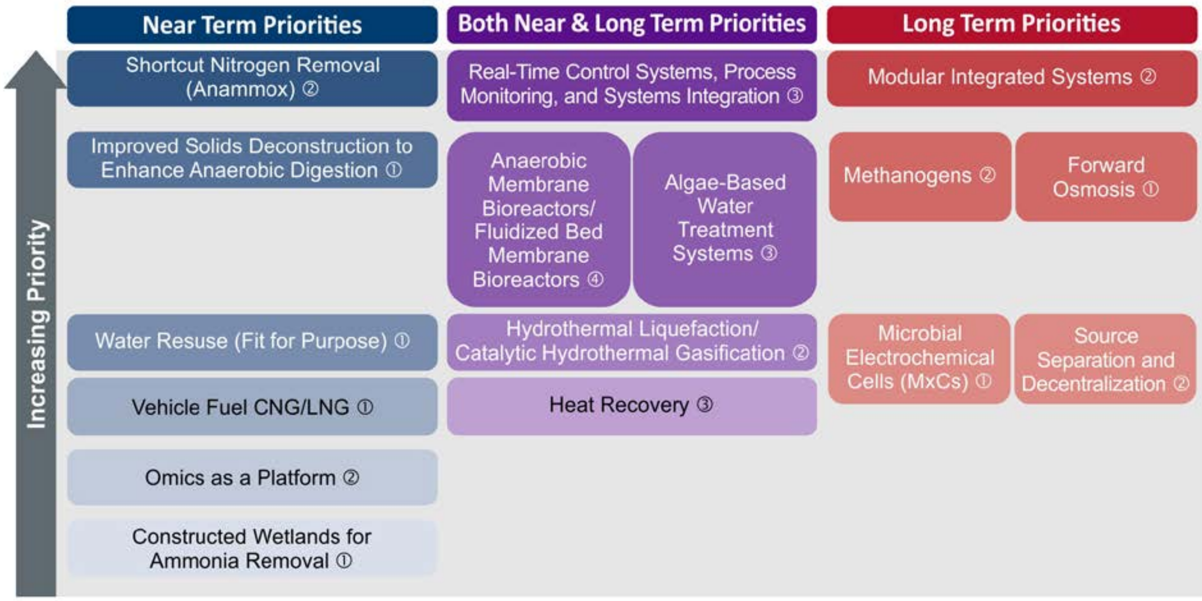
vision, the ideal *WRRF of the Future* should use and recover resources efficiently, coordinate with utilities and other community services, engage customers and the public in new ways, and deploy a range of smart technologies and systems.

- **Resource Efficiency and Recovery—**Beyond merely treating wastewater, *WRRFs of the Future* should emphasize the recovery of diverse resources, including water, nutrients, and energy. WRRF systems should effectively and economically safeguard public health and the environment while producing water, power, and products to meet community needs and standards. Success in recovering nutrients, minimizing energy use, and reducing emissions would ultimately transform these facilities from necessary public systems into prized community assets.
- **Integration with Other Utilities—**To meet the growing demand for clean water, WRRFs should continue to treat variable wastewater streams to high standards. *In addition,* WRRFs could produce electricity, lesser water grades, and saleable products that efficiently and economically serve a mix of shifting local priorities. WRRFs could optimize the recovery and tailored treatment of local wastewater and other waste streams to meet the specialized needs of power plants, manufacturing plants, agricultural systems, local governments, health agencies, and other institutions.
- **Engaged and Informed Communities—**To shift current community perceptions of wastewater treatment toward positive associations with resource recovery, WRRFs should actively engage with their customers, elected officials, industry, and the public. Initial outreach efforts should expand public understanding of sustainable water resources and awareness of WRRF goals. Communities may advocate for WRRFs that reduce carbon emissions, support green infrastructure development, and drive economic growth. Customers can contribute to the success of the *WRRFs of the Future* by better managing waste at the source. Ultimately, effective customer engagement could improve public infrastructure and increase local support for net-zero-water buildings and other integrated solutions to water, energy, and food supplies.
- **Smart Systems—**Future WRRFs could use a host of sensors, software, and innovative equipment to track performance and inform plant operations. Smart systems would enable facilities to actively monitor the volume and content of incoming waste streams, supervise plant operations, and verify the safety or quality of outputs to enable real-time adjustments in processing parameters. These facilities could potentially scale up or down as needed to maintain economical operations under shifting conditions. Advanced technologies could support facility integration beyond traditional plant boundaries, e.g., enabling coordination with the local power company to facilitate demand-response activities.

Research Opportunities

Workshop participants prioritized 16 areas in which concerted research is likely to deliver significant progress. Six of these topic areas are for the near term, five are long term, and five span both the near and long term (see Figure ES-1 and Table ES-1). Research, development, and demonstration in these areas could further catalyze industry investment in building the *WRRF of the Future*.

Aeration represents the largest energy-consuming operation at a WRRF. Participants identified a number of research opportunities that could reduce or even eliminate the need for aeration. For example, shortcut nitrogen removal—anaerobic ammonium oxidation (anammox)—would eliminate the need to aerate during denitrification, and constructed wetlands might also be used to reduce aeration needs, though throughput remains a challenge in natural systems.



①Research area prioritized by a single breakout group; ②Research area prioritized by two different breakout groups; ③Research area prioritized by three different breakout groups; ④Research area prioritized by all four breakout groups

Figure ES-1: Prioritized Research Opportunities

Sludge disposal is one of the largest expenses at WRRFs. Improved solids deconstruction would better break down the biomass, increasing the production of biogas and reducing the remaining digestate. Workshop participants similarly identified anaerobic membrane bioreactors and fluidized bed membrane bioreactors as technologies that could enhance anaerobic digestion (AD) and reduce the volume of sludge for disposal. Together, research on sludge and aeration could significantly reduce energy consumption, increase energy recovery, and minimize the costs of sludge disposal.

Deployment Challenges

In considering potential pathways toward the *WRRF of the Future*, workshop participants identified key challenges to be overcome. These challenges include regulatory, technical, social, and financial barriers.

While compliance with water treatment standards will remain the core mission of future facilities, this long-standing priority has tended to promote a risk-averse culture. As a result, many facilities today are disinclined to deploy and validate advanced resource recovery technologies that could generate economic value. Pioneering facilities are needed to scale up promising technologies, validate them, and help set the standards for safely integrating resource recovery into existing and future WRRFs.

Financing and social acceptance are pivotal issues in deploying these novel technologies. Financing poses a perpetual challenge for the research, development, demonstration, and deployment (RDD&D) of water resource recovery technology. Many WRRFs operate as regulated utilities in structures that leave little revenue for research or innovation. Without capital improvement budgets, these facilities necessarily focus on maintaining existing services instead of building for the future. A better understanding of environmental sustainability, including the social costs of water and carbon pollution, would help justify funding for water resource recovery. Public awareness of the long-term benefits and reliability of these systems could also help attract financing and stimulate adoption of promising water resource recovery technologies.

Table ES-1: Research Priorities Identified by the Four Parallel Participant Breakout Groups*

Near-Term Priorities	Both Near- and Long-Term Priorities	Long-Term Priorities
1. **Shortcut nitrogen removal (anammox)** eliminates the need to aerate the sludge, sharply reducing energy use for denitrification. *(2 groups)*+ 2. **Improved solids deconstruction** makes nutrients more accessible in anaerobic digesters, increasing biogas production and reducing solids handling.‡ 3. **Water reuse** for targeted potable and non-potable applications could reduce stress on existing drinking water supplies and deliver energy benefits. 4. **Compressed natural gas /liquefied natural gas** powered vehicles could utilize upgraded biogas. 5. **Using omics as a platform** (combining fields such as genomics, proteomics, transcriptomics, and metabolomics) could improve the biological processes associated with water treatment. *(2 groups)*+ 6. **Constructed wetlands** should be evaluated as an option for nutrient and pollutant remediation.+	1. **Real-time control systems, process monitoring, and systems integration** could provide greater insight into plant operations and improve the reliability and efficiency of WRRFs. *(3 groups)+* 2. **Anaerobic membrane bioreactors and fluidized bed membrane bioreactors** could increase biogas production; reimagining anaerobic digestion as a continuous process (versus traditional batch flow) would give microbes more time to digest the sludge. *(4 groups)*‡ 3. **Algae-based systems** could leverage existing treatment technologies with photosynthetic resource recovery. *(3 groups)*+‡ 4. **Hydrothermal processes** could be used to convert biomass from wastewater into higher-value products. *(2 groups)*+ 5. **Heat recovery** from wastewater could be used to offset energy demands at the WRRF and throughout the sewage network. *(3 groups)* *Note: Research on topics in this category may need to begin in the near term and continue throughout the long term.*	1. **Modular integrated systems** reduce the physical and environmental footprint of wastewater treatment and enable rapid, distributed deployment. *(2 groups)* 2. **Methanogens** research could improve the resiliency, yields, and throughput of the microbes that digest organic material and produce methane. *(2 groups)*‡ 3. **Forward osmosis** could be used in bioreactors to recover energy and remove pollutants from wastewater streams. 4. **Microbial electrochemical cells** can be used to generate hydrogen, electricity, or higher-value biofuel and bioproduct precursors. 5. **Source separation and decentralization** linked to urban planning could enable systems tailored for specific feedstocks or purposes and reduce dependence on major infrastructure. *(2 groups)*

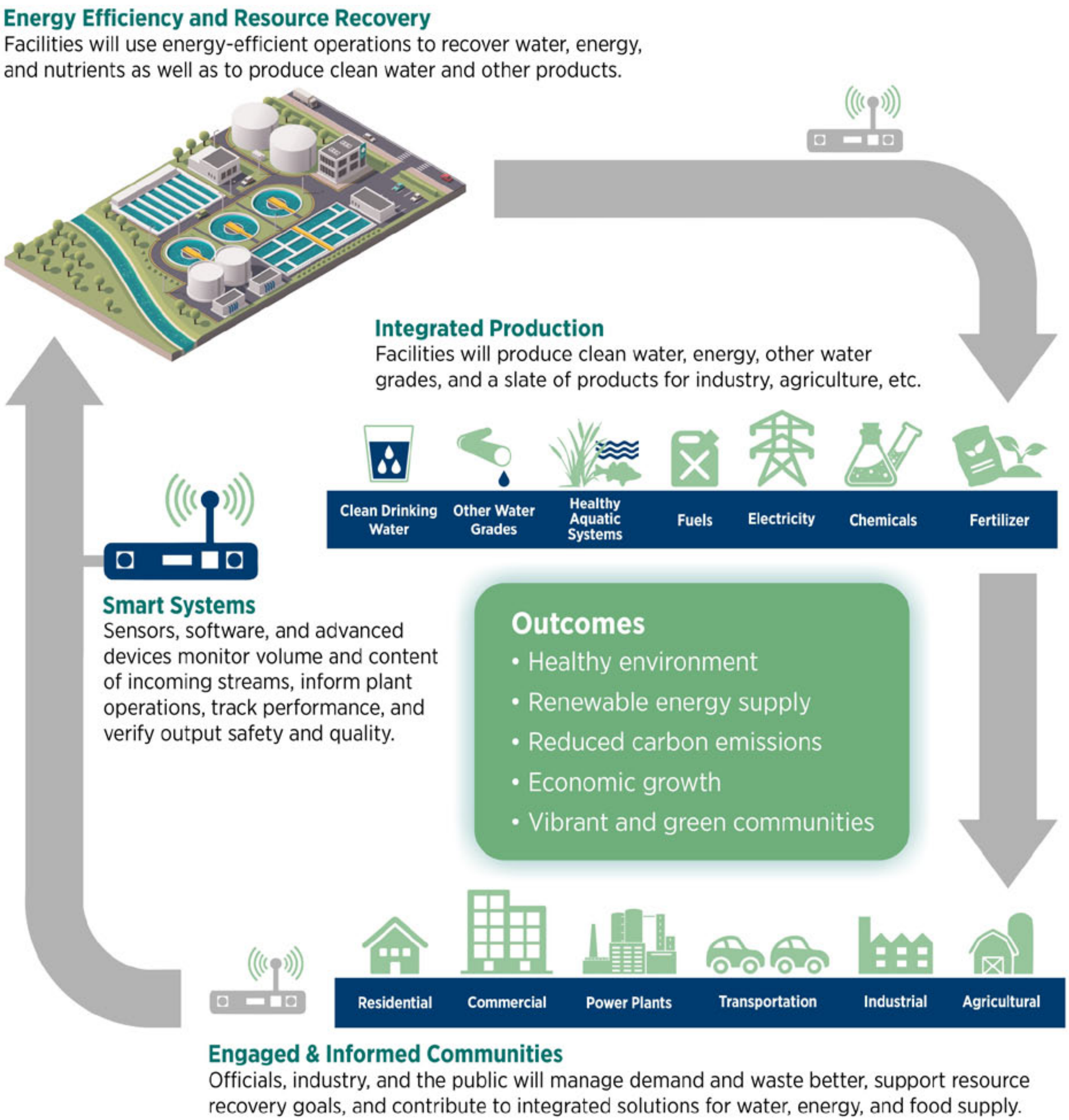
*Numbering within a time period indicates relative prioritization.
+Priority directly reduces need for aeration, the largest energy consuming operation at a WRRF.
‡Priority directly reduces costs associated with sludge treatment and disposal, which are among the highest WRRF costs.
Other identified priorities indirectly address costs and energy needs in the operation of a WRRF.

Moving Forward

As water treatment facilities, pipes, and related infrastructure in cities around the country approach the end of their expected service life, a unique window of opportunity exists to replace the aging infrastructure with the *WRRF of the Future*—reducing stress on energy systems, decreasing air and water pollution, building resiliency, and driving local economic activity.

Water Resource Recovery Facility of the Future

Energy Positive and Beyond: The Vision for Transforming Wastewater Treatment



Acronyms

AD	Anaerobic digestion
AnFMBR	Anaerobic fluidized membrane bioreactor
AnMBR	Anaerobic membrane bioreactor
Anammox	Anaerobic ammonium oxidation
BETO	DOE Bioenergy Technologies Office
BGNDRF	Brackish Groundwater National Desalination Research Facility
CBET	NSF Division of Chemical, Bioengineering, Environmental, and Transport Systems
CHG	Catalytic hydrothermal gasification
CNG	Compressed natural gas
CRRC	Codiga Resource Recovery Center at Stanford University
CWA	Clean Water Act of 1972
DARPA	Defense Advanced Research Project Agency
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DPR	Direct potable reuse
EPA	U.S. Environmental Protection Agency
EPSA	DOE Office of Energy Policy and Systems Analysis
EPWRR	Energy-Positive Water Resource Recovery
ESCO	Energy service company
ESPC	Energy savings performance contract
FCTO	DOE Fuel Cell Technologies Office
FO	Forward osmosis
HTL	Hydrothermal liquefaction
LNG	Liquefied natural gas
MGD	Millions of gallons per day
MxC	Microbial electrochemical cell
NACWA	National Association of Clean Water Agencies
NSF	National Science Foundation
PRO	Pressure retarded osmosis
R&D	Research and development
RDD&D	Research, development, demonstration, and deployment
USDA	U.S. Department of Agriculture
WEF	Water Environment Federation
WERF	Water Environment Research Foundation
WRRF	Water resource recovery facility

Introduction

America's water infrastructure, once widely recognized as a world-class system, now suffers from advanced age and decades of underinvestment. The high cost of maintaining this critical infrastructure has given rise to nascent technologies and innovative water treatment strategies that offer tremendous promise.

People across the United States enjoy high-quality drinking water, as legislated under the Clean Water Act (CWA) of 1972 and the Safe Drinking Water Act of 1974. Under the authority of these acts and subsequent legislation, the federal government has provided more than $100 billion to core wastewater and drinking water infrastructure assistance programs since 1973. The bulk of this federal support came prior to the mid-1990s—aside from funds provided by the Recovery Act of 2009. This decline in funding has left many WWRFs without the resources to pursue improvements.[5]

The need to repair or replace critical water treatment equipment, pipelines, and sewer systems, some of which are now up to 100 years old, is growing more urgent. Our nation's wastewater systems now release billions of gallons of raw sewage into local waterways each year. In addition, old water mains leak trillions of gallons of clean drinking water—worth billions of dollars—each year. Addressing such infrastructure issues for both wastewater and drinking water will require an estimated $600 billion over the next 20 years.[6] The required investment to repair or replace substantial sections of our aging water infrastructure is now beyond the reach of many local governments and traditional federal grant programs.

The emerging and projected impacts of climate change will likely exacerbate the burden already placed on our aging water infrastructure. Climate change impacts like drought, severe storms, and flooding pose additional challenges for this essential infrastructure.

Defense Department Transports 25 Times More Water than Fuel

In fiscal year 2013, the U.S. Department of Defense (DOD) consumed more than 90 billion gallons of potable water and only 3.5 billion gallons of fuel—nearly 25 times more water than fuel by volume. DOD recognizes the importance of reducing water use to enable agile operations and is on track to exceed the federal goal (for all agencies) to reduce water use 26% by 2020 (relative to a 2007 baseline).

In pursuit of reducing water needs at bases, DOD's Strategic Environmental Research and Development Program and Environmental Security Technology Certification Program harness the latest science and technology to develop and demonstrate innovative, cost-effective, and sustainable solutions. With regard to sustainable basing, the following R&D goals have been announced:

- 75% reduction in water
- 25% reduction in energy
- 50% reduction in solid waste

U.S. Department of Defense. Annual Energy Management Report: Fiscal Year 2013. Office of the Deputy Under Secretary of Defense, 2014. www.acq.osd.mil/ie/energy/energymgmt_report/FY%202013%20AEMR.pdf

U.S. Department of Defense (DOD). Fiscal Year 2012 Operational Energy Annual Report. DOD, 2013. http://energy.defense.gov/Portals/25/Documents/Reports/20131015_FY12_OE_Annual_Report.pdf.
Kodack, Mark. Personal communication, April 29, 2015.

[5] Copeland, Claudia, "Funding for EPA Water Infrastructure: A Fact Sheet," Congressional Research Service Report. June 19, 2015. http://nationalaglawcenter.org/wp-content/uploads/assets/crs/R43871.pdf

[6] U.S. Environmental Protection Agency. "Water Infrastructure and Resiliency Finance Center." Last modified May 6, 2015, http://water.epa.gov/infrastructure/waterfinancecenter.cfm

Activities are underway at federal, state, and local levels to reduce water usage, explore innovative funding approaches for wastewater treatment, and improve the energy efficiency of wastewater treatment processes. While all of these strategies should help, the extent of the required investment remains daunting. One relatively new approach promises to improve the long-term sustainability and economics of water treatment and delivery: the recovery of energy and other resources from wastewater to produce a range of valuable commodities.

Collection, transportation, and treatment of wastewater and drinking water consume 1.8% of U.S. electricity.[7] To reduce energy usage and address emerging resource conservation needs, advanced water treatment facilities now regard wastewater as a resource. These facilities—water resource recovery facilities (WRRFs)[8]—produce clean water from wastewater, recover nutrients, and produce renewable energy and other products. These functions represent significant steps beyond merely treating water to permitted levels and passing the incurred costs on to ratepayers.

Vancouver Sewage Heat Recovery

Year round, water flowing through sewage pipes is a fairly constant 70°F—enough energy for a heat pump to provide space heating and hot water to residential and commercial spaces. As part of the Olympic Village, the city of Vancouver, Canada, built the False Creek Energy Center to capture this thermal energy, provide heated water to nearby buildings, and reduce heating-related greenhouse gas emissions by 60%. Sewage now supplies 70% of the energy to meet hot water demand, with the remainder supplied by natural gas boilers. After the thermal energy is captured, the wastewater is sent to a WRRF.

In implementing this system elsewhere, it is important to know who owns the sewage water at every point, especially if multiple parties seek to valorize it.

City of Vancouver. "Southeast False Creek Neighbourhood Energy Utility." Last modified February 27, 2014. http://vancouver.ca/home-property-development/false-creek-neighbourhood-energy-utility.aspx

A Multi-Agency Workshop

The National Science Foundation (NSF), the U.S. Environmental Protection Agency (EPA), and the U.S. Department of Energy (DOE) invited stakeholders from the water resource community to participate in the Workshop on Energy-Positive Water Resource Recovery (EPWRR) in Arlington, Virginia, on April 28 and 29, 2015. The three agencies collaboratively planned and organized this workshop to address this area of overlapping interest. Workshop participants envisioned the features, characteristics, and capabilities of WRRFs 20 or more years into the future—the *WRRF of the Future*.

WRRF of the Future, as used in this document, refers to the workshop participants' vision of the facilities that are expected to recover water and other resources by 2035 or before.

[7] Pabi, S., A. Amarnath, R. Goldstein, and L Reekie. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries, Electric Power Research Institute and Water Research Foundation, 2013. www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002001433

[8] The term "water resource recovery facility (WRRF)" is used throughout this document at the behest of the water treatment community to reflect a shift in self-identification; it is used instead of wastewater treatment plants.

This workshop was preceded by two workshops on closely related topics: the November 2014 Waste-to-Energy Workshop hosted by the DOE Bioenergy Technologies Office (BETO)[9] and the March 2015 Anaerobic Membrane Bioreactor (AnMBR)/Microbial Electrochemical Cells (MxC) Workshop hosted by DOE/BETO and the DOE/Fuel Cell Technologies Office (FCTO).[10] Reports on all three workshops summarize the opinions and perspectives expressed by the participants and do not necessarily reflect the views of the U.S. government or the sponsoring agencies.

The EPWRR workshop featured a series of plenary speakers and facilitated discussions. To encourage the expression of ideas, participants were divided into four parallel discussion groups. Each group was challenged to describe the *WRRF of the Future*, articulate the efforts that would enable such a facility, and identify the priority efforts to be undertaken in the near and long term. Special emphasis was placed on identifying research, development, demonstration, and deployment (RDD&D) activities; the appropriate role of federal government in RDD&D activities; non-technical barriers; and sustainability issues. This report summarizes ideas put forth across the four discussion groups; independent conclusions from each group are provided in Appendix D. The parallel structure of these discussions led to similar conclusions among groups, but the timing of anticipated research outcomes varied from one group to the next, affecting projected research timelines.

Beginning in 2013, the WRRF industry began to outline a blueprint for the future, spearheaded by the National Association of Clean Water Agencies (NACWA), the Water Environment Federation (WEF), and the Water Environment Research Foundation (WERF). Since that time, the aforementioned organizations have jointly published an annual progress

Direct Potable Reuse

Treated Wastewater = Drinking Water

Direct potable reuse (DPR) is the practice of intensively treating wastewater to Safe Drinking Water Act standards and then piping it directly into the drinking water supply without an environmental buffer. In areas that are prone to drought or lack access to clean surface water, these processes can help conserve water resources. The greatest challenge is public acceptance of this practice. Texas, among other water-starved areas, continues to look progressively at conserving water resources through DPR. The Texas Commission on Environmental Quality has begun to implement DPR.

In May 2013, the Colorado River Municipal Water District opened a $14-million Raw Water Production Facility in Big Spring, Texas. The facility can provide up to 2 million gallons/day of drinking water to nearby cities, including Big Spring, Midland, and Odessa (total combined need of 36 million gallons per day). In June 2014, a second DPR facility capable of treating 10 million gallons/day of effluent opened in Wichita Falls. While both of these Texas facilities exceed drinking water standards, the water enters the water supply ahead of the treatment plant.

Martin, Laura. "Texas Leads the Way with First Direct Potable Reuse Facilities in U.S." Last modified September 16, 2014. www.wateronline.com/doc/texas-leads-the-way-with-first-direct-potable-reuse-facilities-in-u-s-0001

Trojan UV. *UV-Oxidation—Raw Water Production Facility (RWPF)*. London, Ontario: Trojan Technologies, Case Study, 2012. http://trojanuv.com/resources/trojanuv/casestudies/ECT/Indirect_Potable_Reuse___Big_Spring__Texas_Case_Study.pdf

9 Bioenergy Technologies Office. Waste-To-Energy Workshop Summary. Prepared by Energetics Incorporated. U.S. Department of Energy, 2015. www.energy.gov/eere/bioenergy/downloads/waste-energy-workshop-summary-report.

10 Bioenergy Technologies Office and Fuel Cell Technologies Office. Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters Workshop Summary. Prepared by Energetics Incorporated. U.S. Department of Energy, forthcoming.

report, the *Water Resource Utility of the Future Annual Report,*[11] which highlights innovative technologies and practices deployed throughout the sector. The report also recognizes the critical role of outside stakeholders in expediting the adoption of these innovations. This workshop builds on those landmark efforts by industry and is designed to ensure that RDD&D investments by the organizing federal agencies will effectively accelerate and enable the *WRRF of the Future*.

Wastewater as a Resource

To understand wastewater as a resource, one must examine the energy and chemicals contained within it. The energy embodied in wastewater can be broken down into three main types (see Figure 1[12]):

- **Thermal Energy:** The average temperature of wastewater is several degrees warmer than ambient temperatures. This low-grade heat could be captured to heat or cool homes[13] or generate electricity, particularly in more extreme climates.
- **Chemical Energy:** Wastewater contains a large number of organic molecules that can be broken down and turned into chemicals or fuels. This is the energy that an anaerobic digester captures to produce biogas.
- **Hydraulic Energy:** Water flowing downhill or under pressure provides a form of energy that can be captured and used to drive turbines or other mechanical systems. This hydraulic energy represents a very small portion of the energy embodied in wastewater (Figure 1).

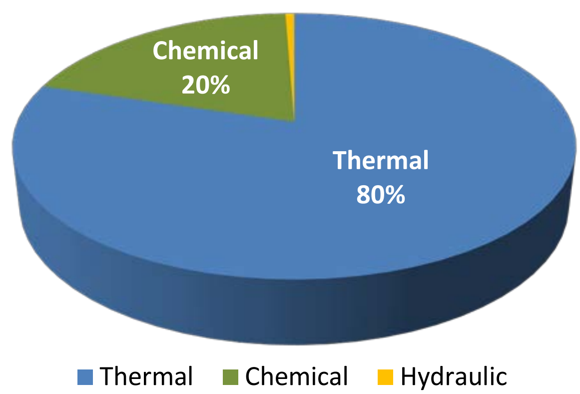


Figure 1: Energy Recoverable from Wastewater

Simplified View of Water Resource Recovery Facility Operations

The WERF report *A Guide to Net-Zero Energy Solutions of Water Resource Recovery Facilities*[14] identifies more than two dozen wastewater treatment process configurations that are representative of most WRRFs in North America. The incorporated analysis finds that water resource recovery facilities are moving closer to energy neutrality through the use of technologies and best practices that enable or promote energy efficiency, demand reduction, and onsite renewable energy production.

[11] National Association of Clean Water Agencies (NACWA), Water Environment Federation, and Water Environment Research Foundation. Water Resource Utility of the Future 2015, Executive Summary. Washington, DC: NACWA,, 2015. http://www.nacwa.org/images/stories/public/2015-07-10wruotf-exs.pdf

[12] Water Environment Research Foundation (WERF) and New York State Energy Research & Development Authority (NYSERDA). Guide to Net-Zero Energy Solutions for Water Resource Recovery Facilities, Executive Summary. WERF and NYSERDA, 2015. http://sites.energetics.com/EPWRR/downloads/WERF.ENER1C12-Executive-Summary.pdf

[13] Absorption chillers are systems able to use low grade heat instead of electricity to cool a space

[14] Water Environment Research Foundation (WERF) and New York State Energy Research & Development Authority (NYSERDA). Guide to Net-Zero Energy Solutions for Water Resource Recovery Facilities, Executive Summary. WERF and NYSERDA, 2015. http://sites.energetics.com/EPWRR/downloads/WERF.ENER1C12-Executive-Summary.pdf

Figure 2 provides a simplified view of the core processes that work together in a WRRF to produce clean water and energy. Advancements in water resource recovery are likely to result in alternative configurations or technologies beyond those depicted in the figure.

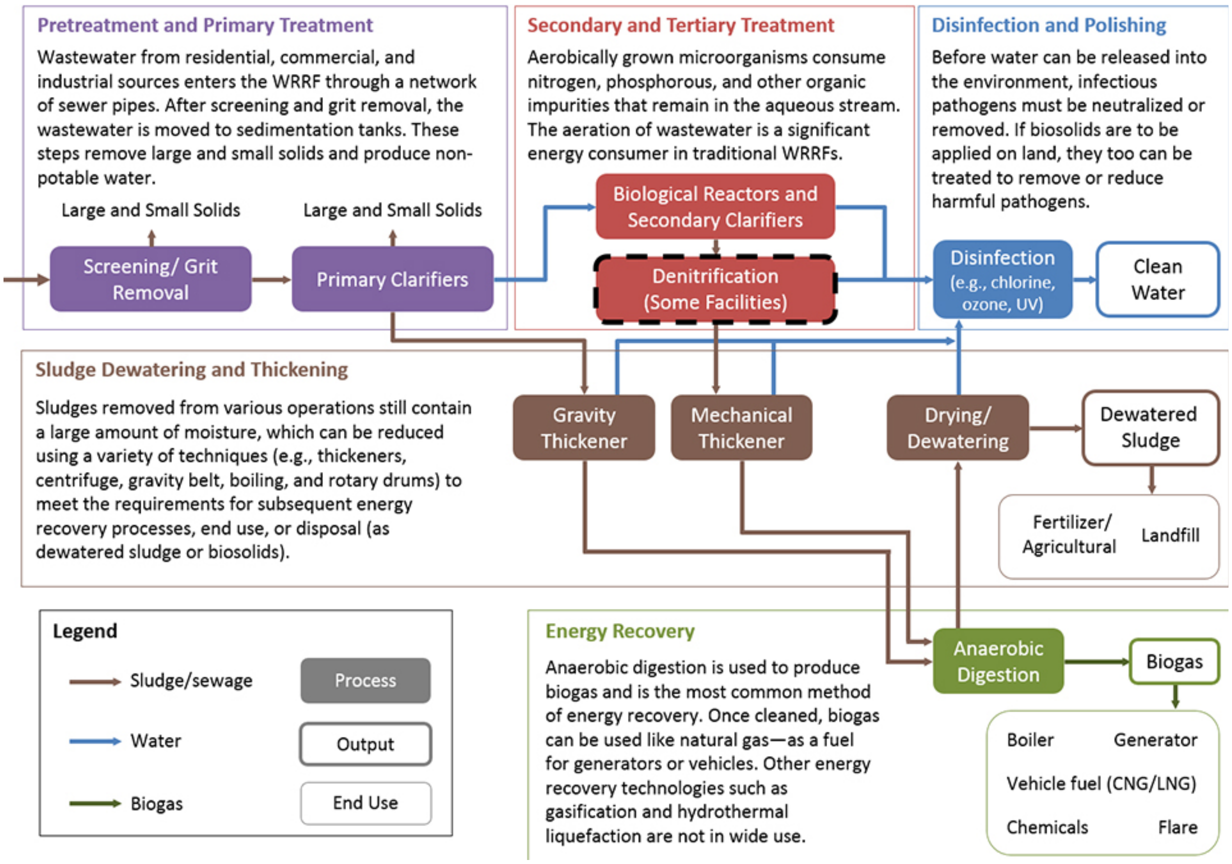


Figure 2: A Simplified View of Water Resource Recovery Facility Operations

WRRF Operation Metrics

New WRRF technologies are designed to improve upon the performance metrics of existing systems. To assess this potential, Lux Research modeled the energy usage and operating metrics associated with an average WRRF:[15]

- Daily wastewater volume: **100,000 m^3**
- Population: **180,000**
- Energy consumption: **0.4 kilowatt hours per cubic meter**
- Staff: **46**
- Annual sludge production: **3,150 tons** dry, or **12,600 tons** at 25% solids
- Minimum footprint: **12.5 acres**
- Annual operating cost: **$4 million**

[15] Giles, Brant. "Giving Wastewater a Boost with Breakthroughs in Secondary Treatment." Lux Research. Presentation, Arlington VA, April 2015. http://sites.energetics.com/EPWRR/downloads/presentations/Giles_Washington_DC_April_2015_WW.pdf

Energy Usage

At an average plant, the single most energy-intensive operation is aeration, which consumes 57% of total energy (Figure 3).[16] During the activated sludge treatment process [red box in Figure 2], microorganisms digest the nutrients in the sludge—a process that requires oxygen. To prevent oxygen diffusion from becoming the rate-limiting step, air is continuously added to the water. Even at the advanced Blue Plains facility operated by DC Water, aeration consumes 34% of the electricity used.[17] Reducing or even eliminating the need to aerate sludge would address the largest single energy-consuming operation at a WRRF.

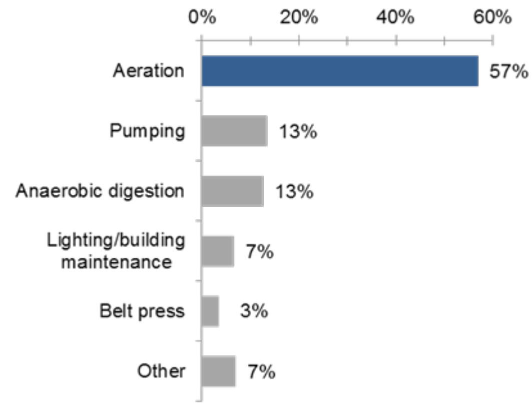


Figure 3: Energy Breakdown at WRRFs

Pumping is part of many plant operations, and the associated energy demand is generally proportional to the volume of sludge that must be moved around the plant. These pumps would require less energy if the waste streams were better separated initially to reduce volume and increase their homogeneity.

Another potential target for energy savings is the anaerobic digestion process [green box in Figure 2], which recovers energy from waste to produce biogas. Increasing biogas yields or production rates would help to offset energy use and potentially enable construction of smaller facilities. Facility operations (e.g., lighting and building maintenance) offer other potential energy-reduction targets, but aeration remains the single largest opportunity.

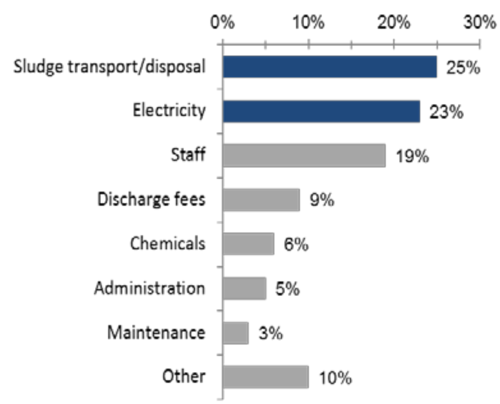


Figure 4: WRRF Operating Cost Breakdown

Operating Costs

Two elements of WRRF operation account for nearly half of operating costs: (1) sludge transport/disposal and (2) energy (electricity), as shown in Figure 4.[18] About 60% of all sludge ends up in landfills—at an average tipping fee of $35 per ton.[19] Finding ways to either reduce the volume of sludge created or endow it with value as a nutrient-rich commodity could significantly reduce operating budgets. In offsetting electricity consumption, facilities seek to recover energy from nutrients and add renewable energy generation onsite (e.g., solar panels).

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16 Giles, Brant. "Giving Wastewater a Boost with Breakthroughs in Secondary Treatment." Lux Research. Presentation, Arlington VA, April 2015. http://sites.energetics.com/EPWRR/downloads/presentations/Giles_Washington_DC_April_2015_WW.pdf

17 Ramirez, Mark. "Report from the Field: Nutrient and Energy Recovery at DC Water." DC Water. Presentation, Washington, DC, March 18–19, 2015. http://energy.gov/eere/fuelcells/downloads/report-field-nutrient-and-energy-recovery-dc-water.

18 Giles, Brant. "Giving Wastewater a Boost with Breakthroughs in Secondary Treatment." Lux Research. Presentation, Arlington VA, April 2015. http://sites.energetics.com/EPWRR/downloads/presentations/Giles_Washington_DC_April_2015_WW.pdf

19 Ibid.

Costs of Water Supplies

Understanding the cost of each incremental unit of water can provide insight on technology choices, particularly in water-starved regions like Southern California. The Los Angeles Department of Water and Power evaluated the costs of various supply options (see Figure 5)[20] and found that the cheapest way to increase the supply of water is to conserve it. The next cheapest strategy is to purchase municipal water, if available. As shown in the figure, stormwater capture may overlap these two resources, but costs largely depend on the physical infrastructure needed to gather and manage this intermittent water supply. In arid regions or during droughts, groundwater and stormwater may not be available options.

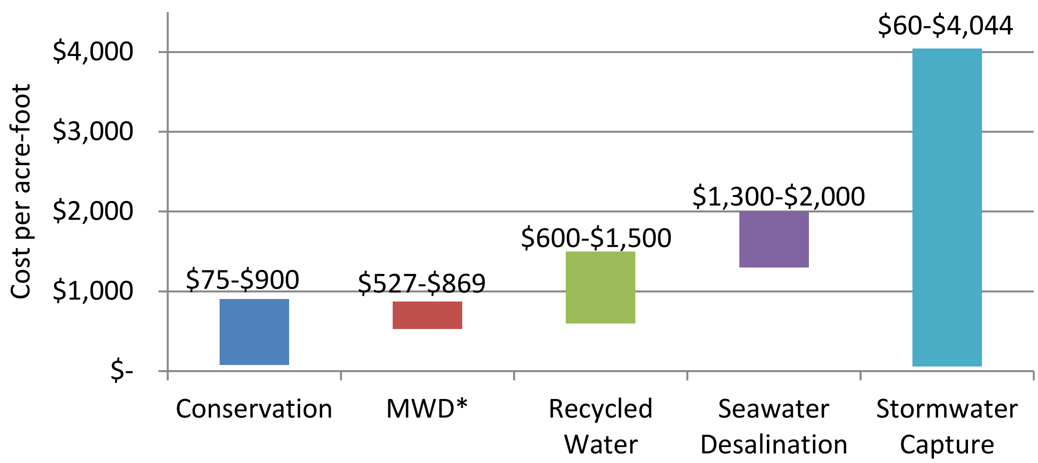


Figure 5: Cost Comparison of Water Supplies in Los Angeles, California (2010)

*Municipal Water District of Southern California Note: These costs do not necessarily apply to other regions of the United States. Costs reported in the graph make no comment on the supply, particularly in light of the ongoing drought (2015).

As water needs threaten to exceed supplies, many communities pursue two of the higher-priced options—recycled water and saltwater desalination—to make up the shortfall. Recycled water is anticipated to be about 35% cheaper (on average) than seawater desalination. Despite the cost, many communities in California, such as San Diego, are turning to desalination to meet consumer demand for potable water.[21] These costs are related to the amount of energy required to treat the water so that it meets drinking water standards.[22]

Small and Large WRRFs

The size of a WRRF implies an array of associated operating characteristics or challenges that can affect the range of practical and cost-effective technology options. (See Table 1). Upgraded hardware designed for small plants may not work at larger plants or vice versa. This bifurcation means that technology developers must properly target each market in accordance with its needs, expectations, and capabilities.

[20] Los Angeles Department of Water and Power. Urban Water Management Plan and Water Resources Division. Last modified December 6, 2011. www.water.ca.gov/urbanwatermanagement/2010uwmps/Los%20Angeles%20Department%20of%20Water%20and%20Power/

[21] Carlsbad Desalination Project. The Carlsbad Desalination Project. Accessed July 24, 2015. http://carlsbaddesal.com/

[22] U.S. Department of Energy (DOE). The Water-Energy Nexus: Challenges and Opportunities. DOE,2014. http://energy.gov/sites/prod/files/2014/07/f17/Water%20Energy%20Nexus%20Full%20Report%20July%202014.pdf

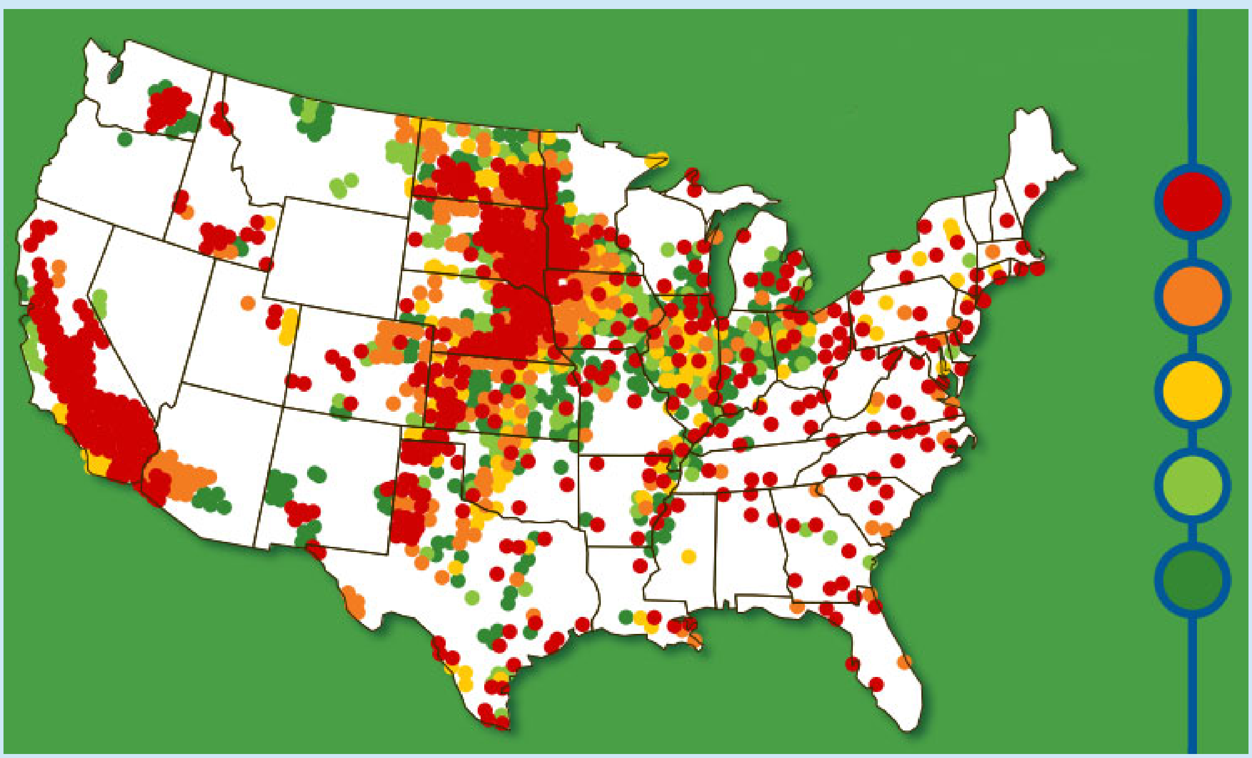
Table 1: Comparison of Typical Small and Large WRRFs[23]

Smaller Facility	Larger Facility
• ~93% of facilities • Process ~23% of all wastewater • Serve ~27% of U.S. population • Largely in rural locations • Space is largely available • <5 million gallons per day (MGD), down to less than a 1 MGD • Many facilities operate below capacity • Close to farms for land application of biosolids	• ~7% of facilities • Process ~77% of all wastewater • Serve ~66% of U.S. population • Close to population centers • Space is at a premium • >5 MGD • Many facilities operate near capacity • Typically need to transport biosolids a significant distance

Note: In 2008, some populated areas of the United States were not served by a WRRF. The size cutoff of 5 MGD is used broadly to indicate typical facility characteristics and is not a prescriptive measure.

Water Scarcity in the United States

Columbia University Water Center compared precipitation data with water use patterns over the past 60 years to identify localities at risk for drought. The analysis does not include imported river water or mined ground water, which commonly supplement precipitation-based drinking supplies. Highest risk areas are shown in red, lowest in green. Areas found to be at high risk include Washington D.C., New York City, California, and the Upper Midwest. If a WRRF were better able to utilize treated water, these communities could continue to grow sustainably.



Source: Shi, Daniel, Naresh Devineni, Upmanu Lall, and Edwin Pinero. *American's Water Risk: Water Stress and Climate Variability.* Columbia Water Center and VEOLIA Water, 2013. http://growingblue.com/wp-content/uploads/2013/05/GB_CWC_whitepaper_climate-water-stress_final.pdf

[23] U.S. Environmental Protection Agency. "Clean Watershed Needs Survey Overview." Last modified September 14, 2012. http://water.epa.gov/scitech/datait/databases/cwns/

The Water Resource Recovery Facility of the Future

Workshop participants discussed the *WRRF of the Future* and the key capabilities it should possess. Functions suggested in the four parallel breakout groups can be summarized as follows: The *WRRF of the Future* (1) recovers the resources in wastewater, (2) is integrated with other utilities, (3) engages and informs stakeholders, and (4) runs smart systems.

Resource Efficiency and Recovery

Wastewater can be constructively understood as a rich mixture of resources worth recovering—in contrast to something that must be remediated. The treatment process can generate numerous beneficial products. The *WRRF of the Future* will recognize the value of each of these streams as it approaches the goal of zero waste.

The need for water treatment is predicated on the responsible stewardship of water, chemical, and energy resources. WRRFs have the opportunity to take a fresh look at their operations and envision a more efficient approach to both inputs and outputs. One essential tactic is to examine the spectrum of fit-for-purpose water (see sidebar on Fit-For-Purpose Water Recycling), wherein water is not always treated to a potable standard, but is instead treated to various standards that enable its efficient reuse in specific applications (e.g., cooling).

Fit-For-Purpose Water Recycling

In the 1990s, unsustainable agricultural water use in Salinas Valley, California, depleted groundwater levels and increased saltwater intrusion into groundwater. In response, a water reclamation facility was built to recycle the water for use in irrigating food crops. The ability to irrigate crops without imported water created more sustainable farmland.

The West Basin Municipal Water District recycling program in Los Angeles, California, produces five types of water for different applications: irrigation water, cooling tower water, seawater barrier and groundwater replenishment water, low-pressure boiler feed water, and high-pressure boiler feed water. While none of these types meet the standards for potable water, they are tailored to the needs of specific applications. Avoiding unnecessary treatment steps conserves energy and reduces wear and tear on equipment.

West Basin Municipal Water District. "Recycled Water." Accessed July 24, 2015. www.westbasin.org/water-reliability-2020/recycled-water/about-recycled-water

Resource Recovery and Utilization

One of the first places to look for underutilized value in a WRRF is the clean, treated effluent, which is often simply released into the nearest body of water. Better ways to manage this water may include treating it to a different standard and selling it. Wise stewardship of resources, particularly water, entails taking a broader perspective and identifying its best use.

Biogas must similarly be understood as an in-situ source of energy—not to be wasted through flaring. This renewable natural gas should be productively used to generate power or made into a range of useful chemical products.

Many streams in a WRRF are rich in nitrogen and phosphorous. Currently, these streams are often used as fertilizer for farmland. These partially treated, nutrient-rich streams may potentially hold value for additional sectors of the economy. Reimagining treatment of these streams to maximize their value while minimizing environmental impacts could significantly reduce energy loads and costs at a WRRF. Building the *WRRF of the Future* demands a comprehensive exploration of the resources contained in wastewater and how best to capture their value.

Improved Aquatic and Marine Ecosystems

Wastewater treatment can help to soften the impact of human activity on aquatic and marine ecosystems. By taking a broader systems perspective, planners might redesign water treatment to create symbiotic relationships with these ecosystems (see sidebar on Water Treatment Nature Preserve). Sustainable solutions must address the needs of the local watershed. The *WRRF of the Future* will require ideas, technologies, and practices that economically and efficiently treat water and enhance environmental quality across the watershed.

Emissions associated with energy use and industrial operations exert a significant impact on ecosystems at a larger scale. Instead of venting the CO_2 fraction of biogas, technologies that economically sequester or use the carbon could reduce greenhouse gas emissions.

Water Treatment Nature Preserve

The Egret Marsh Stormwater Park in Indian River County, Florida, improves water quality by removing 80% to 90% of dissolved nitrogen and phosphorous from runoff. It accomplishes this using an algal turf scrubber. The algae grow after digesting the nutrients and must be thinned every couple of weeks. With the improved water quality, many species of birds, amphibians, fish, reptiles, and insects now flourish in this unintentional nature preserve. Local groups may soon begin offering birdwatching tours through the facility. These passive systems can supplement existing WRRF, but are unable to handle the concentrated volumes of larger systems.

Baker, Richard. "Algae Farm—A New Birding Site!—Egret Marsh Stormwater Park—Thanks to Keith McCully." Last modified September 2010. www.pelicanislandaudubon.org/Hoot_Archive/hoot_september_10.html

Financial Sustainability

In an era of shrinking budgets, a WRRF that adds value—by generating income from recovered nutrients, energy, and chemicals—will likely be attractive to many water districts. If an environmentally and socially sustainable WRRF were to also demonstrate economic sustainability, it would have a clear and positive role in almost any community. Facilities that measure up in all three aspects of this "Triple Bottom Line" will approach true sustainability.

Integration with Other Utilities

The vision for the *WRRF of the Future*, as laid out by the participants, involves a significant amount of collaboration, integration, and coordination with facilities and operations outside of traditional plant boundaries. Participants stressed cooperation and collaboration to improve the services delivered to the public. This integration requires a collective effort to deliver a higher level of service.

Integrated with Power Systems

WRRFs today are often the single largest consumer of energy in a community. The movement toward net-positive water utilities focuses on reducing energy consumption and increasing energy generation during the water treatment process. These steps enable facilities to participate in demand-response activities and potentially delay investments in new power-generating capacity. Integrating the power and water infrastructures represents a new focus for these utilities. Aside from the benefit of producing energy, this approach may enable WRRFs to operate independently of the grid and maintain critical services during power outages.[24]

[24] Olsen, Daniel, Sasank Goli, David Faulkner, and Aimee T. McKane. Opportunities for Automated Demand Response in Wastewater Treatment Facilities in California—Southeast Water Pollution Control Plant Case Study. LBNL-6056E. California Energy Commission and Lawrence Berkeley National Laboratory, 2012. http://drrc.lbl.gov/publications/opportunities-automated-demand

Wikler, Greg, Phil Martin, Bo Shen, Girish Ghatikar, Chun Chun Ni, and Junqiao Han Dudley. Addressing Energy Demand through Demand Response: International Experiences and Practices. Lawrence Berkeley National Laboratory and ENERNOC, Inc., 2012. http://drrc.lbl.gov/publications/addressing-energy-demand-through

Fully Integrated Water Utilities

Wastewater, drinking water, and, in rare instances, stormwater have historically been managed by separate entities, despite their closely related missions. Collaboration among these entities will provide a more complete understanding of water-related infrastructure and could meet the needs of the public more efficiently.

Integrated with Waste Infrastructure

WRRFs and the broader waste infrastructure are managed separately, but both can share the benefits of technology advancements. For example, both WRRFs and landfills produce biogas, so technology improvements in this area could find multiple markets and drive innovation. In addition, anaerobic digesters can use organic waste streams that might otherwise occupy space in landfills. Ultimately, integrated efforts to efficiently utilize all forms of waste to generate the highest value for the entire community will lead to more efficient operations across infrastructures.

Wastewater Power Plants: Strass Plant in Austria

Austria's Strass wastewater treatment plant produces 25% more electricity than it needs to treat the water. Serving 60,000 people in the summer and 250,000 people in the winter (ski season), the plant has a peak capacity of 10 mgd.

The Strass plant generates surplus power through a strategic commitment to being as energy efficient as possible. Enabling developments include implementation of a novel side-stream nitrogen removal process (nitration/anaerobic ammonium oxidation [anammox]), improved dewatering and sludge thickening, better process sensing, and state-of-the-art cogeneration units.

Water Environment Research Foundation (WERF). *Sustainable Treatment: Best Practices from the Strass im Zillertal Wastewater Treatment Plant*. WERF, Case Study, 2010. http://brownfields-toolbox.org/download/office_of_water/Strass%20WWTP%20Energy%20Case%20Study.pdf

Integrated with Nature

WRRFs play a critical role in maintaining aquatic and marine ecosystems, ensuring that only properly treated water is released back into the environment. Efforts to maintain and improve these systems will need to look beyond permitted standards and potentially consider more rigorous treatment targets. Active environmental monitoring could identify needed improvements in the treatment process to avoid harmful, but as yet unmonitored, run-off (e.g., antibiotics). In some cases, treatment operations could even be supplemented by natural filtering and cleaning ecosystems (see sidebar on Water Treatment Nature Preserve, p. 10).

Engaged and Informed Communities

WRRFs are utilities and must therefore answer to the public. Helping ratepayers understand the aims, processes, and challenges of water treatment can build public support for improved WRRFs. Planners need to regularly interface with the public and engage them early in the planning process to integrate community goals and priorities into WRRF operations.

Educated Customers

Water treatment efforts have traditionally remained out of sight. In the future, the public should be more actively engaged. Water utilities need to raise public awareness of water demand, supply, and critical water treatment services. Outreach to teachers and other educators can help to develop lesson plans that engage young minds, enhance understanding, and generate support for building the *WRRFs of the Future*.

Improved customer education may require facilities to find better ways to communicate. Data visualization programs and infographics have produced positive impacts for energy conservation efforts,[25] and these tools could favorably impact water usage and treatment. Sewage bills could be expanded to show usage, tell stories, and incorporate messaging that informs and engages.

Trained Staff

Participants at the workshop identified a shortage of technically capable water treatment professionals. To develop the next-generation workforce, outreach efforts should target students of all ages, with a particular focus on college students choosing a career. A concerted effort to develop and train the next generation of workers will ensure that facilities have ready access to talented engineers, scientists, and operators.

Given the sophisticated systems projected to be in use at WRRFs, a national certification program would help to foster and recognize operator competency. Requiring certified personnel to regularly renew their certification would help disseminate evolving knowledge of best practices and the effective use of new technology—helping to ensure that water treatment professionals stay up to date and employ the latest and best methodologies.

Water Reuse in Space

On the International Space Station, each crewmember is allocated about two liters of water per day. If wastewater is not recycled, it quickly becomes a limiting factor for mission duration, size, and scope. All wastewater streams are processed aboard the station to extract and recycle the water, including urine and sweat. However, the challenges of water treatment are significantly complicated by weightlessness in a free-fall environment.

The unit on the space station currently uses a distiller that spins to generate a centripetal force that counteracts the free-fall environment. Contaminants press against the sides of the spinning drum while the steam gathers in the middle and is pumped to a filter. The collected steam is then filtered in much the same way as on Earth to produce drinking water. In all, the unit recycles about 93% of the water it receives.[a]

NASA researchers are now working on a system capable of recovering more than 95% of all exploration wastewater—including hygiene and laundry. This system uses a membrane-aerated bioreactor to destroy organic contaminants, and a forward-osmosis secondary treatment system to remove dissolved solids. While these technologies were initially developed for use in space, they are helping to improve the sustainability of terrestrial systems.[b]

[a] Siceloff, Steven. "Recycling Water is Not Just for Earth Anymore." Last modified October 23, 2010. www.nasa.gov/mission_pages/station/behindscenes/waterrecycler.html

[b] NASA. "NASA Targets Water Recycling System for Rapid Development." Last modified July 28, 2013. www.nasa.gov/centers/ames/news/2013/WaterRecyclingSystem_7_Feb_2013.html#.VV5YBvm6dqM

Smart Systems

If *WRRFs of the Future* are to accomplish more with the same resources, they will need to make intelligent use of advanced technologies and systems. Existing and emerging technologies, including some already adopted in other economic sectors (e.g., chemicals processing), could significantly enhance the operation of these facilities.

Sensors

The ability to monitor, interpret, and react intelligently to changes in waste stream composition is predicated on the installation of a broad suite of sensors in the *WRRF of the Future*, both on site and throughout the sewer system. Advanced treatment facilities will require detailed knowledge of the

[25] Meyers, Steven, Evan Mills, Allan Chen, Laura Demsetz. "Building Data Visualization for Diagnostics". ASHRAE Journal. June 1996. http://energy.lbl.gov/emills/pubs/pdf/data-vis.pdf

whole system to efficiently anticipate, diagnose, and react to changing conditions and maximize the value of all streams. While sensors generate masses of information, having the right information is critical in decision making. Diagnostic sensing requires the capability to discern the signal from the noise and then to react appropriately. To achieve maximum benefit from this technology investment, the WRRF workforce will need to know how to correctly interpret data from sensor networks and adjust plant operations accordingly.

Tailored Treatment Systems

Treatment technologies at the *WRRF of the Future* will move beyond the one-size-fits-all approach and will dynamically tailor treatments to the characteristics of the resource and local demand options. These tailored treatment systems will enable finer tuning of operations to maintain sustainability and profitability. Adaptive treatment equipment will necessarily entail an advanced degree of automation. Systems will adjust and optimize processing conditions in response to sensor data. Such intuitive processes would make operations leaner on a day-to-day basis, avoiding direct human response and modifications to the system. The ability of the equipment to adapt to a wide variety of processing conditions could improve both the operation and functionality of the WRRF.

Resource Recovery in Breweries

Brewers around the country have found innovative ways to recycle resources to save energy and create value added products.

In 2008, Alaskan Brewery in the remote coastal community of Juneau, Alaska, installed a mash filter press, which reduced water needs in the first year by nearly 2 million gallons. The reduced moisture content of the spent grains also increased the energy efficiency of their spent grain boiler and results in savings of nearly 65,000 gallons of diesel fuel each year.

Blue Marble Biomaterials has developed a proprietary polyculture fermentation technology that uses spent grain to create both biogas and specialty chemicals for use as flavor additives. Another company, Nutrinsic, is piloting a bacterial conversion technology that uses the nutrients in brewery wastewater to produce proteins for animal feed.

Alaskan Brewing Co. "Beer Powered Beer". Accessed July 30, 2015. https://alaskanbeer.com/beerpoweredbeer/

Bomgardner, Melody M. "Plant to Make Protein from Wastewater." C&EN 93 (2015): 19. http://cen.acs.org/articles/93/i21/Plant-Make-Protein-Wastewater.html?type=paidArticleContent

Adaptive Outputs

A salient characteristic of the *WRRF of the Future* will be versatility—the ability to actively adjust operations and generate different outputs in the face of a changing environment. As an example, a power outage may trigger the facility to operate in island mode and to generate as much energy as possible, potentially powering the surrounding community. Such a capability, which would essentially allow a WRRF to serve as a power producer (or manufacturer), would require adjustments in the marketplace. The ability to significantly modify industrial operations and output (e.g., energy, chemicals, or other products) in response to external or internal stimuli would represent a significant advance.

Industrial Resilience

The *WRRF of the Future* should be resilient to the inherent variability of waste streams and be able to intelligently adapt. Wastewater is a highly variable feedstock, occasionally presenting unique and unanticipated elements. Industrial operations often have difficulty in handling this degree of variation, and equipment that better tolerates variability will be valuable to next-generation WRRFs. As an alternative strategy, facilities may minimize variability by blending incoming wastewater streams. The ability to understand the key criteria of the resource and continuously adjust treatment and recovery processes in real time would represent a significant advancement over current operations.

Continuous Process Improvement and Learning

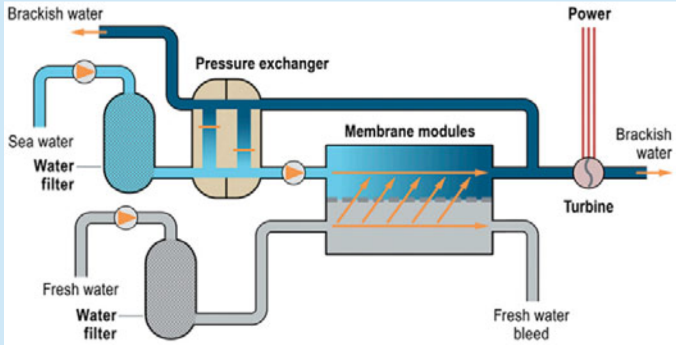
Sensors and automated systems will be used widely in the *WRRF of the Future* and will generate large amounts of discrete data about operations at the facility. The utilization rather than the mere collection of this data will make the industrial systems smarter. The techniques of Big Data, including data management, predictive analytics, and visualization, will provide new insights into optimizing plant operations. Collection of parallel data sets at many different WRRFs will also enable operators to quickly identify best practices and learn from each other. Learning efforts can be further extended to include other industrial sectors with similar machinery, including chemicals and power generation. By incorporating the learning potential of Big Data, WRRFs could continuously improve their operational efficiency without making large investments in new equipment.

Reimagining the WRRF

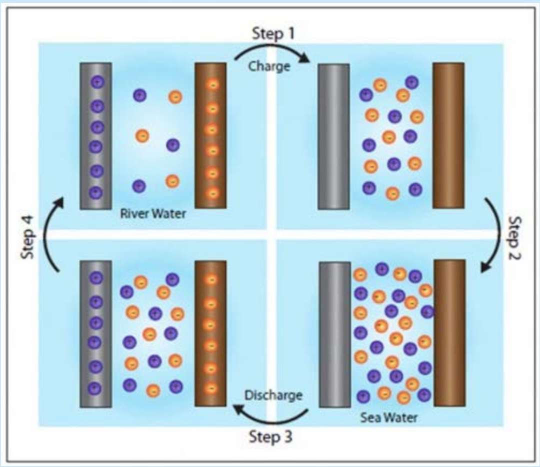
Future facilities should not be constrained by the appearance or operation of current systems. Decentralization is a novel approach that may offer significant benefits. For example, WRRFs might locate scaled-down components close to point sources or industrial parks, where less diluted waste streams could improve efficiency and reduce overall capacity needs. This approach might require rethinking land requirements and finding innovative ways to integrate WRRFs into existing infrastructure. If decentralization provides clear advantages over the traditional centralized facility, modularity might become a key attribute of WRRF systems technology. This modularity would allow facilities to grow or shrink as needed capacities change over time or location.

Potential Energy Recovery from Salinity Gradients

Differences in salinity between the discharges from WRRFs and the brine streams of desalination plants present a potential source of energy. In combination, these streams provide opportunities for both mechanical and electrochemical electricity generation.



Pressure retarded osmosis (PRO): The difference in salinity can constitute sufficient osmotic force (pressure) to push enough water through a semi-permeable membrane to drive a turbine. This process, termed pressure-retarded osmosis, has potential application wherever sufficient sources of both fresh and salt water exist in close proximity. In 2009, the Norwegian power company Statkraft started a prototype facility capable of producing 2-4kW. This prototype at a river mouth was abandoned in 2012 due to unfavorable economics, but advances in membrane technology could make the technology financially viable in niche applications, such as WRRFs co-located with desalination plants or closed-loop systems that utilize waste heat to recharge.



Capacitive mixing: By cycling electrodes between a high potential state and low potential state, energy can be stored and subsequently released by the movement of salt ions. Researchers at Penn State and Stanford developed an example of this process, which they call an "entropy battery." It uses Na+ and Cl- ions (table salt) to store the charge. The electrodes are charged when fresh water flows between the electrodes, removing the salt ions from the electrodes. Once most of the ions have been removed, the water solution is replaced by one with high salinity, causing the ions to move back into the electrodes and generate electricity at 74% efficiency. In The Netherlands, Redstack, Fujifilm, and Wetsus built a 50-kW capacitive mixing pilot plant, which opened in 2014.

PRO: Brandon, Alan. "New Type of Rechargeable Battery—Just Add Water." Gizmag. May 5, 2011. www.gizmag.com/rechargeable-battery-freshwater-seawater/18565/; Thresher, R.; Denholm, P.; Hagerman, G.; Heath, G.; O'Neil, S.; Paquette, J.; Sandor, D.; Tegen, S. "Ocean Energy Technologies," Chapter 9. National Renewable Energy Laboratory. Renewable Electricity Futures Study, Vol. 2, Golden, CO: National Renewable Energy Laboratory; pp. 9-1–9-36.

Capacitive Mixing: Yirka, Bob. "New Entropy Battery Pulls Energy from Difference in Salinity between Fresh Water and Seawater." Phys.org. March 25, 2011. http://phys.org/news/2011-03-entropy-battery-energy-difference-salinity.html

Dutch Water Sector. "Dutch King opens world's first RED power plant driven on fresh-salt water mixing." November, 26, 2014. www.dutchwatersector.com/news-events/news/12388-dutch-king-opens-world-s-first-red-power-plant-driven-on-fresh-salt-water-mixing.htm

Challenges to Advancing the State of the WRRF

Workshop participants discussed the major challenges involved in building the next-generation WRRF. The challenges they identified are presented below. The order of presentation should not be interpreted as a reflection of their relative importance or degree of difficulty.

Regulatory

Narrow Focus

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 action, including fines. The threat of enforcement is a powerful motivator, creating a singular strategic focus among facility managers. The resulting culture emphasizes permit compliance, often at the expense of other actions that are in their self-interest, including investments in energy efficiency to reduce costs. While the 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.

Aquatic Ecosystem Health

Regulations are currently set up to measure the concentration of pollutants in the effluent stream. Instead, it might be possible to focus on the health of the aquatic ecosystems into which the treated water is released. Since not all ecosystems are equal, this approach would allow each WRRF to tailor treatment to the resilience of the ecosystem. A regulatory system focused on aquatic ecosystem health would introduce a degree of flexibility that could potentially yield better results; however, workshop participants recognize that this set up may prove too burdensome or not cost effective.

Technology Deployment and Validation Challenges

Lack of Standards

Facility managers considering the purchase of new equipment or implementation of new practices need access to reliable, validated data from the field. Successful demonstrations build confidence that innovative approaches are compatible with current systems and operating environments. Currently, the lack of rigorous testing protocols and parameters impede the development of field data to support purchasing decisions and accelerate market adoption.

Need for Pioneering Facilities

In a regulated utility environment, there is little benefit for being the first to implement an innovative technology or practice. Historically, each WRRF has been motivated to deliver a basic level of service with well-known technologies. However, technologies only reach this well-known status with a number of implementations at facilities of varying needs and sizes. With few, if any, facilities willing to be the first to use new and innovative technologies and practices, market acceptance can be significantly delayed. A facility—or multiple facilities—dedicated to piloting new technology would overcome this barrier and promote market acceptance.

Scale-Up of New Technologies

In deploying a new technology, applications at the pilot and demonstration scales provide critical information to guide the far more costly and complex process of scaling up to a commercial-size installation. No single scale is recognized as sufficient to attract industry investment, but understanding all that is required to validate a particular technology in its target market is key to gaining market acceptance and accelerating commercial deployment.

Need for Process Monitoring/Sensing

Real-time sensing of process conditions and key metrics (i.e., biochemical oxygen demand) will provide a level of information not currently available to most facility operators. The lack of granular, real-time monitoring of operations limits process improvements at a WRRF.

Monetizing Wastewater Treatment Outputs

Wastewater contains diverse resources that can be recovered and monetized in various ways (i.e., sold as energy or chemicals). Among the largest waste streams are biosolids, which can be a source of organic, nutrient-rich fertilizer. However, land application of biosolids is often limited by the level of contaminants, and biosolids often end up in landfills. Finding a higher-value market or processing biosolids to meet customer specifications could reduce this high-cost item or even convert it into a revenue source. In addition, the public tends to consistently undervalue the role of water treatment in maintaining the environment; greater focus should be placed on identification and monetization of such externalities.

Test Beds for New WRRF Technologies

Test beds have been set up across the country to help developers test equipment. Two operational examples are the Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, New Mexico, and the Codiga Resource Recovery Center (CRRC) at Stanford University in Palo Alto, California.

The BGNDRF opened in 2007 and is run by the U.S. Department of the Interior. It specifically focuses on "brackish groundwater desalination; renewable energy integration; development of systems for rural and Native American communities; concentrate management; and treating water produced from oil and gas production." [a]

Stanford University is building the CRRC facility to accelerate the "commercial development of new wastewater technologies by testing at a scale large enough to demonstrate a process's effectiveness and stimulate investment for full-scale implementation. The center will also test technology that is mobile and can be deployed at remote locations."[b]

[a] U.S. Department of the Interior Bureau of Reclamation. "Brackish Groundwater National Desalination Research Facility." Accessed July 24, 2015. www.usbr.gov/research/AWT/BGNDRF/

[b] Chesley, Kate. "New Stanford Facility Will Test Water-Recovery Technology." Last modified March 24, 2014. http://news.stanford.edu/news/2014/march/water-recovery-facility-032414.html

Research Challenges

Limited Molecular Understanding of Heterogenic Microbial Communities

The molecular processes and reaction kinetics that occur during biological wastewater treatment are not fully understood. These processes and reactions could potentially be enhanced with better characterization of the synergistic interactions that occur among diverse microbial communities during the conversion of municipal sludges into biogas, clean water, and potentially other beneficial products.

Reducing Energy Consumption

Becoming net energy-positive will require facilities to reduce the energy consumed per unit of water processed. Current WRRFs require several energy-intensive processes, led by aeration.[26] As noted earlier, the aeration of activated sludge alone can account for about 57% of WRRF energy consumption. Advanced treatment plants that remove nitrogen must *further* aerate the sludge. DC Water, an advanced treatment facility, spends fully 20% of its energy just on nitrification aeration. Technologies and processes that reduce the energy requirements of aeration or provide an alternative represent a significant energy-savings opportunity, particularly with denitrification. Auditing and applying best practices to other energy-consuming processes at WRRFs—such as pumping, heating, and lighting—could also reduce the energy required to treat water. While energy reduction efforts should focus on aeration, WRRFs will need energy-efficient solutions across the system to become net energy positive.

Methane Recovery

Biogas produced during anaerobic digestion (AD) is a dilute, impure stream of approximately 40%–60% methane (natural gas) and the rest inert CO_2. Prior to combusting the methane for power and heat generation, significant industrial effort must be spent to remove impurities like siloxanes, which foul the combustion systems or cause the system to violate emissions rules. To operate efficiently, some engines—especially vehicle engines—require a higher methane-content (higher heating value) stream, so the CO_2 must be removed. Additional effort is required to separate the dissolved biogas when it is produced in an aqueous stream. Research into separations technologies would improve yields and favorably impact process economics, maximizing energy production from the methane in biogas.[27]

Social and Behavioral Challenges

True Costs of Energy

Water treatment plants spend a significant share of their operating budgets on energy. These facilities have an opportunity to work with regulators and stakeholders to promote a broader view of environmental sustainability and quantify the social costs of carbon and water pollution. Raising awareness in this area would help justify capital investments that improve WRRF operations and reduce environmental impacts.

Political Will

In the absence of crises, there has been little political will to fundamentally change the value placed on water or alter public attitudes toward this resource. Finding creative ways to constructively engage the public and lawmakers (without inciting panic) could help to deploy the *WRRF of the Future* before less optimal decisions are forced in response to a catastrophe.

Support and Acceptance

The water treatment industry must continue—and improve upon—its effort to engage the public and increase public understanding of water resources. Raising awareness of water usage, as in reporting comparisons of neighboring households, can help reduce demand without large capital expenditures.

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[26] Ramirez, Mark. "Report from the Field: Nutrient and Energy Recovery at DC Water." DC Water. Presentation, Washington, DC March 18–19, 2015. http://energy.gov/eere/fuelcells/downloads/report-field-nutrient-and-energy-recovery-dc-water.

[27] National Renewable Energy Laboratory. Biogas and Fuel Cells Workshop Summary Report. NREL/BK-5600-56523. U.S. Department of Energy, 2013. http://energy.gov/eere/fuelcells/biogas-and-fuel-cells-workshop.

Industry Conservatism

The water treatment industry is conservative and has long planning cycles. Historically, water treatment facilities have focused on treating wastewater to meet minimum regulatory requirements. The costs for this treatment are then passed along to ratepayers. In this low-margin environment, the industry has little or no motivation to innovate or improve.

Valuing Clean Water

Water is undervalued in the United States. The general population regards clean water as a precious resource only when there is a shortage. Convincing consumers of the need to consistently conserve and recycle water would help consumers appreciate the role of WRRFs in managing a precious resource and improving community sustainability.

Workforce Education

WRRF operation will require a well-educated technical workforce. Workshop participants cited a lack of access to qualified staff with experience in the field. Among STEM fields, water treatment has failed to attract enough talented students to fill industry needs, creating challenges for plant operations. Creating an educational system that serves as a reliable pipeline for this workforce is essential to future WRRFs.

Energy Efficiency with No Upfront Cost

Energy savings performance contracts (ESPCs) allow federal entities to complete energy-saving projects without up-front capital costs and special Congressional appropriations. Typically, an energy service company (ESCO) will conduct a facility audit and identify improvements to save energy. In consultation with the entity or facility, the ESCO designs and constructs a project that meets the agency's needs and arranges the necessary funding. The ESCO guarantees that the improvements will generate energy cost savings to pay for the project over the term of the contract (up to 25 years). After the contract ends, all additional cost savings go to the owner.

DOE. "Energy Savings Performance Contracts for Federal Agencies." Accessed July 24, 2015. http://energy.gov/eere/femp/energy-savings-performance-contracts

Financial Challenges

A key challenge for the *WRRF of the Future* is the lack of a sustainable financial model that accelerates the deployment of the WRRF while balancing the needs and desires of the public and the environment. Emphasis should be placed on identifying or creating such a model.

Tight Research Budgets

Federal and state government funding for water treatment research has been scarce for decades. Severely constrained government funds have hampered all stages of technology commercialization. Financial support for the full spectrum of research, from basic to field demonstrations, is needed to accelerate technology adoption.

Tight Facility Budgets

Revenue models for water treatment plants are typically based upon costs plus a fixed profit. This structure leaves little revenue for these utilities to conduct research or invest in innovative technologies, particularly at smaller facilities. Without budgets to enable capital improvements, the facilities must focus on maintaining service levels instead of building for the future. Greater leeway in the traditional revenue model could accelerate the timeline of the *WRRF of the Future*.

Innovative Financing

Many facilities that operate as regulated utilities suffer from chronic underfunding. Innovative financing mechanisms could provide funds for needed capital improvements without raising the fees for ratepayers.

Challenges of Upgrading Existing Facilities

Limited Physical Space

Many WRRFs are located near urban centers, where land is at a premium. A number of these facilities have little or no available physical space in which to install new capital equipment. This space limitation often necessitates considerable investment to completely remove existing equipment or purchase adjoining land, which may require rezoning.

Aging Infrastructure

Water utility facilities typically have a useful life of 20–50 years, and many current facilities are approaching the end of their expected lifetimes. Many of the water and sewer pipes buried under cities are also approaching the end of their expected lifetimes. The need to update, rehabilitate, or expand this infrastructure offers a clear opportunity to introduce improvements that go well beyond simple replacement with a newer version of the same technology.

Continuous Operation

WRRFs are often expected to operate continuously. Participants in the workshop challenged this line of thinking, particularly in smaller plants that might benefit from intermittent operation. The impact of such an operational change is not fully understood, however, and merits further research.

Size Bifurcation by Facility

Water treatment facilities can be broadly assigned to one of two facility classes based upon their size (see Table 1 on page 8). Upgraded hardware designed for small plants may not work at larger plants and vice versa. These differences mean that technology developers must properly accommodate and target the needs, expectations, and capabilities of each market.

Equipment Integration

The thousands of water treatment facilities in operation across the United States today were constructed to meet a variety of specifications. Few efficient technologies, particularly newer ones, are versatile enough to work with the full suite of existing equipment.

Water Main Break

On July 29, 2014, a 94-year old water main under Sunset Boulevard near the University of California-Los Angeles broke, spilling 20 million gallons of water. This water damaged buildings, facilities, and cars on and around campus. The Los Angeles Department of Water and Power received 190 claims for damages, including the wood floor of Pauley Pavilion. While insurance will cover the damage, claims related to failure of infrastructure at or beyond its useful lifetime will continue to be an issue across the country.

Gordan, Larry, and Matt Stevens. “UCLA Flood: Estimate of Gallons Lost in Main Break Doubles to 20 Million.” *Los Angeles Times*. July 30, 2014. www.latimes.com/local/lanow/la-me-ln-ucla-main-break-gallons-lost-20-million-20140730-story.html

Walton, Alice. “UCLA Flood: DWP Starts Paying Damage Claims from Water Main Break.” *89.3KPCC.* September 11, 2014. www.scpr.org/news/2014/09/11/46642/ucla-flood-dwp-starts-paying-damage-claims-from-wa/

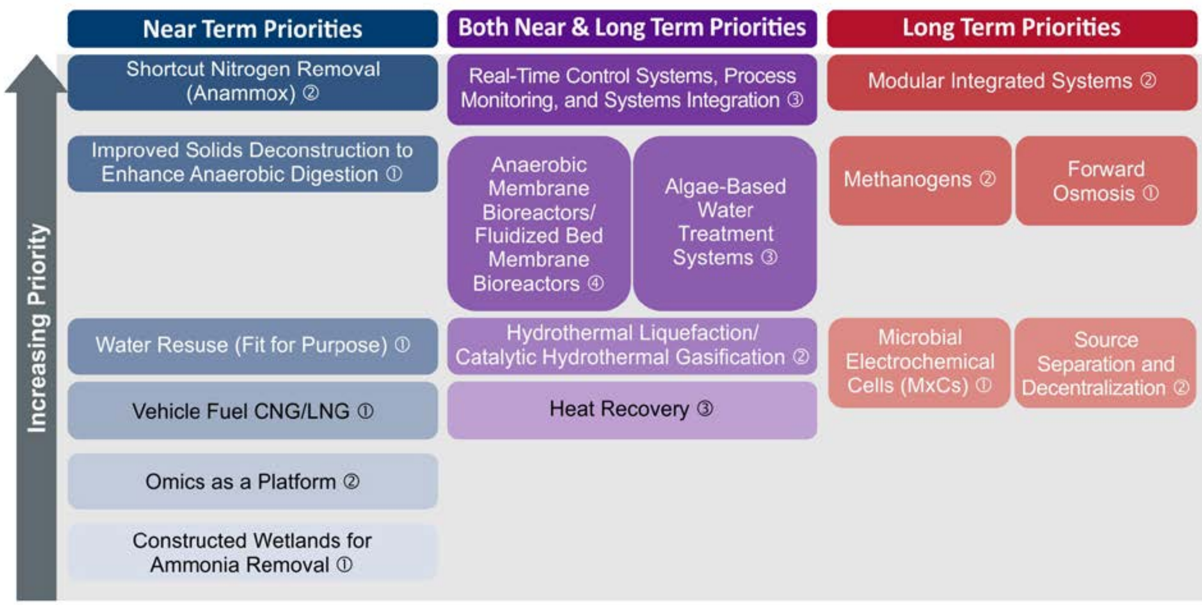
Integrating Utilities

WRRF services should be better integrated with other utilities in the community. Continuity and collaboration among these disparate operations could significantly enhance the services provided and reduce total costs. This could be as simple as adding a heat recovery system to a pipe when a hole already has to be dug to replace a water main. On a grander scale, this integration may require deep changes in regulations and business models.

Research Opportunities

Based on the key challenges involved in building the *WRRFs of the Future*, workshop participants in the four breakout groups identified and discussed key opportunities for research to reduce these challenges and accelerate appropriate technology deployment. In total, the groups identified 106 research opportunities. They identified 16 of these opportunities as top priorities: six near term, five long term, and six to be addressed in both the near and long term. The top research opportunities identified by the participants are summarized in Figure 7 and Table 2. These opportunities reflect the insights and judgements of the participating individuals rather than those of the organizations they represent.

While the participants discussed and voted on the top near-term (within 5–10 years) and long-term (10 years or more) opportunities within their separate breakout groups, some of the groups independently converged on the same topics. Moreover, some research opportunities identified as near term by one group were classified as long term by another, underscoring the uncertainties inherent in research timelines and outcomes. Appendix D contains the prioritization results from the four individual groups.



①Research area prioritized by a single breakout group; ②Research area prioritized by two different breakout groups; ③Research area prioritized by three different breakout groups; ④Research area prioritized by all four breakout groups

Figure 7: Prioritized Research Opportunities

These prioritized research opportunities were subsequently remapped to the broad operations that they impact in a WRRF, as shown below in Figure 8. The layout and color coding intentionally mirror those of Figure 2 (page 5).

Secondary and Tertiary Treatment (top center of Figure 8) operations represent the largest energy-consuming processes at a WRRF and constitute an active area of research. Within this core process area, participants identified research opportunities that could potentially either reduce or even avoid the need for aeration. Shortcut nitrogen removal (anaerobic ammonium oxidation, or “anammox”) would eliminate the need to aerate during denitrification. Constructed wetlands present another potential opportunity to reduce aeration needs, although throughput remains a challenge in natural systems. On a broader level, “omics” as a platform for applying advanced biochemical techniques was identified as a promising approach to improve yields and resource recovery. Algae-based water treatment systems were assigned priority because of their high growth rates and ability to consume nitrogen and phosphorous. Improved solids deconstruction was prioritized because it would broadly benefit many of the metabolic processes that are part of wastewater treatment, particularly AD.

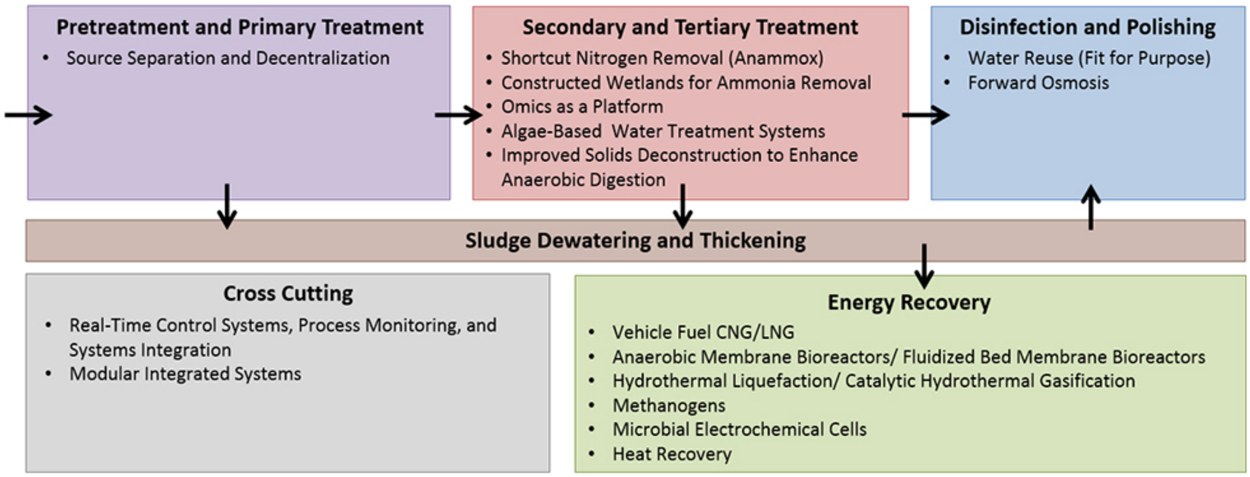


Figure 8: Prioritized Research Opportunities Impact Major Operations at a WRRF

Energy recovery (bottom right of Figure 8) represents another strong area of focus and incorporates a couple of ideas that extend beyond the traditional boundaries of water treatment. Potential research opportunities include developing compressed natural gas (CNG)/liquefied natural gas (LNG), hydrothermal liquefaction (HTL)/catalytic hydrothermal gasification (CHG), and MxC technologies, all of which could be used to produce transportation fuels. Improving AD also attracted priority votes based on its potential to enhance biogas yields through advances in solids deconstruction, AnMBRs/Anaerobic fluidized bed membrane bioreactors (AnFMBRs), and methanogens. Heat recovery was also suggested as a broad energy recovery technology for capturing heat from various industrial processes.

Cross-cutting ideas (lower left of Figure 8) include real-time control systems, process monitoring, and systems integration as well as modular integrated systems. These concepts are broadly applicable to WRRFs of the Future, with the latter technology area potentially allowing for distributed wastewater treatment operations. Moving beyond traditional boundaries, the participants identified promising opportunities by looking upstream to source separation and decentralization and downstream to water reuse. Forward Osmosis is another technology that could help clean effluent streams. No ideas for sludge dewatering and thickening were assigned priority, but this process area is expected to remain a key operation at the *WRRF of the Future.*

On the whole, the participants' vision of the *WRRF of the Future* represents a dramatic reimagining of water treatment—one that should push facilities to recover more resources from water, integrate with other utilities, engage and inform stakeholders, and run smart systems. Table 2 summarizes by timeframe the research opportunities identified by the workshop participants. It also presents technical and non-technical issues associated with each opportunity and the WRRF process that may be impacted.

Table 2: Description of Top Opportunities Leading to the *WRRF of the Future*

Opportunity	Technical Issues	Non-Technical Issues	Process Impacted
Near-Term Opportunities			
Shortcut Nitrogen Removal (Anammox): Use of anammox bacteria eliminates the need to aerate the sludge for denitrification, sharply reducing the energy needed at a WRRF *Prioritized by 2 groups*	• Process control • Stepwise implementation while maintaining effluent and quality • Temperature and flow variation • Collection of struvite and phosphorous recovery from anaerobic/MxC	• Research on production of commercially valuable nitrogen, phosphorous products from wastewater	Secondary/ Tertiary Treatment
Improved Solids Deconstruction to Enhance Anaerobic Digestion: Enhanced deconstruction increases biogas production and reduces need for solids handling	• Need to increase the current level of solids deconstruction • Avoiding increases in residence time or temperature, which can increase energy use • Digester reconfiguration for leveraging syntrophic interactions	*None explicitly discussed by breakout group*	Secondary/ Tertiary Treatment
Water Reuse (Fit for Purpose): Recycled wastewater can be used for various applications (potable and non-potable)	• Reducing/offsetting energy use for biological nutrient removal • Real-time monitoring, sensors, data • Applications beyond industrial uses (e.g., residential)	• Unknown risks related to human behavior and use • Need to ensure redundancy • Marketability, cost relative to other sources of water • Public perception • No regulations for potential contaminants, end-of-pipe standards	Disinfection and Polishing
Vehicle Fuel CNG/LNG: Upgraded biogas can be used in vehicles	• Small-scale CO_2 removal from biogas • Lack of infrastructure outside of California • Need to be cost competitive	• Who will deploy CNG-powered fleets? • Not enough renewable fuel standards (state-driven) • Need market demand • Support for transportation conversion • Awareness, e.g., Clean Cities • Lack of "net metering" for CNG	Energy Generation

Opportunity	Technical Issues	Non-Technical Issues	Process Impacted
Omics as a Platform: Biological analyses can improve the collective characterization and understanding of microbial communities *Prioritized by 2 groups*	• Need reference case for baseline • Limited number of genomes published on anammox and other organisms • Diagnosis, probing, biomarkers for control • Operating at ambient temperatures • Low-strength wastewater • Lack of field-scale systems to investigate • Understanding what types of sugars/biomass can be metabolized	• *None explicitly discussed by breakout group*	Secondary/ Tertiary Treatment
Constructed Wetlands for Ammonia Removal: Microbial, biological, physical, and chemical processes can be used to treat wastewater	• Scalability • Limited lifespans • Temperature issues • Not enough knowledge for site-specific design • Response to climate change/variations	*None explicitly discussed by breakout group*	Secondary/ Tertiary Treatment
Both Near- & Long-Term Opportunities			
Real-Time Control Systems, Process Monitoring, and Systems Integration Use of automation and control systems can improve the reliability and efficiency of WRRF *Prioritized by one group as long-term, and two groups as both near- and long-term*	**Near term** • Sensor reliability and fouling • Cost • Calibration requirements • Response time • Specificity/number of sensors (parameters), more evolved/advanced sensors needed • Identifying parameters for quality measurement (of effluent) • Consider different designs for size of plant/facility • Focused efforts on integrating small product volumes from industrial wastewater streams into WRRF **Long term** • Model development and validation • Whole-plant predictive model (using sensors, etc.) for real-time forecasting of resource recovery	**Near term** • User acceptance • Integration with decision support **Long term** • Access to and quality of data • Transparency/ accountability • Planning and public education • Security • Public processing information • Defense Advanced Research Project Agency (DARPA)-style grand challenge to develop new sensors	Cross-Cutting
Anaerobic Membrane Bioreactors (AnMBRs) and AnFMBRs: AnMBRs combine anaerobic biological treatment and membrane separation in a single process to increase biogas production. AnFMBRs use an alternative reactor design that can help to reduce membrane fouling.	**Near term** • Fouling • Low-temperature operation • Scaling up • Downstream nutrient management • Removal of trace contaminants • Dissolved methane content • Better with high-strength waste	**Long term** • Need to align with environmental/carbon regulations • Manage inputs/outputs, offset risk, siphon off products, etc.	Energy Generation

Opportunity	Technical Issues	Non-Technical Issues	Process Impacted
Prioritized by one group as near-term, one group as long-term, and two groups as both near- and long-term	**Long term** • Soluble methane recovery (different scales) • Reliable sensors to track performance • Insufficient removal of nitrogen or phosphorus; identification of complementary technology or appropriate use • Reduce the energy needed to prevent membrane fouling, e.g., in biogas sparging		
Development of Algae-Based Wastewater Treatment Systems Photosynthetic resource recovery can leverage existing treatment technologies. *Prioritized by one group as near-term, one group as long-term, and one group as both near- and long-term*	**Near term** • Need high-percentage extraction of nutrients • Develop tailored products for specific markets • Stabilize recovered nutrients prior to use • Need control systems and effective separation methods **Long term** • Reduce physical footprint; integrate with landscape • Need predictive models that link design, wastewater treatment, and climate to performance; design parameters for different systems • Need better understanding of emerging pathogens/contaminants (environmental impacts of different effluents, maintaining algal communities) • Product recovery, separations, processing—marketable products	**Near term** • Examine ancillary environmental benefits, green space, carbon sequestration rates, and policy impacts • Maintain public health criteria • Find users for recovered nutrients, tailor products to specific markets **Long term** • Achieve water quality standards/criteria on appropriate time scale	Secondary/ Tertiary Treatment
HTL/CHG Hydrothermal processes can convert biomass from wastewater into higher-value products *Prioritized by one group as near-term and one group as long-term*	**Near term** • Piloting scalable, modular system • Continuous rather than batch process • Input 15%–30% solids • Output organic phase, hydrotreatment (CHG of aqueous phase to biogas) • CHG catalyst lifetime (inorganic poisoning) • Parameterization of different feedstocks • More complex feedstock blends • Larger than 20 kilogram/day pilots **Long term** • Demonstrate success and test crudes • Need to integrate with infrastructure • Scaling • Research on catalysts and separating products for useful purposes	**Near term** • 503 regulations (Clean Water Act solids handling) • Challenges of legal and political reform • Reliability demonstration is essential to clear regulatory hurdles • Check scale of the largest pilot **Long term** • Market and economics	Energy Generation

Opportunity	Technical Issues	Non-Technical Issues	Process Impacted
Heat Recovery: Heat recovery from waste resources could offset the energy consumption of waste treatment processes or could be used in a distributed fashion for industrial and residential purposes *Prioritized by one group as long-term and two groups as both near- and long-term*	**Near term** • Need greater efficiency to reduce footprint • Hard to integrate into existing infrastructure • High cost **Long term** • Delivery to user • Under-heating risk, consequences of heat removal, how much is safe for the system? • Need to understand how much heat is actually in sewage/wastewater	**Near term** • Market economics challenge; hard to compete with primary fuel • Low-grade heat, marketability challenge **Long term** • Enabling a new utility/power source into an existing governance structure and energy market • Need dynamic financial models for existing utilities, adjust to new markets • Overcome public perception issues • Competing with cheap natural gas/electricity • Distributed systems/households will require new pumping codes (re: pipe location)	Energy Generation
Long-Term Opportunities			
Modular Integrated Systems: These systems can reduce the physical and environmental footprint of a WRRF and can be deployed rapidly when needed *Prioritized by two groups*	• System-wide management • Data collection from individual system can build central knowledge base • Technical details are difficult • Need to produce an easily transportable intermediate	• Manage risk of demonstration • Operation and management details, roles and responsibilities • Economies of scale • Terminal with solid business model (depots) • Inability to deviate from permit limits profitability	Cross-Cutting
Methanogens: Research into methanogens (microbes that digest organic material and produce methane) could improve resiliency, yields, and throughput *Prioritized by two groups*	• Mass transfer issues • Separations challenge • Ability to digest variable waste streams; adaptability • Resilience to salinity and pH • Electrochemistry challenges • Impurities could cause issues • Low-temperature operation • Looking beyond methanogenesis	• Economies of scale • Markets and incentives	Energy Generation

Opportunity	Technical Issues	Non-Technical Issues	Process Impacted
Forward Osmosis: This process can be used in bioreactors to recover energy, concentrate nutrients, and remove pollutants	• Cost and efficiency • Materials • Reliability • Multiple barriers, membranes needed	• Liability of operation	Disinfection and Polishing
MxCs: MxCs can generate hydrogen, electricity, or higher-value biofuel and bioproduct precursors	• Materials science on anode and cathode composition and structure • Electrode degradation • Real-world challenges • Lack of sophisticated process engineering • Integration with membrane separation • Low-strength wastewater • Wealth of computing power could facilitate materials identification • Need to integrate with existing infrastructure	• Potential competition with anaerobic digestion	Energy Generation
Source Separation and Decentralization: These practices could enable systems tailored for specific feedstocks or purposes and reduce dependence on major infrastructure *Prioritized by two groups*	• Quality, stability of urine, disease/pathogens, micro-constituents • Physical separation process • Streamlining separation of solid waste • Chemical cycling • Enhancing industrial source separation directly to digesters/address competition • Design for resilience, feedback control	• Human acceptance and behavioral culture aspects (social science) • Inter-jurisdictional/ regulatory coordination, and creating feedback loops with the public	Pretreatment and Primary Treatment

Near-Term Opportunities

Shortcut Nitrogen Removal (anammox)

Improvements over conventional biological nutrient removal may drastically reduce the amount of energy and revenue required by current nitrogen removal methods. Conventional processes require multiple steps to convert wastewater ammonia (NH_3) into inert nitrogen gas (N_2): (1) wastewater ammonia (NH_3) is oxidized to nitrite by autotrophic ammonia-oxidizing bacteria; (2) the nitrite is oxidized to nitrate by nitrite-oxidizing bacteria under aerobic conditions; and (3) de-nitrifying bacteria converts NO_3 back into atmospheric nitrogen (N_2). The overall process requires large amounts of dissolved oxygen and is one of the most energy-intensive processes in a WRRF. The conventional nitrogen removal process also produces high volumes of sludge that can be expensive to handle and discard. With shortcut nitrogen removal, anammox bacteria (ANaerobic AMMonia OXidation) achieve the same conversion in two biological steps. One of the greatest benefits of the anammox process is elimination of the need to aerate. Additionally, the anammox process reduces carbon requirements and results in a net *consumption* of CO_2—in contrast to conventional treatment processes that *release* CO_2.[28]

[28] Water Environment Federation (WEF) and Water Environment Research Foundation (WERF). Shortcut Nitrogen Removal—Nitrite Shunt and Deammonification. WEF and WERF, 2015. https://www.e-wef.org/Default.aspx?TabID=251&productId=45090379

Improved Solids Deconstruction to Enhance Anaerobic Digestion

Workshop participants identified several research and development (R&D) opportunities to increase solids deconstruction rates (i.e., pre-treatment hydrolysis). Pre-treatment solids deconstruction reduces the volume of sludge and helps to break up larger macromolecules, such as cellulose. Making more of the biomass accessible to the AD microbes should increase biogas production, reduce biosolids volumes, and potentially decrease contaminants in the sludge. In addition, reconfiguring the digester into zones may isolate processes and leverage syntrophic interactions that break down more of the sludge. Research should help to clarify the degree of solids deconstruction needed by the microbial communities. Novel post-treatment options may provide other viable routes to reduce biosolids volumes and disposal costs but will not enhance biogas production (as they take place after the AD process). Both pre- and post- digestion solids deconstruction technologies will need to be evaluated in terms of energy use, costs, and other process requirements.

Water Reuse (fit for purpose)

Treated wastewater can be recycled for a variety of beneficial purposes. Recycled water is most commonly used in non-potable applications, such as agricultural and landscape irrigation, industrial processes, toilet flushing, and construction. A number of projects indirectly add recycled water to potable sources, including replenishing ground water basins and augmenting surface water reservoirs. State and federal regulatory oversight provide a framework to ensure water safety in the many water recycling projects that have been developed in the United States.

Although water recycling has effectively and reliably expanded the water supply without compromising public health, a portion of Americans are uncomfortable with the concept of drinking recycled water. Effective marketing strategies are needed to educate the public on the benefits of—and need for—recycled water. As water energy demands and environmental needs increase, water recycling will play a greater role in our overall water supply. Wastewater treatment facilities, municipalities, and other key stakeholders will need to work together to develop effective strategies and standards for water recycling while engaging the public appropriately to counteract the inevitable resistance to water reuse.

Vehicle Fuel: Compressed Natural Gas and Liquefied Natural Gas

Biogas produced at wastewater treatment facilities can be upgraded to renewable natural gas by removing water, carbon dioxide, hydrogen sulfide, and other trace elements. This upgraded biogas is comparable to conventional natural gas and can be injected into the pipeline network or used as an alternative fuel for natural gas vehicles. CNG and LNG are both suitable for use in vehicles and can be used for light-, medium-, or heavy-duty applications. Although natural gas is a clean-burning alternative fuel, only about one-tenth of 1% is used for transportation fuel in the United States.[29] At present, the natural gas vehicle fueling infrastructure is limited, and consumer demand is low. Finding partners—such as a vehicle fleet—to use the fuel may help to incentivize production. To achieve market success, renewable natural gas will need to be cost-competitive with alternative fuel options (both bio-based and petroleum-based) and other uses of biogas. This can be accomplished through technical improvements, policy incentives, or some combination thereof.

[29] U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy. ". "Natural Gas Fuel Basics." Last modified July 7, 2015. www.afdc.energy.gov/fuels/natural_gas_basics.html

Omics as a Platform

Integrated omics analyses (combining fields such as genomics, transcriptomics, proteomics, and metabolomics) are enhancing the knowledge of microbial communities and raise the potential to discover novel biological functionalities within the framework of ecosystems biology. Presently, documentation is limited regarding the genomes of anammox organisms or other microbial communities used in wastewater treatment. Additional data on these organisms will enable meta-analyses to identify structure-function relationships and novel genes on a much larger scale than in previous efforts. Integrated omics may ultimately allow researchers to optimize microbial biotechnological processes for wastewater treatment and the production of value-added products.

Constructed Wetlands for Ammonia Removal

For relatively small volumes of wastewater, wetlands can effectively reduce the levels of nitrogen (as nitrate ion, NO_3^-), phosphorous (as phosphate ion, PO_4^{3-}), and, in some cases, sediments—depending on the source of the wastewater. Some constructed wetlands are part of an overall wastewater treatment scheme (as for the Reedy Creek Natural Water Treatment system at Walt Disney World in Florida and some medium-to-large cities, such as Arcata, California; Orlando, Florida; and Columbia, Missouri). In the late 1990s, approximately 160 municipal wastewater wetland systems were in use.[30]

More recently, a number of investigators showed that these same wetlands can be effective for the removal of pharmaceutical compounds through photochemically mediated processes.[31] This approach is a promising means by which to control many organic compounds that are not removed by conventional treatment processes. Use of the sun to provide energy for this process adds to its appeal. The major drawback is that longer treatment times are needed, requiring larger areas for this treatment.

A third function stimulating growing interest in constructed wetlands is their potential for use in the treatment of storm water prior to its discharge into subsurface aquifers for storage and reuse.

Both Near- and Long-Term Opportunities

Real-Time Control Systems, Process Monitoring, and Systems Integration

Monitoring and control systems have the potential to improve the reliability and efficiency of WRRF operations. By providing plant operators with a detailed view into plant operations, these systems can improve decision making and facilitate rapid problem solving. In the near term, research efforts should focus on sensor reliability and integration into existing facilities. Plants will need to decide whether to design and implement their monitoring and control systems in-house or use outside engineering or

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[30] Kadlec, Robert H., and Robert L. Knight. Treatment Wetlands. Boca Raton, FL: CRC Press LLC, 1996.

[31] Boreen, A.L., W.A. Arnold, and K. McNeill. 2005. "Triplet-Sensitized Photodegradation of Sulfa Drugs Containing Six-Membered Heterocyclic Groups: Identification of an SO2 Extrusion Photoproduct." Environmental Science and Technology 39 (2005): 3630–3638.

Canonica, S., B. Hellrung, P. Muller, and J. Wirz. "Aqueous Oxidation of Phenylurea Herbicides by Triplet Aromatic Ketones." Environmental Science and Technology 40 (2006): 6636–6641.

Vione, D., G. Falletti, V. Maurino, C. Minero, E. Pelizzetti, M. Malandrino, R. Ajassa, R. Olariu, and C. Arsene. "Sources and Sinks of Hydroxyl Radicals upon Irradiation of Natural Water Samples." Environmental Science and Technology 40 (2006): 3775–3781.

Cottrell, B. A., S. A. Timko, L. Devera, A. K. Robinson, M. Gonsior, A. E. Vizenord, A. J. Simpson, and W. J. Cooper. "Photochemistry of Excited-State Species in Natural Waters: A Role for Particulate Organic Matter." Water Research 47 (2013): 5189–5199.

Santoke, H., W. Song, B. M. Peake, and W. J. Cooper. "Photochemical Fate of Antidepressant Pharmaceuticals in Simulated Natural Waters." Hazardous Materials (2012): 217–281, 382–390.

Wang, L., Xu Haomin, W. J. Cooper, and W. Song. "Photochemical Fate of Beta-blockers in NOM Enriched Waters." Science of the Total Enviroment 426 (2012): 289–295.

system integration services. In-house expertise provides greater control over the system and reduces risks associated with a lack of full-time access to this specialized expertise. Outside engineering provides greater standardization and transferability of knowledge, best practices, and control systems workers. These systems will need to be validated to satisfy WRRFs that they are safe to implement and not vulnerable to cyberattack. In the long term, model development efforts should focus on integrating individual operations to the WRRF as a whole. Whole-plant or system-level predictive models could be used to forecast resource recovery in real time. In addition to reporting real-time operating conditions, control systems could facilitate environmental regulation reporting.

Anaerobic Membrane Bioreactors and Anaerobic Fluidized Bed Membrane Bioreactors

Anaerobic membrane bioreactors (AnMBRs) combine anaerobic biological treatment and membrane separation in a single process. The key advantage over traditional anaerobic processing is that the membranes allow for different retention times for solids and liquids. This duality is critical since anaerobic bacteria tend to grow much more slowly than their aerobic counterparts but require no energy for aeration. By separating hydraulic and solids retention times, AnMBRs could completely replace the largest energy-consuming process in traditional wastewater treatment. In addition, since AnMBRs also produce biogas, they could extend the economic viability of anaerobic digestion to smaller-scale operations. AnFMBRs are quite similar to AnMBRs; however, they allow granular activated carbon to circulate in the reactor and overcome some of the issues associated with membrane fouling.

Traditional challenges for AnMBRs include the amount of energy required to minimize membrane fouling and the persistence of dissolved methane in the aqueous permeate. The workshop included presentations on some novel solutions to these issues, which have achieved energy-positive wastewater treatment without co-digestion at pilot scale.[32] Dissolved methane is a particularly acute problem at wastewater temperatures below 20°C, conditions common during winter months in temperate climates. While some promising strategies were presented at the workshop, more work remains to bring these possibilities to commercial reality.

Algae-Based Water Treatment Systems

Algae and other photosynthetic organism-based processes have long been recognized for their potential to treat wastewater and recover nutrients. In practice, these processes have proven challenging to implement. Traditional algae growth in open ponds requires a large physical footprint and is vulnerable to microbial contamination and influent toxicity. In addition, effective bioflocculation techniques are needed to separate the algae from the water for harvesting. Increased interest in algae-based biofuels has led to significant advancements in algal research and bioreactor development. These advances could integrate the symbiotic growth of bacteria and photosynthetic algae into wastewater treatment systems and double as a reliable source of bioenergy feedstock.

In the near term, fast-growing algae with high rates of nitrogen and phosphorus removal could be identified for use in wastewater treatment applications. Research can also focus on developing products from the biomass, including biofuels, animal feeds, nutraceuticals, and fertilizers. The physical integration of algae-based systems with wastewater treatment facilities will also need to be optimized for light availability, growth conditions, and biomass harvesting. Existing infrastructure can be leveraged

[32] McCarty, Perry L. "The Anaerobic Fluidized Bed Membrane Bioreactor for Energy-Efficient Wastewater Reuse." Workshop presentation, Department of Civil and Environmental Engineering, Stanford University,2015. http://energy.gov/sites/prod/files/2015/04/f21/fcto_beto_2015_wastewaters_workshop_mccarty.pdf.

to pilot and demonstrate possible configurations for these processes. In the longer term, developing advanced control systems could enable more efficient algae-based treatment systems.

Additional research will enable the development of more resilient microbial communities through improved strain selections and an increased understanding of contaminants and inhibitors. Deployment of algae-based wastewater treatment systems will yield significant quantities of biomass and, over time, may result in the conversion of algal biomass to high-value products.

Hydrothermal Liquefaction/Catalytic Hydrothermal Gasification

HTL and CHG processes offer promising options to convert biomass from wastewater into higher-value products. Depending on the temperature, reaction time, and presence of catalysts, the reaction products are mainly liquid or gaseous components. HTL occurs at temperatures around 250°–350°C, breaking down biomass to produce a bio-crude oil (similar to petroleum) as well as an aqueous phase, gas phase, and solid residue phase. At higher temperatures, CHG can achieve near-complete biomass degradation into a gas phase. These processes can be employed individually or together, depending on the desired end products and biomass characteristics.

Waste feedstocks can be highly complex and must be characterized for different HTL and CHG operating conditions and process configurations to clarify their impacts on catalyst lifetimes and system performance. In addition, outputs from these processes have highly variable properties and may require subsequent upgrading or processing. In the near term, researchers need a greater understanding of the fundamentals of these processes. Pilot efforts should focus on developing scalable, modular systems. Reliable small-scale systems need to be demonstrated to enable longer-term deployment efforts.[33]

Heat Recovery

Approximately 80% of the recoverable energy in wastewater streams is in the form of thermal energy. While much of this is low-grade heat, it represents an opportunity to either offset heating and cooling needs at the WRRF or throughout the community (see sidebar on Vancouver Sewage Heat Recovery, p. 2). Facility operations that focus on growing microbes (e.g., anaerobic digestion) must maintain constant temperatures. By offsetting the need for external heat sources, heat recovery could reduce plant energy consumption and operating costs.

In the near term, heat recovery efforts should focus on optimizing heat exchanger efficiency. Current designs are also difficult to integrate into the existing infrastructure and can be costly. To maximize energy savings and produce an economically viable arrangement, custom configurations may be needed for each plant. New plants should take heat recovery into consideration during planning. In the longer term, low-grade heat from wastewater can be repurposed, not only for wastewater treatment applications, but also to offset a portion of industrial and residential demands. Due to the low-grade nature of this waste heat, it must be accessed close to its source. Heat recovery may be feasible to support in-building heating applications, but additional research is needed to better understand the

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[33] Jones, Susanne B., Yunhua Zhu, Daniel B. Anderson, Richard T. Hallen, Douglas C. , Elliott, Andrew J. Schmidt, Karl O Albrecht, Todd R. Hart, Mark G. Butcher, Corinne Drennan, Lesley J. Snowden-Swan, Ryan Davis, and Christopher Kinchin. Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading, PNNL-23227. Prepared by Pacific Northwest National Laboratory. Oak Ridge, TN: DOE, 2014. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23227.pdf;

Elliott, Douglas C., Patrick Biller, Andrew B. Ross, Andrew J. Schmidt, Susanne B. Jones. "Hydrothermal liquefaction of biomass: Developments from batch to continuous process." Bioresource Technology, Volume 178 (2015), Pages 147–156, ISSN 0960-8524 http://www.sciencedirect.com/science/article/pii/S0960852414013911.

quantity of heat in sewage and the opportunities to access it. Heat removal from sewer systems could adversely impact wastewater treatment processes, which must receive influent at a minimum temperature to operate properly.

Long-Term Opportunities

Modular Integrated Systems

Modular technologies may play a key role in biosolids energy recovery in the *WRRFs of the Future*. Modular designs can reduce up-front capital costs, operating costs, and total expected present value costs. Research and development efforts should focus on scaling down processes such as anaerobic digestion and biomass conversion technologies. This would enable low-emission power generation while reducing the physical and environmental footprint of a WRRF. Standardizing modular integrated systems could help to outweigh the economies of scale currently achieved by larger, customized wastewater treatment options. Additionally, plants with modular systems can appropriately size their treatment processes and respond to changes in influent flows. Modular systems can also be deployed more readily to meet wastewater treatment demands in remote areas or emergency situations. Modular systems will need to demonstrate that they can be integrated with WRRF control systems to ensure optimal performance. Successful demonstrations will reinforce confidence in the ability to process wastewater in compliance with regulatory standards.

Methanogens

Methanogens are microorganisms that produce methane as a metabolic output from intermediate compounds found within AD microbiomes—most notably acetate, hydrogen, or related compounds. Methanogens are used in wastewater treatment to help break down organic material that would otherwise pollute water sources and degrade the environment. The methane produced by methanogens in WRRFs can be subsequently used to produce other bioproducts and/or used as an energy source. Research is needed to evaluate the performance of different methanogen species, reactor designs, and process configurations on various wastewater compositions to increase their productivity, particularly at lower temperatures, while also increasing resilience to contaminants. In addition, research into methanogens could also potentially be coupled with methanotrophs, which would convert the produced methane into more valuable products and fuels.

Forward Osmosis

Forward osmosis (FO) uses the osmotic pressure difference between relatively saline and fresh waters to drive water across semi-permeable membranes. Given the availability of an appropriately saline "draw" solution, such as seawater or brine from a desalination facility, the process can require less external energy than reverse osmosis, the currently dominant desalination technology. The process also helps to concentrate nutrients, enabling smaller reactor volumes in subsequent processing steps. In some configurations, FO can use available waste heat to regenerate the "draw" solution that "pulls" the water across the relevant membranes, thus further reducing primary energy requirements. FO would likely be incorporated into a larger operational solution to treat wastewater.

Research is needed to improve the affordability and efficiency of FO materials and processes. New membranes might offer greater flux without compromising membrane performance. In the future, FO membranes may potentially be incorporated into microbial osmotic fuel cells to simultaneously remove organics from wastewater and produce electrical power, or they might be used in pressure-retarded osmosis systems to drive turbines and generate electrical power. Remaining challenges include: balancing tradeoffs between membrane flux and fouling tendencies, effective removal of all contaminants present in natural saline water sources, and determining the practical combination of waste heat generation sources with water treatment requirements. If these limitations can be overcome, FO may enable a larger solution that provides integrated wastewater treatment, energy recovery, and indirect desalination.

Microbial Electrochemical Cells

MxCs integrate microbiology, electrochemistry, materials science, and engineering to generate products from biodegradable materials (microbial electrolysis cells generate hydrogen and microbial fuel cells generate electricity). Use of MxCs has proven challenging in practice, and limitations remain to be overcome in the areas of treatment, energy production, and cost. Materials science research efforts should focus on electrode degradation and anode and cathode composition and structure. MxC integration with membrane separation—as mentioned in the preceding section on forward osmosis—could also enhance MxC functionality. Issues concerning the composition and variability of the wastewater must also be addressed to ensure a reliable energy output. Quantitative studies are needed to identify suitable applications and evaluate the scalability of those processes.

Source Separation and Decentralization

Wastewater treatment systems must take into account the wide variability of waste streams. Centralized systems tend to have relatively stable influent characteristics, whereas small systems are more subject to daily or seasonal variations. Separating waste streams at the source could provide more consistent feedstocks and enable modular resource recovery solutions. For instance, industrial waste streams could be utilized in energy-positive resource recovery systems that recycle the recovered energy and water back to the plant. In other cases, where individuals interact directly with the decentralized treatment technology (e.g., toilets that recycle flush water), the public may first need to be educated about the safety and benefits of water reuse.

The costs of retrofitting existing infrastructure must be evaluated, and building/community developers should assess the benefits and viability of incorporating waste separation into their designs. Decentralized systems can help to reduce the burden on major centralized systems, but clear regulatory guidelines and monitoring will be needed to ensure that the systems comply with all environmental and health standards. Advanced effective monitoring and integrated control systems can ensure the resilience of these systems.

Conclusion

The aging U.S. water infrastructure is rapidly reaching the end of its expected service life and is estimated to require an investment of about $600 billion over the next 20 years[34] to continue reliably transporting and treating wastewater and delivering clean drinking water. Looking beyond traditional bounds of wastewater treatment, the industry is galvanized by the opportunity to build the *WRRF of the Future*—a utility that (1) recovers the resources in wastewater, (2) is integrated with other utilities, (3) engages and informs stakeholders, and (4) incorporates smart systems. While elements of this facility are in various stages of development, a sustained RDD&D effort supported by both the public and private sectors will be required to realize this vision.

In pursuit of this goal, the workshop participants outlined a number of research opportunities that would reduce energy consumption and costs while also paving the way for the energy-positive *WRRF of the Future*. This research could impact a number of processes at the typical WRRF plant and may dramatically alter the way wastewater is treated. The broad benefits of the envisioned facilities should extend well beyond the plant gates—reducing stress on energy systems, decreasing air and water pollution, improving community resilience, and driving local economic activity.

[34] EPA. "Water Infrastructure and Resiliency Finance Center." Accessed July 27, 2015 at http://water.epa.gov/infrastructure/waterfinancecenter.cfm

Appendix A: Attendee List

Name	Organization
Nancy Andrews	Brown and Caldwell
Robert Bastian	U.S. EPA
Tamara Battle *	National Science Foundation
Diana Bauer *	U.S. DOE, Energy Policy and Systems Analysis (EPSA)
Charles Bott	Hampton Roads Sanitation District
Jeanette Brown	Manhattan College
Joseph Cantwell	Leidos Engineering, LLC
Soryong Chae	University of Cincinnati
Kartik Chandran	Columbia University
Shahid Chaudhry	California Energy Commission
Young Chul Choi	RTI International
William J. Cooper *	National Science Foundation
Haydee De Clippeleir	DC Water
Gary Decker +	Meridian Institute
Dionysios Dionysiou	University of Cincinnati
James Dobrowolski	U.S. Department of Agriculture, National Institute of Food and Agriculture
Paget Donnelly ‡	Energetics Incorporated
Corinne Drennan	Pacific Northwest National Laboratory
Douglas Elliott	Pacific Northwest National Laboratory
Selena Elmer +	Meridian Institute
Lauren Fillmore	Water Environment Research Foundation
Cynthia Finley	NACWA
Anthony Fiore	NYC Department of Environmental Protection
Aaron Fisher * ‡	Energetics Incorporated
Daniel Fishman	U.S. DOE, BETO
Brent Giles	Lux Research
Eugenio Giraldo	Natural Systems Utilities
Jeremy Guest	University of Illinois at Urbana-Champaign
Bruce Hamilton *	National Science Foundation
Scott Hutchins *	U.S. DOE, Advanced Manufacturing Office
Matt Hutton	MicroBio Engineering, Inc.
Matthew Kayatin	NASA Marshall Space Flight Center
Marc Kodack	U.S. Army
Paul Kohl	Philadelphia Water Department
Caroline Kramer ‡	Energetics Incorporated
Jeffrey Lape *	U.S. EPA
JoAnn Lighty	National Science Foundation
Jin-Ping Lim	SRI International
Barry Liner	Water Environment Federation
Nancy Love	University of Michigan

Patrick Lucey	Aqua-Tex Scientific Consulting Ltd.
Richard Luthy	Stanford University
Erika Mancha	Texas Water Development Board
Molly Mayo *+	Meridian Institute
James McCaughey	Narragansett Bay Commission
Ed McCormick	WEF
Mark McDannel	Los Angeles County Sanitation Districts
Lisa McFadden	Water Environment Federation
Rachel Melnick	U.S. Department of Agriculture, National Institute of Food and Agriculture
James Mihelcic	University of South Florida
Jeff Moeller	Water Environment Research Foundation
Ardra Morgan *	U.S. EPA
Kerri Neary	U.S. DOE
Christian Nilsen	ReNUWIt/Stanford University
Daniel Noguera	University of Wisconsin Madison
Bryan Pai +	SRA
Chul Park	University of Massachusetts Amherst
Donna Perla	U.S. EPA Office of Research and Development
Mark Philbrick *	U.S. DOE
Becca Price ‡	Energetics Incorporated
Nalini Rao	EPRI
Zhiyong (Jason) Ren	University of Colorado Boulder
Grace Richardson *	U.S. EPA
Bob Rose *	U.S. EPA
Brandi Schottel *	National Science Foundation
Patrick Serfass	American Biogas Council
Benjamin Shuman	USDA, Rural Utilities Service
Siva Sivasubramanian	U.S. DOE, BETO
Seth Snyder	Argonne National Laboratory
Brad Spangler +	Meridian Institute
Thomas Speth *	U.S. EPA
Timothy Strathmann	Colorado School of Mines / National Renewable Energy Laboratory
Sarah Studer *	U.S. DOE, Fuel Cell Technologies Office
Stephen Tarallo	Black & Veatch
Jason Turgeon *	U.S. EPA Region 1
Art Umble	MWH Global
Suzanne van Drunick	U.S. EPA
Robert C. Weaver	Kelly & Weaver P.C.
John Willis	Brown and Caldwell
Alan Wilson	National Science Foundation
Y. Jeffrey Yang *	U.S. EPA, Office of Research and Development

* Steering Committee Member + Facilitator ‡ Scribe

Appendix B: Workshop Agenda

Workshop presentations are available at:
http://sites.energetics.com/EPWRR/AdvanceInformation/index.html#Presentations

Day One – Tuesday, April 28, 2015

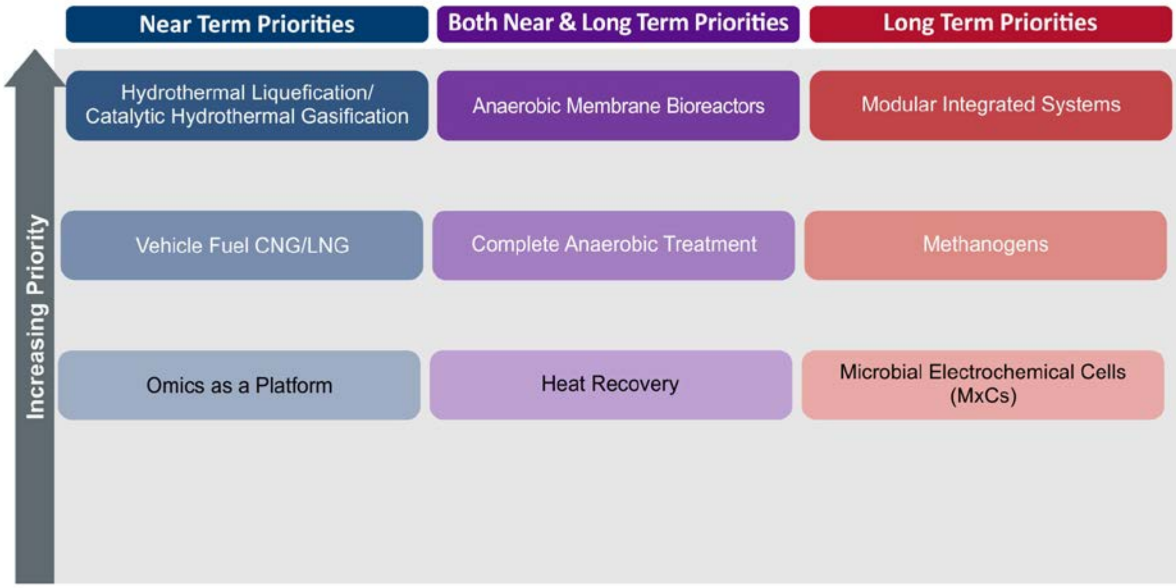
Time	Subject
7:30	**Registration Opens**
8:30 - 8:45	Welcome and Introduction • Dr. JoAnn Lighty, Division Director ENG/CBET, NSF • Ardra Morgan, Senior Advisor, EPA • Dr. Diana Bauer, Director ESAISAI, DOE
8:45 – 9:30	Keynote 1: *Energy-Positive Water Resource Recovery Facilities* • Ed McCormick, President, WEF
9:30 – 10:15	Keynote 2: *Energy-Positive Wastewater Treatment and Re-Use* • Dr. Dick Luthy, Director, ReNUWIt, Stanford University
10:15 – 10:45	**Break**
10:45 – 12:00	Panel Discussion: Achieving Energy-Positive Water Resource Recovery Facilities *Tom Speth, Director, Water Supply/Resources Division, ORD-NRMRL, EPA (Moderator)* • Dr. Brent Giles, Senior Analyst, Lux Research • Dr. Kartik Chandran, Director WWTP and Climate Change, Columbia University • Paul Kohl, Energy Program Manager, Philadelphia Water Department
12:00 – 12:10	Afternoon Breakout Session Summary and Charge • Group 1: Rapporteur: Dr. Barry Liner, Director, Water Science & Engineering Center, WEF • Group 2: Rapporteur: Shahid Chaudry, Senior Mechanical Engineer, CEC • Group 3: Rapporteur: Dr. Haydee de Clippeleir, R&D Chief, DC Water • Group 4: Rapporteur: Dr. Jason Ren, Professor, CU Boulder
12:10 – 1:30	**Lunch**
1:30 – 3:00	Breakout Session One – Envisioning the Possibilities *This session will focus on visualizing the EPWWR facility 20+ years from now, and focus on long-term goals.*
3:00 – 3:30	**Break**
3:30 – 5:00	Breakout Session Two – Assessing gaps and hurdles *Where are the gaps in terms of what we are trying to achieve versus the opportunities identified in the first breakout session?*

Day Two – Wednesday, April 29, 2015

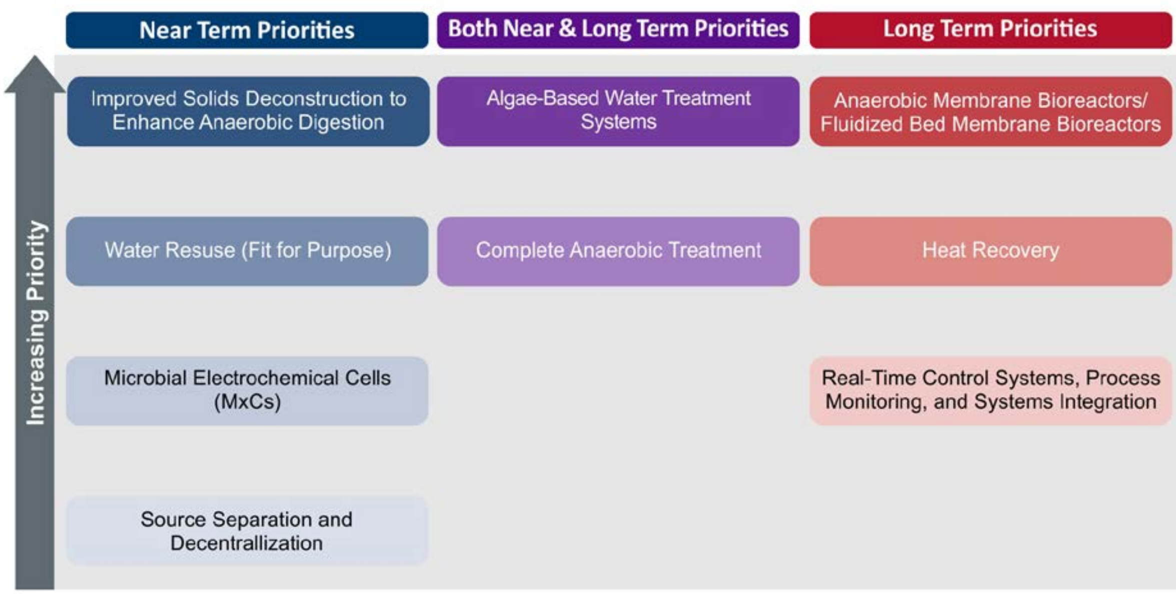
Time	Subject
8:30 – 8:40	**Welcome Back**
8:40 – 9:50	Breakout Presentations from Day One. *Presentations from Breakout Reporters followed by Q&A and discussion.*
9:50 – 10:00	Breakout Recharge
10:00 – 10:30	**Break**
10:30 – 12:00	Breakout Session Three – Where could additional RDD&D have the greatest impact? *Identify priority areas for technology and R&D investment.*
12:00 – 1:30	**Lunch**
1:30 – 2:00	Reflections from Breakouts
2:00 – 3:15	Federal Panel: RDD&D Status and Plans from NSF, EPA, DOE, and DOD *Presentations followed by discussion and Q&A* *Dr. Bruce Hamilton, Program Director, NSF (Moderator)* • Dr. Diana Bauer, Director ESAI, DOE • Dr. Suzanne van Drunick, National Program Director, Safe and Sustainable Water Resources, EPA • Dr. Marc Kodack, Program Manager, Office of the Assistant Secretary for Energy and Sustainability, DOD • Jeff Lape, Deputy Director, Office of Water, EPA • Dr. JoAnn Lighty, Division Director ENG/CBET, NSF
3:15 – 3:45	**Break**
3:45 – 5: 15	Panel: Facilitating Deployment – Moving Systems to Market *Jason Turgeon, Environmental Scientist, US EPA Region 1 (Moderator)* • Lauren Fillmore, Senior Program Director, WERF • Ben Shuman, Senior Environmental Engineer, USDA-RUS • Erika Mancha, Team Lead, Innovative Water Technologies, Texas Water Development Board • Kerri Neary, General Engineer, DOE
5:15 – 5:30	**Closing and Next Steps**

Appendix C: Summary Images of Individual Groups

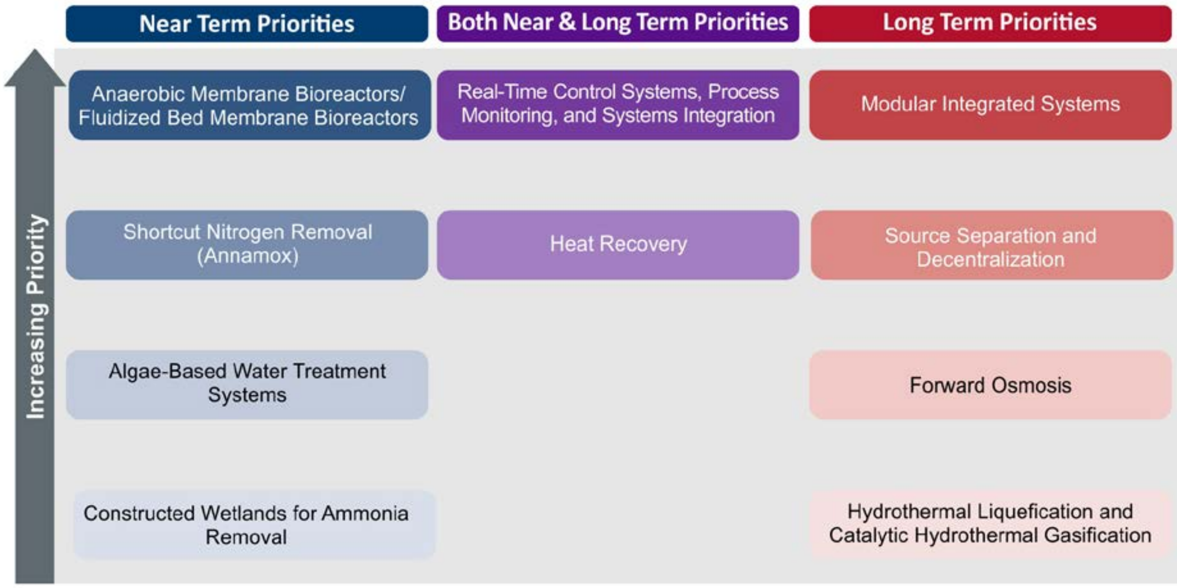
For the facilitated portion of the workshop, participants were broken up into four parallel groups. This section shows the outcomes of the prioritization exercises undertaken by each group. Top priorities within a group were determined by relative weighting within that group, with higher priorities toward the top. Topics identified by multiple groups represent coincidental convergence. Each group examined in greater detail six opportunities of their choosing (generally three near and three long term). For this reason some of the lower-priority opportunities identified herein were not discussed at length by the workshop participants.



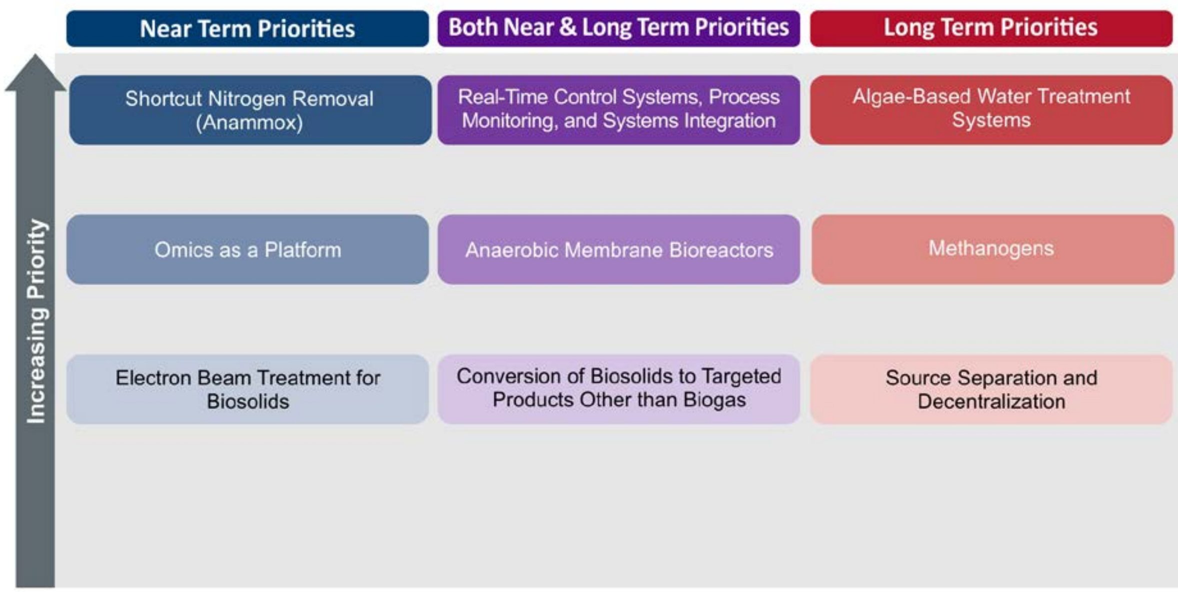
Group A: Research Prioritization



Group B: Research Prioritization



Group C: Research Prioritization



Group D: Research Prioritization

treatment management
solids infrastructure
integrate regulations education
microbial models utility
technology systems quality
capital enhanced
social design economic market control
source public metrics
methane tech water fuel biosolids
nutrient sensors
products
energy
health
waste
heat
resource
potable carbon
performance digestion process test
modular scale cost regulatory
need data recovery demo benefits
federal utilities value
membrane research footprint
technologies collection anaerobic
separation climate facilities
integrated wastewater
mainstream