By Eoin Casey, Sara Beaini, Sudeshna Pabi, Kent Zammit, and Ammi Amarnath

©ISTOCKPHOTO.COM/TCMAKE_PHOTO

The Triple Bottom Line for Efficiency

ENERGY AND WATER HAVE BEEN INTEGRATED throughout most of modern history, and that linkage will continue into the future, not only in the physical infrastructure but also through digital infrastructure (e.g., the Internet of Things). The term *energy–water nexus* is quickly expanding to refer to more than simply water used for energy production and energy used for water treatment and transport. Just as the energy grid is changing—becoming more flexible and resilient and providing energy-efficiency gains—the water network is also changing. The integration of these two systems can provide optimization and opportunities that would not otherwise be possible. This integration of "electrons and molecules" is being enabled by advances in Internet connectivity and wireless communications, so that energy in all its forms can be employed most effectively by end users to optimize efficiency, reliability, security, economics, and environmental performance.

Benefits of System Integration: A Triple Bottom Line

Addressing the energy–water nexus invites a system-integration approach (Figure 1). Today's electric grid has become the integrated energy network, which requires versatility across power paths and adapting to the new

Digital Object Identifier 10.1109/MPE.2016.2629741
Date of publication: 2 February 2017

Authorized licensed use limited to: Panstwowa Wyzsza Szkola Zawodowa w Tarnowie. Downloaded on December 14,2020 at 23:39:48 UTC from IEEE Xplore. Restrictions apply.

Integrating Systems Within Water and Energy Networks

energy end user, called a *prosumer*, who may also produce energy. Similarly, the water network has taken on an increasingly dynamic role as more decentralized, small-scale systems are implemented. Think of the interaction between the water network and the smart electric grid as the *integrated energy network* (or "integrated network of resources"), where further efficiencies may be gained through this integration of systems. With this integration, we drive resource use toward a more sustainable and efficient utilization and management of resources (Figure 2)

Many potential benefits can be realized by integrating the electricity and water sectors. Some examples include

- ✔ load leveling, e.g., pricing signals used to control demand for systems such as water pumping to head tanks, desalination, wastewater treatment (WWT), irrigation pumps, and water heaters in residential and commercial buildings, with benefits for both customers and energy suppliers
- ✔ carbon reductions achieved through the electrification of water systems, replacing fossil fuel point sources and increasing efficiency for the pumping, heating, treatment, and transport of water and wastewater
- ✔ off-peak water treatment, water heating, and water pumping to reduce both energy costs and generating-unit downturn
- ✔ distributed water treatment/WWT and local reuse, providing greater system security and resiliency
- ✔ expanded availability of Energy Star and WaterSense appliances for water and energy savings, enabling easy ways to achieve customer savings and satisfaction as well as to implement energy and water conservation methods.

In particular, water presents strategic challenges and opportunities for the electric sector.

- ✔ Using less water for power production conserves a scarce resource for other necessary uses.
- ✔ Minimizing the environmental impacts of water use for power production preserves environmental resources and protects human health.
- ✔ Using efficient electric technologies for water treatment, transport, desalination, industrial processes, and other end uses can conserve electricity, thereby reducing any imbedded water demand.

figure 1. The energy–water nexus. Integrating the energy grid and water network to create an integrated energy network can drive more sustainable and efficient resource utilization.

Authorized licensed use limited to: Panstwowa Wyzsza Szkola Zawodowa w Tarnowie. Downloaded on December 14,2020 at 23:39:48 UTC from IEEE Xplore. Restrictions apply.

> Today's electric grid has become the integrated energy network, which requires versatility across power paths and adapting to the new energy end user, called a *prosumer*.

Smart grids are characterized by connectivity, flexibility, and resiliency, all of which effectively optimize their efficiency, reliability, security, economics, and environmental performance. Numerous system integration technologies are emerging today that promote these smart features. Energy systems integration (ESI)—a multidisciplinary area ranging from science, engineering, and technology to policy-making, economics, regulation, and human behavior—is coming to the fore in the planning, design, and operation of the global energy system. ESI seeks to optimize the energy system and other large-scale infrastructures—in particular, water—by leveraging synergies across all scales and pathways.

Evaluating an integrated energy network allows us to address efficiency with a triple bottom line: financial, environmental, and social impacts. In other words, the system's optimization will be driven by a primary target with consideration given to secondary impacts. The primary or secondary targets might include greenhouse gas emissions, power-load profiles, water conservation metrics, and the population density served, among others. Deciding which are the primary or secondary targets depends on the driving or pressing factors. Utilities, municipalities, and building and facility operators may reap the benefits of the integration of water and energy networks with the triple bottom line.

figure 2. Resource management has become more intricately integrated, specifically for water and energy resources. Although not as obvious as energy consumption, water usage covers a variety of applications, from power generation and industrial and agricultural applications to municipal needs with water treatment/WWT, and also includes the goal of sustaining of natural ecosystems. (Image courtesy of the Electric Power Research Institute.)

The examples that follow here demonstrate the emerging integration of the water network and energy grids, particularly in the WWT part of the water sector and the end-use part of the electric grid. Specifically, for both the water and energy sectors, these examples highlight demand response (DR) opportunities, energy-efficient technologies, and the important role that reconceptualizing WWT plants can play as part of future energy systems in terms of virtual storage and as resource factories.

Demand Response

DR, as defined by the U.S. Federal Energy Regulatory Commission, refers to changes in electric usage by end-use customers "from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." This implies the shedding of some loads when the electric system reaches critical peaks and loads cannot be served by existing generation plants (Figure 3). Because water treatment and conveyance require large amounts of energy, the potential exists for large DR capabilities in these sectors. Examples of DR implementation include

- ✔ agricultural irrigation DR signaling so that pumps operate when electricity demand and associated rates are low
- ✔ pumping to head tanks at off-peak hours
- ✔ off-peak water treatment
- ✔ flexible load management and energy storage in water heaters.

Water treatment and WWT facilities are good candidates for DR because they are energy intensive. In some cases, a water storage capability could offer some flexibility in the operation of certain processes, including pumps and centrifuges. This operational flexibility, in turn, can be leveraged for DR if properly coordinated, making these facilities ideal partners for electric utilities seeking to manage electric load through DR programs. Furthermore, water storage can be used in conjunction with on-site power generation to provide greater demand reduction. For example, water storage can be used to shave power requirements at high electricity load

Authorized licensed use limited to: Panstwowa Wyzsza Szkola Zawodowa w Tarnowie. Downloaded on December 14,2020 at 23:39:48 UTC from IEEE Xplore. Restrictions apply.

Evaluating an integrated energy network allows us to address efficiency with a triple bottom line: financial, environmental, and social impacts.

points so that on-site generation can be sold into the grid at the higher rates. The stored water can then be treated later, with power purchased at lower rates.

Water distribution systems contain potentially large amounts of storage, which provide system pressure and backup. When properly managed, water utilities can reduce distribution system pumping and allow the water supply system to "coast" during peak electrical periods. Wastewater systems, on the other hand, may divert a portion of the incoming sewage into holding cells or reduce aeration during peak electrical periods (Figure 4). Under the right circumstances, DR from water and wastewater facilities can be significant, benefiting both electric utilities (by reducing the need for peak generation) and water treatment/WWT facilities (through DR incentives; see Figures 5 and 6). For example, a third-party DR aggregator has enrolled in excess of 100 MW of curtailable loads and on-site generator capacity at about 700 U.S. water treatment and WWT facilities.

WWT systems struggle with significant flow changes, particularly during rainfall events. Infiltration into the collection system represents a challenging problem for many systems, so many plants have storage available at the front of the treatment plant to capture excess flow for treatment at a later period. Basin management decisions are usually based on keeping storage available for the next storm event, but, depending on the plant, this storage could be used to manage peak electric demand by diverting wastewater to these basins during peak electric periods. Fortunately, peak electric

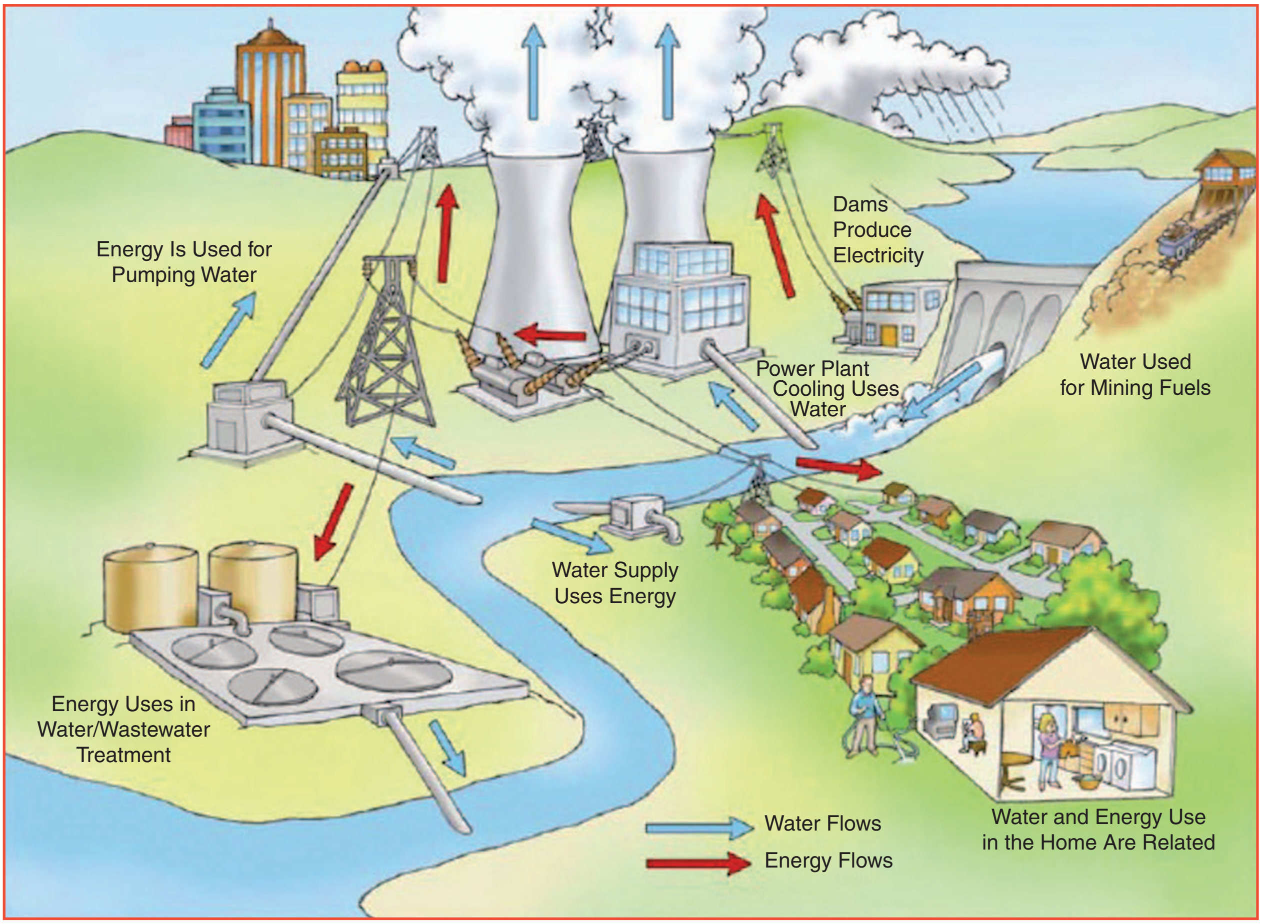


figure 3. Water system quality can be maintained while pumps, heaters, and other equipment can provide DR, which shifts electrical load away from peak periods to off-peak periods. (Image courtesy of the U.S. National Renewable Laboratory.)

Authorized licensed use limited to: Panstwowa Wyzsza Szkola Zawodowa w Tarnowie. Downloaded on December 14,2020 at 23:39:48 UTC from IEEE Xplore. Restrictions apply.

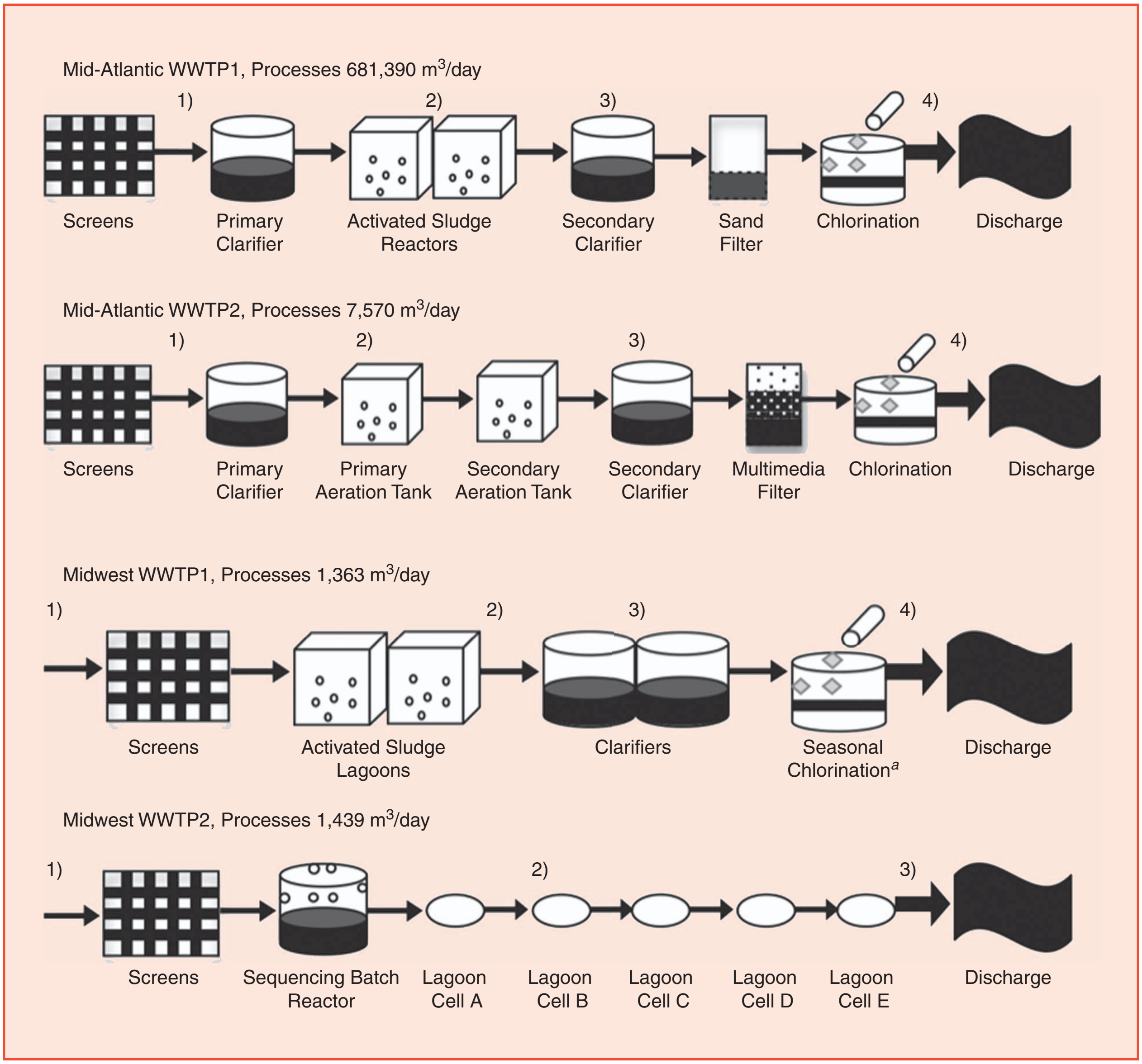


figure 4. WWT plants provide opportunities for electric system flexibility.

demand periods often coincide with hot and dry weather, giving plant managers some flexibility in keeping storage available while reducing electrical demand.

WWT plants comprise a number of unit processes that typically operate in continuous mode. Energy demand is closely correlated with liquid flow rates into the plant. Because flow rates are variable (diurnal cycles) or weather-related (rainfall), energy demand is not constant. Wastewater utilities typically pay for their electricity according to a fixed rate, although dynamic pricing structures do exist. When the electricity grid experiences peak demand, the opportunity exists for a plant to voluntarily curtail its electricity usage by turning down or shutting off equipment in return for rebates from the electrical utility. Load shifting strategies in WWT facilities include pre-aeration, utilization of storage capacity, and the scheduling of some operations (e.g., dewatering and filter back-washing) during off-peak periods.

However, without proper design, the duration of this curtailment has potential implications for WWT operations in terms of water quality. There are some documented examples of turning off aeration blowers for several hours as a DR measure. However, this can have a negative impact on the water quality (for example, turbidity) in the treated wastewater. Another interesting approach is the concept of over-oxygenating of wastewater by over-aerating wastewater prior to a DR event. This load-shifting strategy shows promise for significant DR reductions. Other constraints include meeting discharge consents, dealing with major fluctuation in storm water flows, and public health risks.

Authorized licensed use limited to: Panstwowa Wyzsza Szkola Zawodowa w Tarnowie. Downloaded on December 14,2020 at 23:39:48 UTC from IEEE Xplore. Restrictions apply.

> With proper management, water utilities can reduce distribution system pumping and allow the water supply system to coast during peak electrical periods.

An integrated energy system approach allows opportunity for decision support on process operation strategies that increase/decrease loading to follow electricity tariffs and/or short-term loading response to provide power system flexibility. Thus, there is a need for real-time data analysis and forecasting systems that will inform process-control strategies. The benefits of such an approach include cost savings, improved control and decision-support systems for planning plant upgrades as part of long-term wastewater throughput, and tightening of nutrient discharge limits.

Water storage tanks in municipal water treatment facilities and water heaters in residential and commercial buildings represent an energy storage opportunity for the electricity grid. For example, there are roughly 53 million homes in the United States with electric water heaters; a direct load-control program could result in an estimated 0.40 kW in savings per home, thereby providing peak demand reduction of 5,300 MW, assuming a 25% participation rate.

To realize this water–energy load management and storage potential, there is a need to develop standardized communication protocols and ubiquitous communication networks for the secure messaging of energy price and event information related to distributed energy resources, such as storage tanks and water heaters. In addition to these enabling standards and communication technologies, more research is needed to determine how best to integrate and aggregate large numbers of small resources, such as electric water heaters, into the overall energy management system.

Efficiency Approaches

The sourcing, treatment, and distribution of water require significant energy. Approximately 3% of the electricity in the United States is used to move and treat water and wastewater. There are opportunities to optimize energy and water consumption in the water sector by deploying technologies such as advanced supervisory-control and data-acquisition

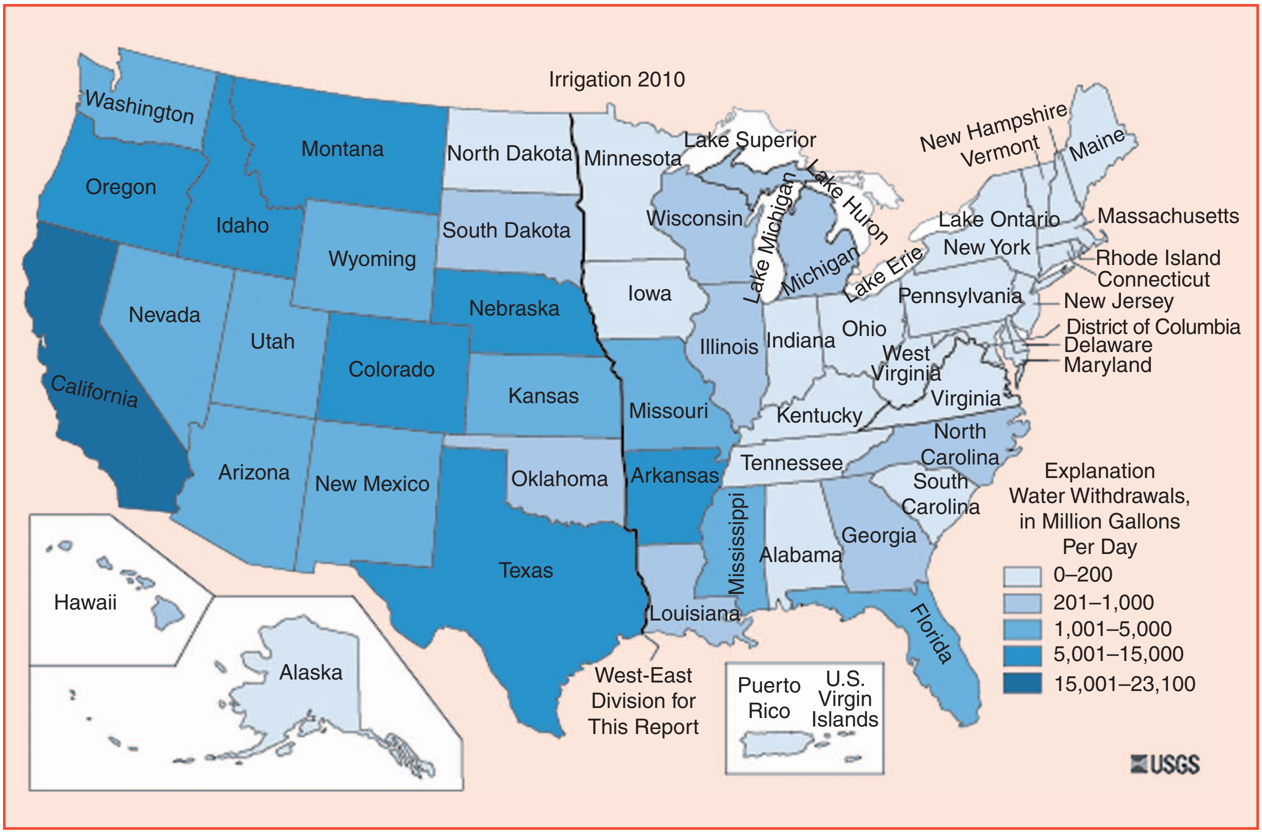
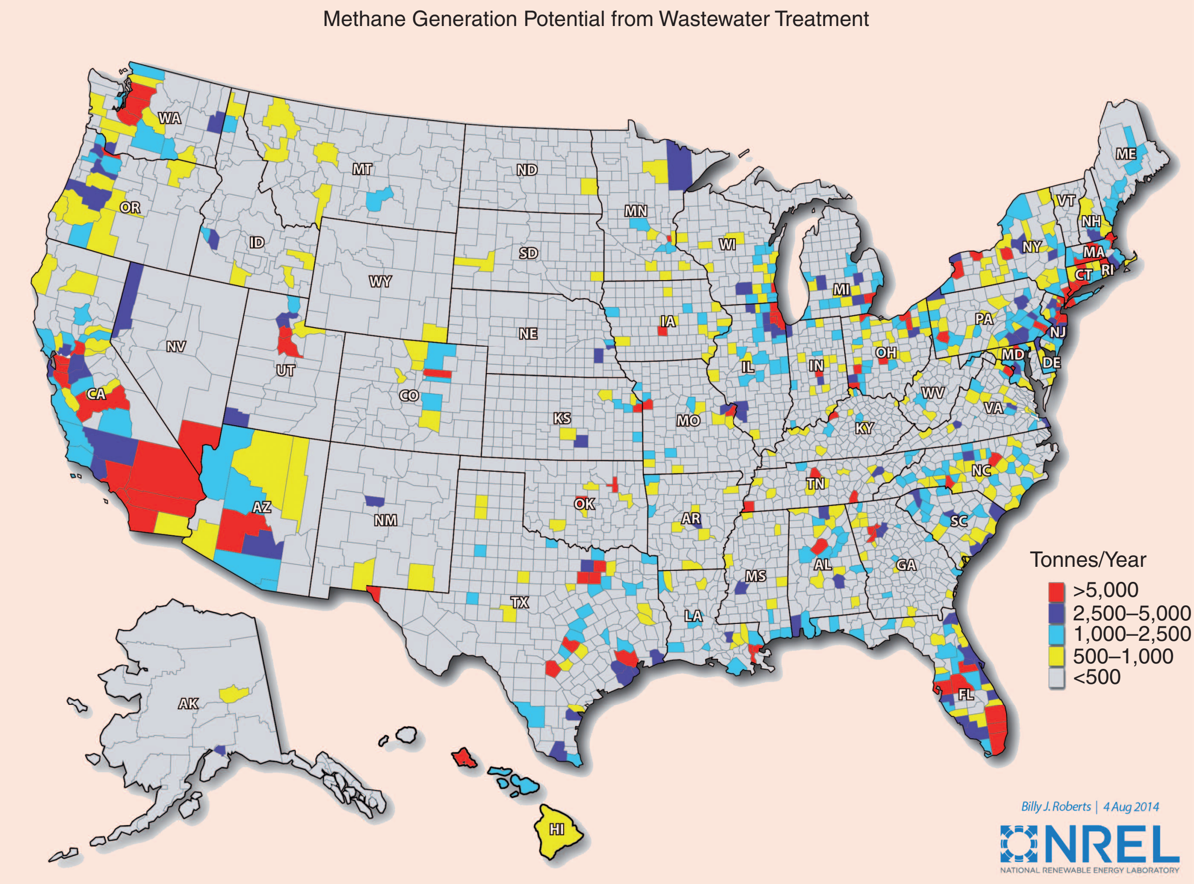


figure 5. The operation of irrigation systems can provide DR services to the electrical system, especially in the western United States. (Source: U.S. Geological Survey.)

Authorized licensed use limited to: Panstwowa Wyzsza Szkola Zawodowa w Tarnowie. Downloaded on December 14,2020 at 23:39:48 UTC from IEEE Xplore. Restrictions apply.



This analysis estimates the methane generation potential of wastewater treatment plants using methodology from the EPA's inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2011 and data from the EPA Clean Watersheds Needs Survey (2008). The results were further aggregated to country level.

figure 6. Wastewater plants provide opportunities for electric power generation fueled by biomass. EPA: U.S. Environmental Protection Agency. (Image courtesy of the National Renewable Energy Laboratory.)

(SCADA) systems, forward osmosis, bubbleless aeration, membrane distillation, capacitive de-ionization, and emerging biological treatment processes. Deploying these energy-efficient technologies will require a comprehensive assessment, from lab-scale to field demonstration, to characterize their performance in real-world applications.

In addition, the adoption of end-use energy and water conservation methods by the business and residential sectors would reduce the imbedded energy and water required to meet those needs. Current research into new technologies to conserve water and energy at end use will have ripple effects on water and energy conservation upstream. In addition to the potential for energy- and/or water-use savings, these technologies could also provide opportunities to more effectively treat water in municipal and industrial applications that currently use chemical treatment. End-use conservation would directly reduce water and energy demand. Some examples of efficiency opportunities in water treatment/WWT are discussed in the following.

Efficiency via Data Monitoring and Process Control

As with any complex industrial process, the potential for efficiency gains via computer-based monitoring and control in water and wastewater systems is significant. Monitoring and control technologies vary from simple devices to advanced SCADA systems. SCADA systems are used for precise control of key equipment and processes, including raw-water wells, water treatment, and distribution pumping. Typically, these SCADA systems pull data from field devices, such as programmable logic controllers, remote terminal units, and electric meters, and analyze/format the data to be viewed by operations staff or used for process control. SCADA systems are being implemented in the water and wastewater industries, but traditionally there has been a greater focus on improving process quality and reliability than on controlling systems to optimize energy efficiency.

Authorized licensed use limited to: Panstwowa Wyzsza Szkola Zawodowa w Tarnowie. Downloaded on December 14,2020 at 23:39:48 UTC from IEEE Xplore. Restrictions apply.

> The adoption of end-use energy and water conservation methods by the business and residential sectors would reduce imbedded energy and water requirements.

It has been estimated that an electric energy savings potential of 5–10% across the U.S. public water supply can be achieved with advances in pumping and water treatment process control. Assuming the public water supply currently uses about 39 billion kWh per year, the potential electric energy savings associated with advanced SCADA systems ranges from 2.0 to 3.9 TWh per year. This translates into electricity savings ranging 5.4–10.9 million kWh per day across the United States. One such energy-saving technique is to use a SCADA system for automatically selecting the best pump combination, reducing system pressure when possible, checking the system efficiency in real time, and then notifying the operator when changes are required.

The most sophisticated control systems "learn" the characteristics of the distribution system, relying on predictive modules to assist in scheduling pumping. This option is extremely valuable in systems where the pump station takes advantage of time-of-day electric rate schedules.

Efficiency via Water Conservation

Water conservation is an overlooked challenge as an energy-efficiency measure in both water treatment and WWT. Lowering water demand reduces the volume of water drawn from public water supplies; this, in turn, reduces the energy required to pump and treat the water supplied to end users. A lower demand for fresh water also translates directly into a reduced demand for wastewater transport and treatment and a corresponding reduction in energy used.

There are two main challenges for water conservation in water supply and wastewater disposal. On the water supply side, the opportunity lies in detecting and eliminating leaks in the supply system. On the wastewater side, inflow and infiltration lead to significant increases in flow to the treatment facility, particularly during rain events. The additional volume of inflow water combines with wastewater effluent and increases the amount of wastewater that must be pumped and treated.

Reducing Demand for Water in End Uses

Considerable opportunities exist for reducing fresh water demand for landscape irrigation. Based on U.S. Environmental Protection Agency and U.S. Bureau of Reclamation data, the potential savings from advanced irrigation controls in residential and commercial applications is estimated to be 1.5–3% of total electricity use in the public water supply. At a current electricity use rate of 39,000 million kWh per year, this equates to potential savings of 0.5–1.2 TWh per year in the public water supply. While this is not a small number, the nature of the savings through numerous, small actions makes the impact of this measure extremely challenging to measure.

Providing timely information on usage patterns has proven to be an effective way to increase awareness and transform consumer behavior in both the energy and water industries. There is a substantial opportunity to modify consumer behavior and detect leaks by providing a greater degree of visibility into use patterns. An example is energy savings due to reducing hot-water demands with low-flow devices.

Energy Recovery and Generation

A new and growing trend in the water and wastewater industry is the emphasis on recovering energy whenever possible. In water treatment, the focus is on recovering some of the pumping energy through the use of energy-recovery devices in the distribution system. In WWT, the emphasis is on biological treatments combined with opportunities in capturing energy in the wastewater itself. These include cogeneration using digester biogas and the recovery of excess line pressure to produce electricity (microhydro).

Advanced Technologies in Water Treatment for Energy Efficiency

There are significant growth opportunities in advanced technologies in water treatment and WWT spurred mainly by drivers associated with water scarcity and the need to meet stricter discharge limits. However, many of these processes—including, for example, reverse osmosis for desalination, advanced ionization for micro-pollutant removal, and membrane bioreactors—are expected to continue to be highly energy intensive. Some emerging developments to address this problem include forward osmosis or membrane distillation using low-grade waste heat. Another significant opportunity is to couple desalination with renewable-energy systems. Energy efficiency can also be improved through the integration of space-conditioning and water-heating systems. For residential and commercial building applications, newer systems are under development that use waste heat from outdoor air-conditioning compressor units to heat water. Research is underway to determine the overall efficiency of such systems. This technology is fairly mature in the industrial sector, where heat pumps are used recover heat from industrial processes to heat-process water.

Authorized licensed use limited to: Panstwowa Wyzsza Szkola Zawodowa w Tarnowie. Downloaded on December 14,2020 at 23:39:48 UTC from IEEE Xplore. Restrictions apply.

In WWT processes, energy-efficiency measures include retrofitting plants with high-efficiency pumps, variable-speed drives, and advanced monitoring and process control for the biological reactor. Traditionally, WWT plants are fitted with oversized pumps to cope with hydraulic load fluctuations; as such, these pumps are inherently inefficient. Thus, there is a need for real-time data analysis and forecasting systems that will inform process-control strategies. The benefits of such approaches include cost savings, flexibility, and improved control and decision support for planning plant upgrades.

Reconceptualizing the WWT Plant as an Energy- and Resource-Generation Facility

Future WWT plants will no longer be just pure waste management facilities but rather recovery systems for clean water, energy, and minerals. The chemical energy in wastewater is in the form of biodegradable and inert chemical oxygen demand and reduced nitrogen (NH^{4+} or organic N). Large-scale WWT plants recover 5–15% of this energy through anaerobic digestion. However, because other important parts of the treatment plants are energy-intensive (aerobic biological oxidation requires 0.40–0.65 kWh/m^3), it follows that most treatment plants are net users of energy. With the advent of new and improved treatment technologies, a net-energy-positive WWT plant is now considered achievable. Emerging process technologies, including anammox, bubbleless aeration, and aerobic granular sludge, can deliver significant savings in energy demand.

Biogas is central to energy neutrality in WWT. Biogas can be produced continuously, and there are several possible uses: on-site electricity generation, combustion for thermal processes (e.g., Cambi), or direct injection into the gas grid; however, there are upsides and downsides with each (for example, for injection into the grid, the biogas needs to be pretreated). Currently, large-scale WWT plants typically recover only 5–20% of the chemical energy through anaerobic digestion (the production of biogas and cogeneration). Codigestion of excess sludge with external solid/liquid organics is a potential approach toward carbon neutrality.

Additionally, the transformation of WWT plants can be seen with the emergence of decentralized, small-scale setups. By reducing the scale of and decentralizing some water and wastewater operations, it is possible to lower costs and improve efficiency.

- ✔ Decentralized WWT lowers the cost for pumping wastewater to central stations for treatment, then back to communities for reuse.
- ✔ Not all water uses require potable water quality: residential wastewater can be treated to use for local irrigation, flushing toilets, etc.
- ✔ Decentralization can also have benefits in minimizing the need to increase infrastructure for high-density infill projects. Building codes could minimize runoff; storm water reuse reduces drain flows.
- ✔ Forward osmosis and other emerging low-energy technologies are proving beneficial as ways to treat water for potable use locally.

Conclusions

Transitioning toward an integrated energy network requires many drivers. Important players for implementing and accelerating this change in resource management include new regulations from resources agencies, economic incentives for end users, and commercialization of new technologies with improved performance and lower costs. When rallying the diverse stakeholders toward the triple bottom line of efficiency, the dialog will revolve around the advantages of the system integration approach for the energy–water nexus. The emerging system-integration case studies presented here in terms of DR, efficiency approaches, and reconceptualizing the WWT plant as an energy- and resource-generation facility all work to enable the goals of efficiency, reliability, security, flexibility, collaborative excellence, and technology leadership for both the smart energy grid and the water network.

Acknowledgment

This publication has emanated from research conducted with the financial support of the Science Foundation Ireland (SFI) under the SFI Strategic Partnership Programme Grant Number SFI/15/SPP/E3125.

For Further Reading

R. Hamilton, B. Braun, R. Dare, B. Koopman, and S. A. Svoronos, “Control issues and challenges in wastewater treatment plants,” *IEEE Control Syst. Mag.*, vol. 26, no. 4, pp. 63–69, 2006.

B. Sparn and R. Hunsberger, “Opportunities and challenges for water and wastewater industries to provide exchangeable services,” National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-5500-63931, 2015.

S. Pabi, L. Reekie, A. Amarnath, and R. Goldstein. “Electricity use and management in the municipal water supply and wastewater industries,” Electric Power Research Institute. Palo Alto, CA, EPRI Rep. 3002001433, 2013.

Biographies

Eoin Casey is with University College Dublin, Ireland.

Sara Beaini is with the Electric Power Research Institute, Palo Alto, California.

Sudeshna Pabi is with the Electric Power Research Institute, Palo Alto, California.

Kent Zammit is with the Electric Power Research Institute, Palo Alto, California.

Ammi Amarnath is with the Electric Power Research Institute, Palo Alto, California.

Authorized licensed use limited to: Panstwowa Wyzsza Szkola Zawodowa w Tarnowie. Downloaded on December 14,2020 at 23:39:48 UTC from IEEE Xplore. Restrictions apply.