Water System Optimization: An Energy Efficiency View

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ABSTRACT

Water and energy are inextricably linked in the hydrologic cycle, so a reduction in the use of one concurrently reduces the other. Nowhere in the United States is this cycle more important to future sustainability than in the state of Arizona. Arizona has a highly complex water supply and distribution system to provide for a rapidly growing state. Yet Arizona continues to experience extreme drought conditions that will only exacerbate water shortages. These water shortages will make the need for water system optimization critical in the years to come.

The costs associated with the operation and maintenance of water distribution and treatment systems are large. The majority of operating costs are incurred through the purchase of electricity to power the motors and drives pressurizing the water distribution and transmission lines. Capital costs are driven by a need for enhanced infrastructure to offset system leakage, replace inefficient system components, and extend reach to obtain water. Optimization and calibration of the pressure required in water distribution systems offer significant annual energy cost savings, reduce direct water use, and provide indirect lowered water use in power generation. Utility incentive programs can play a key role to help reduce the first-time costs of these measures through utility-sponsored rebate programs.

This paper quantifies and characterizes the energy savings of representative Arizona water system energy efficiency projects. The findings from this study will help water purveyors better understand the energy efficiency implications of capital improvements and guide future project adoption.

Study Objectives and Methodology

The four energy efficiency projects surveyed in this paper received ratepayer-funded incentives under the Arizona Public Service (APS) Solutions for Business program that began in 2006. DNV GL provides energy efficiency implementation services under contract to APS. These services include engineering support, technical review, and site surveys of energy efficiency project applications.

In this paper, we provide an overview of the sources and uses of water in the state. We then draw from secondary literature to highlight the relationship between water use and energy use for water distribution systems. We also evaluate the current understanding of energy intensity for water systems and some recent trends that have impacted this understanding.

The featured projects represent energy efficiency retrofit projects implemented across a broad array of Arizona municipal water distribution systems, all of which are unique in their water supply, population served, and system infrastructure. Key findings and observations from our work are shared and we provide recommendations for future opportunities for water system energy efficiency projects.

Overview of Arizona Sources and Uses of Water

There are four categories of water sources available in Arizona: the Colorado River, surface water other than the Colorado River, groundwater, and reclaimed water (effluent). The use of each type of water depends on its quantity, quality, reliability, and economic feasibility.

Water supplied through the Colorado River comes directly from the river and from a system of reservoirs on the river to harness its supplies for use in several states. Arizona, California, Nevada, New Mexico, Utah, Colorado, Wyoming, and Mexico share the river, and it is the principal water supply for western Arizona.

Additionally, the Central Arizona Project supplies 1.6 million acre-feet (MAF) to central and southern Arizona via a 336-mile diversion canal that originates in Lake Havasu City. Rights to use Colorado River water are quantified by a group of legal authorities known as the Law of the River, which grants Arizona the right to use 2.8 MAF annually. (Bureau of Reclamation, 2014)

The second category of surface water comes from lakes, rivers, and streams; however, because of Arizona's desert climate, the amount of surface water available can vary dramatically from year to year, season to season, and place to place. In order to make the best use of the surface water, storage reservoirs and delivery systems have been constructed throughout the state. Almost all of the natural surface water in Arizona has been developed.

Groundwater is a third source of water and is found beneath the earth's surface in natural reservoirs called aquifers. In most cases, the water stored in these reservoirs has been in place for millions of years. Historically, groundwater has been pumped out more rapidly than it is being replenished, creating a condition called overdraft. Though a large amount of water remains stored in Arizona's aquifers, its availability is limited by location, depth, and quality.

Reclaimed water, or effluent, is an increasing water source in many states including Arizona. Reclaimed water is treated to a quality that can be used for a variety of purposes such as agriculture, golf courses, and industrial cooling.

Arizona has grown from a population of 2.7 million people with an economy of approximately $30 billion in 1980 to nearly 6.6 million people with an economy of $260 billion in 2009. Annual water demand is expected to grow from the current estimate of 7.1 MAF in 2014 to between 8.2 to 8.6 MAF in 2035, between 8.6 and 9.1 MAF in 2060, and 9.9 to 10.5 MAF in 2110 (Arizona Department of Water Resources 2014). The demand for water by major user segment is approximately 70% agriculture, 8% industrial, and 22% municipal (Arizona Department of Water Resources 2015)

A breakdown of the sources for annual usage is provided in Table 1:

Table 1. Sources of Arizona's annual water supply.

Arizona's Annual Water Supply Budget			
Water Source	**Million Acre-Feet (maf)**		**% of Total**
SURFACE WATER			59.1%
Colorado River		2.8	39.4 %
CAP	*1.6*		*22.5%*
On-River	*1.2*		*16.9%*
In-State Rivers		1.4	19.7%
Salt-Verde	*.9*		*12.7%*
Gila & others	*.5*		*7.0%*
GROUNDWATER		2.7	38.0%
RECLAIMED WATER		0.2	2.8%
Total		7.1 maf	

Source: State of Arizona, Department of Resources 2014 Annual Report.

The Arizona Water Atlas (Atlas) was developed by the Arizona State Water Resources Department to support water planning and development efforts by providing water-related information on a local, regional and statewide level. The Atlas divides Arizona into seven planning areas (see Figure 1). "Planning areas" are composed of groundwater basins and are an organizational concept that provide for a regional perspective on water supply, demand and resource issues.

Figure 1. Arizona Regional Water Planning Areas

Source: Arizona Department of Water Resources. 2014. Arizona Water Atlas, Executive Summary, Volume 1

How Water Supply and Distribution Systems Use Energy

Water supply involves the transportation of water from its source to treatment plants, storage facilities, and end users. Currently, most of the electricity used in water systems is for pumping; comparatively little is used in treatment. (Environmental Protection Agency 2013)

Surface water treatment typically consists of chemical addition, coagulation, and settling, followed by filtration and disinfection. As drinking water regulations increase, a need arises to address contaminants of emerging concern. More energy-intensive, advanced treatment technologies including membrane filtration, ozonation, and ultraviolet irradiation have gained a greater share of the market since the mid-1990s and are likely to continue to grow market share.

Water distribution accounts for most energy use. After treatment, water is usually pumped at high pressure to the distribution and storage system, which consists of storage tanks or reservoirs and, in some cases, additional pump stations to deliver water to other distribution zones. Distribution pumping and storage serves several operational purposes including:

- Overcoming pipe friction within the distribution system
- Providing adequate pressure for the water end-users

- Providing adequate storage volume and pressure for firefighting and other emergency uses
- Providing adequate equalization storage volume to meet water demand if the water needs in a system exceed constant pumping capacities

High-service pumps and booster pumps provide the distribution system pumping by distributing water to users under adequate pipe pressure. High-service pumps are generally large horsepower (hp) pumps located at the water treatment plant that pump treated water into the service area under high head pressure conditions. Booster pumps are distributed throughout the distribution system and provide a similar function to deliver water to other distribution zones. What is considered “adequate” pressure can vary widely from one system to the next, with a typical range of 40–100 pounds per square inch (psi) measured in the distribution mains. State health departments often specify a minimum pressure of 20 psi. With less than 40 psi, there may not be adequate pressure to provide minimal fire safety requirements in public and commercial buildings. High-rise buildings usually have their own booster pumps to serve upper floors. Water storage and system pressure are both “tools” that system operators can actively manage for electrical demand and electrical energy savings (Electric Power Research Institute [EPRI] 2013).

Energy intensity will vary in terms of water system characteristics; however, pumping comprises the majority of energy usage for most surface water and groundwater distribution systems (Carns 2005). Given the large impact of pumping on overall system energy use, energy efficiency improvements should begin at the pumping systems. Table 2 shows estimated energy intensities (kWh/day) of three types of pumping processes used at three different pumping efficiencies and at different production rates.

Table 2. Energy intensities of different processes and pumping efficiencies at different production rates.

Source Water and Finished Water Pumping Intensity as a Function of Pumping Efficiency (in kWh/day)

Unit Process	Pumping Efficiency[a]	Plant Production (MGD)						
		1	5	10	20	50	100	250
Raw water pumping, surface plant	High	118	589	1,177	2,355	5,887	11,774	29,435
	Medium	145	725	1,449	2,898	7,246	14,491	36,228
	Low	188	942	1,884	3,768	9,419	18,838	47,096
Raw water pumping, groundwater plant	High	750	3,748	7,496	14,992	N/A	N/A	N/A
	Medium	923	4,613	9,226	18,452	N/A	N/A	N/A
	Low	1,199	5,997	11,994	23,988	N/A	N/A	N/A
Finished water pumping	High	845	4,328	8,969	17,520	39,629	79,257	198,143
	Medium	1,040	5,327	11,038	21,563	48,774	97,547	243,868
	Low	1,352	6,925	14,350	28,032	63,406	126,811	317,029

[a] Pumping efficiency is "wire-to-water," not motor efficiency; high=75%, medium=65%, low=50%

Source: Electricity Use and Management in the Municipal Water Supply and Wastewater Industries, EPRI, November 2013, p. 4-7.

Survey of Water System Projects

City of Yuma Surface Water Supply: Colorado River

Yuma is nestled in the southwestern portion of Arizona, along the Arizona/California border and in the Lower Colorado River Water planning area. This area contains the driest and hottest portions of the state. Yuma is in the Low Elevation Climate Zone that consists of deserts ranging from 100 feet to 3,500 feet (Arizona Department of Water Resources 2015a). Annual precipitation in Yuma is 3.01 inches, with average summer maximum temperatures and winter minimum temperatures of 100º F and 45.8º F degrees, respectively. Yuma represents the last stop along the Colorado River's path as it winds out of the United States and into Mexico. The city has a population of 93,064 residents (2010).

Given its location and extremely arid climate, Yuma is an especially interesting focal point when dealing with the hydrologic implications of water and energy usages. The water system serves 120.41 square miles of city land and residential water use accounts for 60% of total water consumption in the region.

The majority of the water used comes from the Colorado River through a series of canals called the All American Canal. Water is diverted from the Colorado River by the Imperial Dam, which is about 20 miles north of Yuma. The majority of water for the region comes through the All American Canal; however, recently, several groundwater wells have been installed and put into service.

All water from the canals and the groundwater wells is sent to the water treatment plant operated by the city of Yuma to be treated prior to consumption. The water treatment plant treats and distributes approximately 14,000 acre-feet annually. Given such a large load and, more importantly, that all water coming in and going out of the plant has to be pumped, it becomes apparent that Yuma has a significant energy footprint related to water usage.

Through the utility-sponsored program, the city of Yuma had a large portion of its pumps tested to determine current overall plant efficiency. This process led to a number of energy efficient upgrades including:

- Installing variable frequency drive (VFD) motors on three 500 hp pumps
- Installing VFDs on three 350 hp pumps
- Upgrading motors on three 350 hp pumps

Following these installations, the plant improved its operating points from 60 hertz and 92 psi to 53 hertz and 80 psi. This step decrease in pressure offers enormous energy savings as well as maintenance and leak prevention implications. The total rebate for these energy conservation measures exceeded $154,000 with deemed energy savings claims of 6.5 million kWh. Based on these savings and the incentives offered by the utility, the overall simple payback for these projects was less than one year.

Table 3. City of Yuma project measures and estimated savings.

Name of Organization	Project Name	City	Type	Status	Requested Incentive	Payment	Annual kWh Savings	kW Savings
City of Yuma	VSD Installation-City of Yuma	Yuma	Prescriptive Measures - Retrofit	Paid	$51,217.34	$51,217.34	2457980	46.5
City of Yuma	City of Yuma Pump Tests	Yuma	Technical Assistance & Studies	Paid	$2,290.00	$2,290.00	0	
City of Yuma	Zone 2 Booster Pump Station Upgrade Pumps 1-3	YUMA	Prescriptive Measures - Retrofit	Paid	$52,500.00	$52,500.00	2580879	48.868
City of Yuma	Yuma Civic Center Main Hall Lights	YUMA	Prescriptive Measures - Retrofit	Paid	$6,000.00	$6,000.00	53611.2	13.484
City of Yuma	Zone 2 Booster Pump Station upgrade Pumps 4	YUMA	Prescriptive Measures - Retrofit	Paid	$17,500.00	$17,500.00	860293	16.289
City of Yuma	VFD 500 HP high Speed Pump @MSWTP	YUMA	Prescriptive Measures - Retrofit	Paid	$24,750.00	$24,750.00	614000	82.632

Source: APS Solutions for Business Program Operations Database

City of Flagstaff Surface Water and Groundwater Supply

Flagstaff is located in north central Arizona in the Eastern Plateau area. With a population of approximately 70,000 people and located at an altitude of 6,910 feet, the city has a dry semi-continental climate with snow in winter (average annual snowfall is 77 inches) and a dry, hot early summer (average temperatures of 80º F) followed by monsoons from July to September. (U.S. Climate Data 2015)

The city represents a niche market for water use within the state of Arizona given its mountainous climate and elevations in the predominantly arid state. Historically, Flagstaff derived the bulk of its water use from two surface water sources, Lake Mary and Inner Basin, and one groundwater source, Woody Mountain well field. All three of these importation projects lie outside of the city limits, and it was not until 1990 that well fields were developed within the city limits. The final component of the city's total water supply is the reclaimed water from treatment plants, which in 2010 made up 18% of total water usage.

Flagstaff's current water distribution volume is approximately 8,400 acre-feet per year Data from 2008 show Flagstaff has one of the lowest per capita residential usage rates in the state at 61 gallons per capita per day compared with, for instance, Phoenix at 123 gallons .(City of Flagstaff 2011). Over the past two decades, the city implemented many water conservation programs that led to a stabilized water consumption rate as the population grew.

The APS Solutions for Business rebate program provided financial assistance to fund the technical assistance studies and audits completed on 13 well pumps and both of the city's wastewater reclamation facilities. These studies helped identify opportunities within the water distribution and treatment system for improved efficiencies based on capital improvements. Those projects submitted through the program included:

- Installing VFDs on two raw water pumps
- Installing VFDs on Lake Mary well 8
- Installing VFDs on Fort Tuthill Well
- Resizing raw water pump station
- Installing shop well VFD
- Upgrading shop well pump, including a full pump and motor replacement

These projects received incentives of more than $145,000, and provided estimated deemed energy savings of 5.8 GWh per year and annual cost savings of $300,000.

Table 4. City of Flagstaff project measures and estimated savings.

Name of	Project Name	Type	Status	Requested Incentive	Payment	Annual kWh Savings	kW Savings
City of Flagstaff	(2) Variable Frequencies Drives @Raw Water Pump St	Prescriptive Measures - Retrofit	Paid	$25,000.00	$25,000.00	1228990	23.27
City of	City of Flagstaff Water System Audit	Technical Assistance &	Paid	$3,150.00	$3,150.00		
City of Flagstaff	Flagstaff, AZ - Lake Mary Well No 8	Prescriptive Measures - Retrofit	Paid	$20,000.00	$20,000.00	983040	18.613
City of Flagstaff	Flagstaff, AZ -Fort Tuthill Well	Prescriptive Measures - Retrofit	Paid	$30,000.00	$30,400.00	1494220.8	28.292
City of Flagstaff	Raw Water Pump Station Pump Resizing	Custom Measures - Retrofit	Paid	$10,402.12	$10,941.98	121577.5	21.84
City of	Flagstaff, AZ - Shope Well	Prescriptive Measures -	Paid	$30,000.00	$28,500.00	1400832	26.524
City of	Shop Well Upgrade	Custom Measures -	Paid	$27,000.00	$27,000.00	654463.5	103.84

Source: APS Solutions for Business Program Operations Database

City of Holbrook Groundwater Supply: Coconino Aquifer

Holbrook is located in northeast Arizona in the Eastern Plateau area, and is in the High Elevation Climate Zone. This zone consists of cool plateau highlands at 4,000–6,000 feet and cold mountains at 6,000–8,000 feet. It is semi-arid to arid, but the highest elevations may receive up to 30 inches of precipitation annually (Arizona Department of Water Resources 2015b).

The city operates a water supply and distribution system serving a community of approximately 5,800 people with approximately 1,000 acre-feet of water per year. The primary source of water is from the Coconino Aquifer (C-Aquifer), a groundwater supply. The water distribution system is relatively simple comprising seven wells that pump water from the C-Aquifer into a major water pipeline that flows to the southern end of the city and to three water tanks on top of a hill. Water flows from these tanks to supply the northern part of the city.

A series of four energy efficiency projects for this water system comprised the following elements:

- Replacing City of Holbrook Well #3 and upgrading to a VFD
- Retrofitting City of Holbrook Well #5 to include a VFD
- Retrofitting City of Holbrook Well #7 to include a VFD

Water conservation resulting from increased system efficiency was not the primary project objective; however, it is estimated that these capital improvements resulted in direct water conservation savings through reduced leakage. Furthermore, the estimated energy savings from improved pump and motor efficiency created indirect water savings of roughly 70 acre-feet from reduced power generation requirements at the nearby Cholla Power Plant. This savings is approximately 7% of the City of Holbrook's overall water use.

These projects provided incentives to the City of Holbrook exceeding $45,000. Total estimated energy savings from these projects amounted to nearly 1.75 million kWh per year, or estimated energy cost savings of more than $100,000 per year.

Table 5. City of Holbrook project measures and estimated savings.

Name of Organization	Project Name	Type	Status	Requested Incentive	Payment	Annual kWh Savings	kW Savings
City of Holbrook	City of Holbrook Well 3	Custom Measures -	Paid	$16,938.90	$16,937.68	188196.4	0
City of Holbrook	Holbrook Booster Plant	Prescriptive Measures -	Paid	$10,000.00	$10,000.00	494558	9.364
City of Holbrook	Holbrook Well 5 VFD	Prescriptive Measures -	Paid	$5,000.00	$5,000.00	247279	4.682
City of Holbrook	Holbrook Wells 3 and 7 WWTP VFD's	Prescriptive Measures -	Paid	$15,000.00	$15,000.00	743934	14.086

Source: APS Solutions for Business Program Operations Database

Carefree Water Company Surface Water Supply (Central Arizona Project) and Groundwater Supply

The town of Carefree is located in central Arizona, 33 miles northeast of Phoenix. Carefree is in a Low Elevation Climate Zone consisting of deserts at altitudes ranging from 100 to 3,500 feet. Annual precipitation is 3 to 12 inches.

The Carefree Water Company operates a water supply and distribution system serving a community of approximately 3,500 people. It is equipped to supply up to 1,500 acre-feet of water per year. Peak daily usage occurs in the summer and is approximately 1,000,000 gallons. Approximately half of the total water use in this area is by the municipal sector, with the remainder used by agriculture and industry. Water storage reservoirs and the Central Arizona Project allocation of 1,200 acre-feet per year allow for a relatively high proportion of surface water use in some places. The remaining 30% of the total water supply is groundwater. (Carefree Water Company Web Site 2015)

Over the past 10 years, the Carefree Water Company has completed many improvements to the storage and distribution system, including:

- Completing construction of a new 1,000,000 water storage reservoir
- Enhancing water wells for emergency supply capabilities
- Upgrading well to enhance efficiency
- Upgrading pumping system to enhance efficiency
- Installing VFD on selected pump

Much of these system enhancements received incentives under the APS Solutions for Business program, inclusive of:

- Installing a new motor and pump on one of the wells
- Replacing a motor on the second well
- Replacing both the motor and bowl on one of the boosters
- Replacing just the bowl on two additional boosters
- Replacing just the motor on one additional booster

The City of Carefree received an incentive of $33,000, realized estimated annual energy savings from these projects amounting to nearly 425,000 kWh per year, and estimated energy savings of more than $30,000 per year. Carefree receives most of its electric power from the Palo

Verde Nuclear Generating (PVNG) Station. This power plant evaporates the water from the treated sewage from several nearby cities and towns to provide the cooling of the steam that it produces. Thus, the reduction in electricity consumption in Carefree reduces the use of effluent at PVNG.

Table 6. Carefree Water Company project measures and estimated savings.

Name of Organization	Project Name	Type	Status	Requested Incentive	Payment	Final Received	CBusName	Annual kWh Savings	kW Savings
Carefree Water Company	Carefree - Well 6 Upgrade	Custom Measures - Retrofit	Paid	$11,220.03	$11,220.03	12/20/2010	The Pump Co.	117943	0
Town of Carefree	Town of Carefree Admin Office & Water Company	Prescriptive Measures - Retrofit	Paid	$2,874.00	$2,710.02	5/9/2011	J.E. Bowen Construction	26239.4	3.865
Carefree Water Company	Carefree Pumping System Upgrade	Custom Measures - Retrofit	Paid	$9,169.82	$6,697.45	5/3/2011	The Pump Co.	60885.9	0
Carefree Water Company	Carefree Pumping System Upgrade Phase 2	Custom Measures - Retrofit	Paid	$9,169.82	$793.20	11/2/2011	The Pump Co.	7210.9	2.75
Carefree Water Company	Carefree Water Company - Well 2 Upgrade	Custom Measures - Retrofit	Paid	$5,257.08	$5,257.08	2/3/2014	The Pump Co.	60156.6	0.33
Carefree Water Company	Carefree Water Company VFD Install	Prescriptive Measures - Retrofit	Final Appro	$6,250.00	$6,250.00	2/27/2015		153500	20.658

Source: APS Solutions for Business Program Operations Database

Key Findings and Observations

Through our research we found Arizona to be an excellent laboratory for studying and developing technologies around the water-energy nexus due to the state's following characteristics:

- Diversity of climate
- Diversity of ecosystem
- Diversity of urban and rural water uses
- Diversity of water sources
- Well established policies governing water supply and use

The learnings derived from Arizona can be applied broadly throughout the U.S. especially in areas that share one or more similar characteristics as the case studies reviewed.

The systems that convey and distribute water are complex. Notably, we also found that water supply sources are systems unto themselves, inter-dependent, and highly complex, These water supply systems are impacted by many variables: climate, multiple uses, variability within use, geography, and dynamic public policy. These systems---both water distribution systems and water supply systems----must be managed thoughtfully with a deep understanding of these many variables, interdependent effects, and potential unintended consequences.

Indirect water savings realized through thermal energy reductions can be material. We question whether they are fully or properly valued when an energy efficiency project is adopted. When that energy efficiency project also reduces direct water use, the combined water and energy savings can create a significantly reduced resource footprint inclusive of water reduction, energy reduction, and GHG emissions reduction.

Given the system complexity we observed, we found that water distribution systems are inherently unique. Even within the State of Arizona, we found significant differences across supply, distribution systems, and use. Every water system has a story. Spending the time to understand the story and its history helps assure that efficiency and conservation enhancements are real, verifiable, and sustainable.

Future Opportunities/Areas of Future Research

At this time of severe drought in the West, we also find there to be significant areas for future research and analysis across many technical and policy parameters, including:

- Understanding how the EPA Clean Power Plan may impact Arizona's water- energy systems
- Better correlation between system component changes (pumps/VFDs) and overall system pressure changes; and a need to more tightly correlate system pressure changes to leak reductions
- Developing a clearer understanding of the wide variation in per capita water use and water conservation efforts; and determining the real and illusory cause and effect relationships that may or may not exist.
- Continued understanding of water system-energy use intensity to help enhance benchmarking
- Better understanding how energy efficiency improvements provide scalable benefits to water systems
- Enhancing integrated energy efficiency and water conservation program design around energy efficiency projects that serve water systems with the goal of expanding the value proposition to include reduced water use in power generation.
- Exploring lessons to be shared and learned between 1) electric grid enhancement and 2) water distribution system optimization
- Using pricing, tariffs, and economic incentives as tools to optimize water-energy projects and accompanying water-energy use

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