THE ARIZONA WATER-ENERGY NEXUS: ELECTRICITY FOR WATER AND WASTEWATER SERVICES

By

Joseph Hamilton Hoover

A Thesis Submitted to the Faculty of the

DEPARTMENT OF GEOGRAPHY AND REGIONAL DEVELOPMENT

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF ARTS
WITH A MAJOR IN GEOGRAPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

2009

STATEMENT BY AUTHOR

SIGNED: Joseph Hamilton Hoover

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

__________________________________ April 6, 2009

Christopher A. Scott — Date

Assistant Professor of Geography

ACKNOWLEDGMENTS

I would like to thank my advisor Chris Scott for the guidance and support provided during my program. You have helped me develop many valuable skills. Thank you to the rest of my committee, Andrew Comrie and Kathy Jacobs, for your guidance and support throughout my thesis project. I would also like to thank my fellow graduate students from whom I sought guidance. Lastly, thank you to my family who have been incredibly supportive and helpful.

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ABSTRACT

The water-energy nexus is the dependent relationship between water and energy resources. The nexus results in complex policy and management challenges for resources that have been historically managed independently. This study quantifies electricity used for water service provision in Arizona. Employing the water use cycle as an analysis tool, this study divides municipal water use for the Tucson metropolitan area and city of Phoenix into four components. The findings suggest that energy intensity differences between Phoenix and Tucson exists due to geographic variables. The city of Phoenix and Tucson metropolitan area currently consume 1.2% of statewide electricity for water and wastewater service. Electricity demand for water and wastewater service in Tucson for 2008-2030 will be 110-131%, which is greater than the 85% electricity growth statewide. Water and wastewater agencies now face decisions regarding future plans to meet water demand and maintain a low overall energy use for service provision.

INTRODUCTION

Water and wastewater treatment plants across the United States use approximately 75 billion kilowatt-hours of electricity annually (Cohen, 2007), and in 2000 thermoelectric power plants accounted for 48% of national freshwater and saline water withdrawals (Hutson, et al., 2004). These two statistics illustrate the significance of the water-energy nexus, which is the interdependent relationship between water and energy resources; water is necessary for energy production and energy is required to provide water services. The nexus raises complex policy challenges for water and energy resources that have been managed historically in independent ways (Larson, Lee, Tellinghuisen, & Keller, 2007). In the United States, economic growth, economic security and resource availability impact decisions to ensure that both energy and water resources are available to meet future growth needs (US Department of Energy, 2006). A review of existing research and reports (Carns, 2004; Gleick, 1994; Grenoble, 2007; Hightower, 2007; Hightower & Pierce, 2008; King & Webber, 2008; Klein, Krebs, Hall, O'Brien, & Blevins, 2005) suggests that quantification of the water-energy nexus occurs on both national and regional scales. For example, Sandia National Laboratories published a report discussing the national water-energy nexus and recommended areas for research and joint management of these resources. According to the Sandia National Laboratories report research opportunities regarding the water-energy nexus include stretching current water supplies, water reuse, desalination, coordinated water and energy conservation, synergistic water and energy production and renewable energy production (US Department of Energy, 2006).

One geographic location in the United States that is characterized by increasing and inter-related water and energy demands is the southwest, particularly Arizona. With the population in Arizona expected to grow 50% by 2030, water providers must address increasing energy use related to water services; balancing population growth demands with affordability (Scott, Varady, Browning-Aiken, & Sprouse, 2007) , and aging infrastructure (Arizona Investment Council, 2008). Additionally, regional water-energy management issues are important to Arizona due to reliance on the Central Arizona Project (CAP), an energy-dependent system that transports Colorado River water to central and southern Arizona, particularly the growing cities of Phoenix and Tucson. Over the aqueduct's course the elevation rises nearly 900 meters and the furthest extreme is more than 500 kilometers from the source, requiring large energy expenditures. Therefore, external drivers such as population growth and topography result in increasing resource consumption.

Research on the water-energy nexus includes determining water needs for electricity production and electricity usage for water services. A review of research indicates that water demand for energy generation is relatively well documented (EPRI, 2002a; Hutson, et al., 2004; King & Webber, 2008; Pasqualetti & Kelley, 2007, 2008; Solley, Pierce, & Periman, 1998); however, few research projects exist that report quantified electricity demands for water services, particularly for the state of Arizona. Pasqualetti and Kelley

(2007) researched the water requirements for electricity in Arizona and wrote, "A companion study should examine the other side of the coin—the energy embedded into every unit of water delivered and used in Arizona" (p. 2). In support, Scott et al. (2007) suggested the need for research investigating the energy demand required to provide water services in Arizona.

This research draws on the methodology of Wilkinson (2000) who researched electricity for water services in the state of California by classifying electricity data within several water use stages: 1) primary water extraction and delivery; 2) water treatment and distribution; 3) on-site water use; and 4) wastewater collection and treatment. Thus the California energy-water nexus has been quantified at the state level utilizing the water use cycle (Cohen, Nelson, & Wolff, 2004; Klein, et al., 2005; Larson, et al., 2007; Lofman, Petersen, & Bower, 2002; Wilkinson, 2000); however, the same approach has not been applied in Arizona. This research extends the approach of Wilkinson (2000) by considering an additional fifth: 5) reclaimed water. Explicit discussion of reclaimed water will directly enable researchers to examine the energy intensity of reclaimed water, which is an important additional water source for both the city of Phoenix and Tucson metropolitan area (Phoenix Water Services, 2005; Tucson Water, 2008). Reclaimed water is emerging as an important source of water for other semi-arid regions as well, which makes discussion of this resource particularly relevant (Asano, 2005). Due to data limitations, the energy intensity of on-site water use by consumers (stage 3) was omitted from the project. The reader is referred to (Cohen, et al., 2004; Wilkinson, 2000) for discussion of the energy associated with the end use stage of the water use cycle.

In conducting this research, I reviewed 34 recently published documents developed by water providers and state agencies discussing water resources in Arizona. These documents addressed water quantity and quality in detail; however, they contained no discussion of the electricity demand for water services. In addition, I identified only two recent research documents describing the electricity used for water and wastewater services in Arizona (Scott, et al., 2007; Sprouse, Canfield, & Mumme, 2007). Scott et al. (2007) discussed energy issues related to water conveyance and wastewater treatment and concluded that there exists a need to further investigate the energy used for water services in Arizona. In a conference proceedings paper, Sprouse et al. (2007) detailed monthly electricity use at a southern Arizona wastewater treatment plant and outlined the importance of future energy projects on water resources. The material written by these authors were the only research documents found that directly discussed the electricity needs for water service in Arizona. The research reported on here addressing electricity use for water and wastewater services in the city of Phoenix and the Tucson metropolitan area attempts to fill this water-energy knowledge gap in the state of Arizona. The studies conducted by Pasqualleti and Kelley (2007), Scott et al. (2007) and Sprouse et al. (2007) provide a research foundation for the need to investigate the specific uses of electricity for water services in Arizona.

On the basic conceptual level, research is needed to characterize the Arizona water-energy nexus specifically investigating how electricity is used for water and wastewater service. Issues such as the energy intensity of water service and wastewater service are unanswered. Another important issue for Arizona is the energy intensity of reclaimed water, which will be more important in the future as municipalities look to this water source to augment existing water supplies. Furthermore, a review of water and wastewater agency documents did not identify thorough discussion of energy implications of service nor discussion regarding the energy implications of projected water demand. Answers to the following research questions are essential to better understand current and projected water-energy needs in the state of Arizona:

1) What is the energy intensity of water service?
2) What is the energy intensity of wastewater service?
3) What is the energy intensity of using reclaimed water?
4) How will projected population growth and projected water demand impact electricity use for water and wastewater service by 2030?
5) What are the policy implications of these energy intensities and electricity projections?

Quantified electricity demands for water services further advance understanding of the water-energy nexus in Arizona.

I am the lead author on the appended paper, intended for submission to Environment and Planning B. In addition, I performed all of the data analysis and a majority of the writing.

PRESENT STUDY

The methods, results and conclusions of this study are presented in the paper appended to this thesis. The following is a summary of the most important findings in this document.

Method and Approach

This research draws upon case study methodology due to its emphasis on complex interactions among resources and policy (i.e., water-energy nexus) as well as the use of multiple sources to gather information necessary to answer the research questions. Additionally, case study methodology is appropriate for bounded situations in which a detailed analysis is desired (Creswell, 2007). This study of electricity use for water and wastewater service addresses a complex social situation, relies on multiple sources of information and is limited to specific geographic areas. Electricity data were gathered for each water use stage described below.

Primary water extraction and delivery. This water use stage refers to long distance conveyance of surface water and groundwater pumping. For the state of Arizona electricity data are provided for delivery of imported water (i.e., CAP) and groundwater pumping.

Water treatment and distribution. This stage of the water use cycle includes electricity necessary for the treatment and distribution of water such as CAP and SRP, groundwater treatment and pumping. Electricity and water data for this stage refer to two distinct processes: 1) drinking water treatment; and 2) drinking water distribution.

Wastewater collection and treatment. This stage includes electricity required to collect and treat wastewater. This includes pumping water through a treatment plant and electricity required during the wastewater treatment process. Three wastewater treatment plants in Phoenix and ten wastewater treatment plants in Tucson were included in this stage.

Reclaimed water. Reclaimed water is “the end product of wastewater reclamation that meets water quality requirements for biodegradable materials, suspended matter and pathogens” (Levin and Asano, 2004, p. 203A). Reclaimed water undergoes reclamation, which is includes treatment to make it reusable (Levine & Asano, 2004). In Tucson the reclaimed water use stage includes: recharge and recovery; treatment at two water reclamation plants; and, distribution of reclaimed water to users. In Phoenix, reclaimed water is treated at and distributed from one water reclamation facility.

I completed three sets of calculations by water use stage for Phoenix and Tucson. First, I calculated the energy intensity by water use; second, I tabulated electricity use by stage to determine the total electricity requirement; third, I applied the energy intensities previously calculated to projections of future water demand to estimate potential electricity use in 2030. All calculations completed for this research project pertain solely to electricity and, therefore, excluded non-electrical or off-grid energy consumption such as natural gas.

The study of electricity for water services in the Tucson area and city of Phoenix resulted in advancing knowledge useful for management and policy decision-making for each water use stage:

Primary extraction and delivery

- Long-distance conveyance (i.e., the Central Arizona Project) is the largest electricity user in both the city of Phoenix and Tucson metropolitan area
- In the Tucson metropolitan area, the energy intensity of CAP water is two times the energy intensity of reclaimed water

Water treatment and distribution

- Water treatment in the Tucson metropolitan area requires approximately 155 kilowatt-hours per acre-foot (kWh/AF) which is three times higher than water treatment energy intensity in the city of Phoenix

Wastewater collection and treatment

- Wastewater treatment and collection in the city of Phoenix is near the national average of 517 kWh/AF; however, wastewater collection and treatment in the Tucson metropolitan area is much lower with an energy intensity of 329 kWh/AF.

Reclaimed water

- In Phoenix reclaimed water has an energy intensity of 2,984 kWh/AF, which is nearly twice as high as the energy intensity for reclaimed water in Tucson

Projected electricity use by 2030

- In the Tucson metropolitan area, the growth rate of electricity is projected to range between 110 and 131% which will exceed the expected statewide electricity growth of 85% between 2008 and 2032 (Arizona Investment Council, 2008)
- In contrast, the projected electricity growth in Phoenix will nearly equal the expected state wide electricity growth of 85%

Overall electricity demand

- Currently, electricity use for water and wastewater service in the Tucson metropolitan area and city of Phoenix accounts for 1.2% of statewide electricity consumption for 2005 (Energy Information Administration, 2007)
- Projected electricity demand for Tucson and the city of Phoenix will equal approximately 1.1% of statewide electricity demand by 2030
- Electricity use for water and wastewater service in the Tucson metropolitan area accounts for approximately 5% of total residential, commercial and industrial electricity use in the metropolitan area (Hayes, Dickerson, Comrie, & Cotty, 2008)

Nationally, 3-4% of electricity is used for water and wastewater service (EPRI, 2002b). The city of Phoenix and Tucson metropolitan area consumption of electricity for water and wastewater service amounts to less than 2% of statewide total electricity. The 2% electricity use number represents a portion of total electricity for water use statewide due to the study's focus on Phoenix and Tucson. In the Tucson metropolitan area, electricity use for water and wastewater service accounts for approximately 5% of metro area total electricity consumption. Therefore, the Tucson metropolitan area uses slightly more electricity for water and wastewater service than the national average.

While overall electricity use in the Tucson metropolitan area and city of Phoenix are currently low, water and wastewater agencies are approaching a decisions crossroads. Future water management choices regarding water supply and treatment techniques may also result in an increase in overall electricity use. Simultaneous consideration of water and electricity resources will be necessary to maintain the current low overall electricity use for water and wastewater services. When considering the low overall electricity use in the Tucson metropolitan area and city of Phoenix for water and wastewater service, continued management of the water-energy nexus may require a greater focus on water for energy production as well as continued efforts to maintain current electricity use intensities. Future research should also investigate the electricity use of the 1.3 million AF of CAP water delivered outside of the city of Phoenix and Tucson metropolitan area, which represents 80% of CAP delivery. Also, there exists a need to determine electricity use of other major water providers in Arizona as well as smaller water providers around the state. As previously mentioned, additional research is needed to determine end use electricity consumption in the residential, commercial and industrial sectors as well as the magnitude of electricity use by the agriculture sector in Arizona. Overall, results from studies on the aforementioned research topics will complement results form this project to ascertain a more comprehensive view of the water-energy nexus in Arizona.

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APPENDIX A

THE ARIZONA WATER-ENERGY NEXUS: ELECTRICITY FOR WATER AND WASTEWATER SERVICES

Joseph H. Hoover* and Christopher A. Scott

Department of Geography and Regional Development, The Udall Center for Studies in Public Policy, Tucson AZ

*Corresponding author

ABSTRACT

The water-energy nexus is the dependent relationship between water and energy resources. The nexus results in complex policy and management challenges for resources that have been historically managed independently. This study quantifies electricity used for water service provision in Arizona. Employing the water use cycle as an analysis tool, this study divides municipal water use for the Tucson metropolitan area and city of Phoenix into four components. The findings suggest that energy intensity differences between Phoenix and Tucson exists due to geographic variables. The city of Phoenix and Tucson metropolitan area currently consume 1.2% of statewide electricity for water and wastewater service. Electricity demand for water and wastewater service in Tucson for 2008-2030 will be 110-131%, which is greater than the 85% electricity growth statewide. Water and wastewater agencies now face decisions regarding future plans to meet water demand and maintain a low overall energy use for service provision.

INTRODUCTION

Water and wastewater treatment plants across the United States use approximately 75 billion kilowatt-hours of electricity annually (Cohen, 2007), and in 2000 thermoelectric power plants accounted for 48% of national freshwater and saline water withdrawals (Hutson, et al., 2004). These two statistics illustrate the significance of the water-energy nexus, which is the interdependent relationship between water and energy resources; water is necessary for energy production and energy is required to provide water services. The nexus raises complex policy challenges for water and energy resources that have been managed historically in independent ways (Larson, Lee, Tellinghuisen, & Keller, 2007). In the United States, economic growth, economic security and resource availability impact decisions to ensure that both energy and water resources are available to meet future growth needs (US Department of Energy, 2006). A review of existing research and reports (Carns, 2004; Gleick, 1994; Grenoble, 2007; Hightower, 2007; Hightower & Pierce, 2008; King & Webber, 2008; Klein, Krebs, Hall, O'Brien, & Blevins, 2005) suggests that quantification of the water-energy nexus occurs on both national and regional scales. For example, Sandia National Laboratories published a report discussing the national water-energy nexus and recommended areas for research and joint management of these resources. According to the Sandia National Laboratories report research opportunities regarding the water-energy nexus includes stretching current water supplies, water reuse, desalination, coordinated water and energy conservation, synergistic water and energy production and renewable energy production (US Department of Energy, 2006).

One geographic location in the United States that is challenged with increasing water-energy demands is the southwest, particularly Arizona. With the population in Arizona expected to grow 50% by 2030, water providers must address increasing energy use related to water services; balancing population growth demands with affordability (Scott, et al., 2007). Arizona is one area of the country where regional water and energy issues are important due to increasing consumption of these resources driven by population growth, thereby stressing an already aging infrastructure (Arizona Investment Council, 2008).

Research on the water-energy nexus includes determining water needs for electricity production and electricity usage for water services. A review of research indicates that water demand for energy generation is relatively well documented (EPRI, 2002a; Hutson, et al., 2004; King & Webber, 2008; Pasqualetti & Kelley, 2007, 2008; Solley, Pierce, & Periman, 1998); however, few research projects exist that report quantified electricity demands for water services, particularly for the state of Arizona. Pasqualetti and Kelley (2007) researched the water costs for electricity in Arizona and wrote, “A companion study should examine the other side of the coin—the energy embedded into every unit of water delivered and used in Arizona” (p. 2). In support, Scott et al. (2007) suggested the need for research investigating the energy demand required to provide water services in Arizona.

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METHOD AND APPROACH

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Reclaimed water. Reclaimed water is “the end product of wastewater reclamation that meets water quality requirements for biodegradable materials, suspended matter and pathogens” (Levin and Asano, 2004, p. 203A). Reclaimed water undergoes reclamation, which is includes treatment to make it reusable (Levine & Asano, 2004). In Tucson the reclaimed water use stage includes: recharge and recovery; treatment at two water reclamation plants; and, distribution of reclaimed water to users. In Phoenix, reclaimed water is treated at and distributed from one water reclamation facility.

Water and Wastewater Agencies

Nine water and wastewater agencies were contacted and agreed to provide data; however, two water agencies were unable to provide data for reasons unknown to the researchers. Therefore, seven water and wastewater agencies provided data for the study. Collectively, these seven agencies provide eighty three percent of water service in Tucson, eighty five percent of wastewater service in Tucson and one hundred percent of water and wastewater service in the city of Phoenix. Below is a brief description of the agencies along with the water use stage for which water and electricity data were provided.

Central Arizona Project. The Central Arizona Project canal transports water from Lake Havasu on the Colorado River to water users in central and southern Arizona. Each year the CAP delivers approximately 1.5 million acre-feet of water to more than 80 municipal, industrial, agricultural and Indian users in Arizona. The canal is 541 kilometers in length from the Colorado River to the city of Tucson and requires 14 pumping stations to move the water uphill (Central Arizona Project, 2008). The CAP data applied to one of the four water use stages: primary water extraction and delivery.

Tucson Water. Tucson Water, owned by the city of Tucson, is the primary water provider for the Tucson metropolitan area. In 2006, Tucson Water supplied drinking water to approximately 71 percent of Tucson's metro area population (Tucson Water, 2004). The water agency projects to service as many as 1.1 million people by 2030 (Tucson Water, 2008). Tucson Water annually supplies more than 100,000 acre-feet of drinking water. The agency uses both local groundwater and recharged Colorado River water imported through the Central Arizona Project canal (CAP). Upon delivery, CAP water is diverted into infiltration basins and allowed to mix with local groundwater prior to pumping. Tucson Water also operates a reclaimed water system that provides approximately 15,000 acre-feet of reclaimed water each year to users for turf irrigation and other uses. Reclaimed water is treated three different ways in Tucson: 1) effluent from a wastewater treatment facility is recharged and recovered; 2) effluent from a wastewater treatment facility is pumped to a water reclamation facility where it undergoes additional treatment; and 3) wastewater is treated at a separate reclamation facility and pumped into the reclaimed system. Tucson Water provided data for three of the four water use stages: primary water extraction and delivery; treatment and distribution; and reclaimed water.

Metro Water District. Another participating water agency from the Tucson metropolitan area is the Metro Water District, which in 2007 served more than 50,000 people. Metro Water District operates within a 67 square kilometer service area and delivers annually more than 8,800 acre-feet of groundwater (Block, personal communication, November 3, 2008). Metro Water District provided data for two water use stages: primary water extraction and delivery; and, water treatment and distribution.

Oro Valley Water Utility. The city of Oro Valley is located in the northern Tucson metro area. The water utility for the city serves approximately 48,000 people and provides more than 8,000 acre-feet of water annually to customers (Ruiz, personal communication, November 25, 2008). Oro Valley Water Utility provided data for three of the four water use stages: primary extraction and delivery; water treatment and distribution; and, reclaimed water.

Private Water Company. Additionally, one private water provider participated in the study. This water utility serves approximately 22,000 people providing nearly 3,000 acre-feet of groundwater annually. The private water company provided data for two of the four water use stages: primary water extraction and delivery; and, water treatment and distribution.

Pima County Regional Wastewater Reclamation Department. Pima County Regional Wastewater Reclamation Department (PCRWRD) manages 11 wastewater facilities in Pima County, including the Tucson area. The growing population in PCRWRD’s service area is expected to rise from 850,000 people in 2007 to more than

1.1 million people by 2030 (Pima County Regional Wastewater Reclamation Department, 2006). By 2030 approximately 67 percent of the population in the Tucson metropolitan area will be in the PCRWRD service area should anticipated population growth occur. The provided data were applicable to two water use stages: wastewater treatment and collection; and, reclaimed water.

City of Phoenix Water Services Department. Water and wastewater services in the city of Phoenix are provided by one utility, which is owned by the city. The water utility serves more than 1.5 million people within 1,400 square kilometer service area. The Phoenix Water Services Department provides more than 300,000 acre-feet of drinking water annually. The water supply for the city of Phoenix is a combination of groundwater, Colorado River water transported via the CAP and surface water provided by the Salt River Project (SRP). Additionally, the water services department operates three wastewater treatment facilities and one water reclamation plant (City of Phoenix Water Services Department, 2005). The current population of Phoenix is expected to increase from 1.5 million to more than 2 million by 2020, which is a 25 percent increase in population (City of Phoenix, 2001). The city of Phoenix Water Services Department provided electricity and water data four all four water use stages: primary water extraction and delivery; treatment and distribution; wastewater collection and treatment; and, reclaimed water.

Data Collection and Categorization

On-site visits and email communications were used to contact these water and wastewater agencies to gather electricity and water data. Agencies were asked to provide electricity data in tabular form for the most recent year data were available, which included either 2005 or 2007 for each agency. Each agency was requested to provide electricity for water use data categorized within the four water use stages investigated in this project. As described above, water and wastewater agencies provided electricity and water data for applicable stages. Six of the agencies provided electricity data categorized within the stages and I categorized the data for one water provider.

Once collected, I organized the categorized data in a Microsoft Excel spreadsheet and subsequently completed several calculations. Categorical aggregation of collected data is an accepted practice for case study research (Stake, 1995). Categorizing electricity data for water use into these water use stages facilitates the application of various calculations to interpret research results.

Data Calculations

I completed three sets of calculations by water use stage for Phoenix and Tucson. First, I calculated the energy intensity by water use; second, I tabulated electricity use by stage to determine the total electricity requirement; third, I applied the energy intensities previously calculated to projections of future water demand to estimate potential electricity use in 2030. All calculations completed for this research project pertain solely to electricity and, therefore, excluded off-grid energy consumption such as natural gas.

Energy intensity. The term energy intensity refers to the total energy (for this project energy is synonymous with electricity) required to pump, treat, distribute or otherwise use a volume of water (Wilkinson, 2000). I calculated an energy intensity value for: 1) primary water extraction and delivery; 2) water treatment and distribution; 3) wastewater collection and treatment; and, 4) reclaimed water. I calculated the energy intensity for each water use stage by dividing electricity units (kWh) by water volume (Acre-Feet). The water use stages are comprised of individual water uses that have their own energy intensities. Wilkinson states that when multiple sources of water are used a weighted average energy intensity is necessary to account for the percentage of each water source (Wilkinson, 2000). Additionally, we spoke with a data analysis employee at PCRWRD who compiled water and energy data and she suggested we use a weighted average to account for relative contribution of electricity use by water source. In reference to the water-energy nexus, the term "weighted average" means calculating individual water use energy intensities and then accounting for the percent of supply by volume in order to calculate an aggregate energy intensity for each water use stage. The energy intensity of individual water uses were multiplied by the percentage of total water used in each stage, as illustrated in Equation 1.

$$\left(\frac{E_1}{V_1} \times \frac{V_1}{V_t}\right) + \left(\frac{E_2}{V_2} \times \frac{V_2}{V_t}\right) + \ldots + \left(\frac{E_n}{V_n} \times \frac{V_n}{V_t}\right) = EI \qquad (1)$$

In the above equation E represents electricity (kWh), V represents the volume of water (AF) and EI (kWh/AF) represents the calculated energy intensity. The energy intensity of each stage is a combination of the per-unit energy intensities weighted by water volume.

Completed per-unit energy intensity calculations include: conveyance and pumping for stage 1; treatment and distribution for stage 2; wastewater collection and treatment for stage 3 and reclaimed water use for stage 4.

Tabulated electricity. The second calculation was summation of electricity use by stage to determine the total amount of electricity used for water services in the Tucson metropolitan area and city of Phoenix. In the Tucson metro area, electricity data were compiled from five water and wastewater agencies and the CAP and aggregated into one value for each water use stage. In the city of Phoenix, CAP and city of Phoenix data were aggregated into one value for each water use stage.

Projected electricity use, 2030. Lastly, we projected electricity use by 2030 for water and wastewater service. We used the previously calculated per-unit energy intensity values of individual water use stages and applied the intensities to published estimates of future water demand for Phoenix and Tucson in the manner illustrated below.

$$\left(EI_1\right)\times\left(V_1\right)+\left(EI_2\right)\times\left(V_2\right)+\ldots+\left(EI_n\right)\times\left(V_n\right)=E_t \qquad (2)$$

In the above equation EI represents the per-unit energy intensity of a water use (kWh/AF), V represents the volume of water (AF) the agency expects to serve and E_t (kWh) represents the total electricity usage for water and wastewater service. Water volume by source was ascertained by consulting water utility documents detailing future water demand scenarios for both Phoenix and Tucson. For Phoenix, four different water availability scenarios and two population growth scenarios were identified from official

Water Services Department documents. For each scenario the electricity use for each water use stage was determined using equation 2 and then consolidated into a single electricity value for each scenario.

Tucson Water developed four different supply scenarios for its service area extending out until 2050. These scenarios only address Tucson Water demand, not the metro area. As a result, I extrapolated potential metro area water use from the Tucson Water demand scenarios. In scenarios A and B Tucson Water will serve 62% of the Tucson area population (Tucson Water, 2008) and other water providers serve the remaining 38% of the population. For scenarios C and D Tucson Water will serve 69% of the Tucson area population (Tucson Water, 2008) and other water providers serve the remaining 31% of the population. Several smaller water providers in Tucson have CAP allocations, which we assumed would be used by 2030. We assumed that remaining water demand outside of the Tucson Water service area would be local groundwater. The energy use for each water use stage was determined using equation 2.

In addition, we completed a simple sensitivity analysis to ascertain a range of potential electricity use numbers reflecting technology choices. The first step was to determine the energy impact of reclaimed water use for scenarios B, C and D in Tucson. I computed electricity projections for increased reclaimed water or groundwater use. The second calculation was based on the assumption that technology changes would occur between now and 2030 thus altering the energy intensities for the water use stages. Tucson Water recently conducted a survey inviting consumers to determine the most desirable mineral concentration for drinking water: either 450 parts per million (ppm) or 650 ppm total dissolved solids (TDS). The projected financial difference between these two TDS concentrations for drinking water is approximately 25%. Therefore, we used the 25% difference value and applied it to the current energy intensity value for drinking water treatment to determine the electricity impact of a 25% increase or decrease in energy intensity. We also investigated a 25% increase and decrease in the energy intensity value for wastewater treatment and reclaimed water use.

RESULTS

Energy intensity

Energy intensity results for Tucson and Phoenix are illustrated by water use stage in the table below. The first two stages have a weighted energy intensity comprised of individual water uses. In Tucson, energy intensity for conveyance was four times larger than groundwater pumping. In Phoenix, the energy intensity of reclaimed water is two times greater than conveyance.

Table 1: Energy intensity for each water use stage

Water Use Stage	Tucson Metro Area (kWh/AF)	City of Phoenix (kWh/AF)
Primary water extraction and delivery	1,579[a]	673[a]
Conveyance	3,140	1,525
Groundwater pumping	781	919
Water treatment and distribution	253[a]	390[a]
Treatment	155	48
Distribution	248	400
Wastewater collection and treatment	329	519
Reclaimed water	1,530	2,984

Note. Unless otherwise noted, the energy intensity values are unweighted

[a] calculated as a weighted average using Equation 1

Conveyance and drinking water treatment are more energy intensive in Tucson and groundwater pumping, water distribution, wastewater treatment and reclaimed water use are more energy intensive in the city of Phoenix.

Total electricity use for water and wastewater services

Table 2 summarizes electricity calculations for water and wastewater service in the Tucson metropolitan area. The table illustrates electricity use by water use stage and individual water use including percent of total electricity use.

Table 2: Energy intensity and electricity use for Tucson metropolitan area

Water Use Stage	Percent Total Electricity Use	Tucson Metro Area (GWh[a])
Primary water extraction and delivery	75.7	262.0
Conveyance	51.3	177.7
Groundwater pumping	24.4	84.3
Water treatment and distribution	10.6	36.7
Treatment	0.2	0.7
Distribution	10.4	36.0
Wastewater collection and treatment	7.0	24.2
Reclaimed water	6.7	23.4
Total	100.0	346.3

[a] GWh represents 1 x 10^6 kWh

Primary extraction and delivery represents more than 75% of total electricity use for water service in the Tucson metro area. Specifically, conveyance (i.e., the CAP) accounts for more than 51% of total electricity use. Nearly 11% of total electricity use is for water treatment and distribution, wastewater treatment represents approximately 7% and reclaimed water use accounts for slightly more than 6% of total water use. In total, water providers in the Tucson metro area use more than 346 GWh of electricity annually. Detailed results associated with the Tucson Water reclaimed water system are presented below.

Table 3: Reclaimed water, Tucson metropolitan area

Water Use Stage	% Total Electricity	Energy Intensity
Primary water extraction and delivery	10	153[a]
Treatment and distribution	90	1,377[a]
Treatment	46	1,284
Distribution	44	675
Total	100	1,530

[a]Weighted energy intensity calculated using Equation 1.

In Tucson approximately 45% of reclaimed water is recharged and recovered effluent and 55% is treated at two water reclamation plants. Recharge and recovery of effluent accounts for 10% of total electricity use and reclaimed water treatment requires 46% of total electricity. Distribution of reclaimed water accounts for 44% of the total electricity use. The calculated energy intensity of reclaimed water in Tucson is 1,530 kWh/AF. Table 4 summarizes the energy intensity calculations for water and wastewater services in the city of Phoenix.

Table 4: Energy intensity and electricity use, city of Phoenix

Water Use Stage	Percent Total Electricity use	City of Phoenix (GWh[a])
Primary water extraction and delivery	45.1	220.0
Conveyance	41.9	204.35
Groundwater pumping	3.2	15.7
Water treatment and distribution	30.1	147.0
Treatment	3.7	18.1
Distribution	26.4	128.9
Wastewater collection and treatment	22.8	111.3
Reclaimed water	2.0	9.8
Total	100.0	488.1

[a] GWh represents 1 x 10^6 kWh

Primary water extraction and delivery accounts for 45% of total electricity used for water service in Phoenix. Specifically, conveyance (i.e., CAP) uses nearly 42% of total electricity. Drinking water treatment and distribution accounts for 30% of total electricity use, wastewater treatment represents 23% and reclaimed water uses 2% of total electricity.

Projected electricity use, 2030

Illustrated in Table 5 are projections of electricity use derived from projected water demand for the Tucson metropolitan area.

Table 5: Projected water and electricity demand, Tucson metropolitan area by 2030

Scenario	Total Water Demand (AF)	% Growth of Water	Electricity Use[a] (GWh)	% Electricity Growth
Current Use[b]	173,045	-	375.6	-
A	278,065	61	787.3	110
C-Groundwater[c]	296,500	71	800.7	113
C-Effluent	296,500	71	808.9	115
B-Groundwater	325,823	88	831.3	121
B-Effluent	325,823	88	839.1	123
D-Groundwater	347,200	101	848.1	126
D-Effluent	347,200	101	866.8	131

Note. For further discussion of individual scenarios see (Tucson Water, 2008). [a]Electricity use was calculated using Equation 2. [b]Current water demand and electricity use were extrapolated from data provided by water utilities to estimate total metro area demand. [c]Groundwater use refers to pumping, treating and distributing local groundwater, not recharged CAP water.

In the aforementioned table the water demand scenarios are ordered from least to greatest water demand. As illustrated in the table water demand may increase between 61 and 101% and electricity use to provide water and wastewater service may increase between 110 and 131%. Projected electricity demand may be as much as 866.8 GWh annually. A sensitivity analysis was also completed to assess how energy intensity variations impact overall electricity use. The four sensitivity scenarios include: α) a energy intensity increase of 25% for water treatment, wastewater treatment and reclaimed water; β) a energy intensity decrease of 25% for water treatment, wastewater treatment and reclaimed water; γ) a energy intensity increase of 25% for water treatment, and a 25% decrease in energy intensity for wastewater treatment and reclaimed water; and, δ) a energy intensity decrease of 25% for water treatment, and a 25% increase in energy intensity for wastewater treatment and reclaimed water.

Table 6: Sensitivity analysis of Tucson area electricity projections by 2030

Scenario	Current[a]	α	β	γ	δ	Stdev	% Stdev
A	787.3	804.1	770.5	777.7	815.1	21.2	2.7
B Groundwater	831.3	848.1	814.5	821.7	859.1	21.2	2.6
B Effluent	839.1	861.8	816.3	823.5	872.8	27.9	3.3
C Groundwater	800.7	817.6	783.9	791.1	828.6	21.2	2.6
C Effluent	808.9	831.6	786.1	793.4	842.6	27.9	3.4
D Groundwater	848.1	865.0	831.3	838.5	876.0	21.2	2.5
D Effluent	866.8	897.8	835.7	843.0	908.8	37.3	4.3

Note. The numbers in the table columns have units of electricity in GWh.

[a]Electricity projection values from Table 5.

In the above table one standard deviation of the sensitivity analysis ranges between 21.2 and 37.3 GWh of electricity. This equates to 2.5-4.3% of the original electricity projection for each scenario. The next table is a summary of the electricity projections calculated for the city of Phoenix investigating two growth scenarios and four supply availability scenarios.

Table 7: Projected water Supply and Electricity Use for city of Phoenix, 2030

Scenario	General Plan (AF)	General Plan (GWh)	High Density (AF)	High Density (GWh)
CAP Normal & SRP Normal	475,687	722.7	581,020	774.7
CAP Moderate & SRP Moderate	417,687	612.4	447,000	635.6
CAP Severe & SRP Moderate	370,687	503.5	400,000	526.7
CAP Severe & SRP Severe	206,100	452.2	306,000	452.2

Note. For a full discussion of the water supply by source see (City of Phoenix Water Services Department, 2005).

In the above table, four different supply scenarios were used to assess potential electricity demand. If CAP and SRP supply scenarios are normal (e.g., no drought or supply shortage) electricity use will increase to as much as 774.7 GWh annually. The subsequent table illustrates how overall electricity use can change with energy intensity variation.

Table 8: Sensitivity analysis for city of Phoenix general growth plan

Scenario	General Plan[a]	α	β	γ	δ	Stdev	% Variation
CAP Normal & SRP Normal	722.7	771.0	663.2	675.5	758.8	55.6	7.7
CAP Moderate& SRP Moderate	612.4	651.1	562.5	572.4	641.1	45.8	7.5
CAP Severe & SRP Moderate	503.5	537.5	458.2	467.0	528.7	41.0	8.2
CAP Severe & SRP Severe	452.2	479.9	413.2	420.5	472.6	34.5	7.6

Note. The numbers in the table columns have units of electricity in GWh.

[a]Electricity values from Table 7.

In the above table the standard deviation of projected electricity values are between 34.5 and 55.6 GWh or 7.6-8.2% of the original projected electricity value for each supply scenario. For normal supply availability a 25% increase in all three energy intensities results in a maximum electricity use of 771.0 GWh and a 25% decrease in all three energy intensities results in a minimum electricity use of 663.3 GWh. The table below illustrates the same sensitivity analysis for the high density growth scenario for the city of Phoenix.

Table 9: Sensitivity analysis for the city of Phoenix high-density growth scenario.

Scenario	High Density	α	β	γ	δ	Stdev	% Variation
CAP Normal & SRP Normal	774.7	829.5	708.8	722.6	815.6	62.2	8.0
CAP Moderate & SRP Moderate	635.6	677.2	582.8	593.5	666.6	48.7	7.7
CAP Severe & SRP Moderate	526.7	563.6	478.5	488.0	554.1	44.0	8.4
CAP Severe & SRP Severe	452.2	479.9	413.2	420.5	472.6	34.5	7.6

Note. The numbers in the table columns have units of electricity in GWh.

In the above table the standard deviation of projected electricity values for each availability scenario ranges between 34.5 and 62.2 GWh of electricity. The standard deviation values are 6.6-7.2% of the original high-density electricity project.

DISCUSSION

The calculated energy intensity values reveal much information regarding specific electricity needs for water and wastewater services in Tucson and Phoenix. Similarities and differences exist between the Tucson metropolitan area and city of Phoenix. Overall, primary water extraction and delivery accounts for a majority of electricity use in both cities. The results from the city of Phoenix and Tucson metropolitan area are comparable to research completed regarding the water-energy nexus in California as well as national evaluation. As discussed in the introduction, the water use cycle has been applied to water and wastewater service in California and as a result there exists much opportunity to compare energy intensity values.

Primary water extraction and delivery

To answer the project's first research question evaluation of primary water extraction and delivery is necessary. Water supply in the Tucson metropolitan area is a combination of imported CAP water and local groundwater. On a per-unit basis the CAP requires 3,140 kWh/AF to move water from the Colorado River to Tucson. Energy intensity values of this magnitude are common for large intrastate water transfer projects. For example, in California the State Water Project (SWP) moves water from northern to southern California through 660 miles of aqueduct and the cumulative energy intensity values at the terminus of the SWP in southern California is 3,236 kWh/AF. The SWP project moves water twice as far as the CAP and the system includes power generation due to gravity flow components of the system. By comparison, the movement of CAP water to Tucson is slightly less energy intensive than the SWP in California; however, the movement of water is entirely uphill. In addition, groundwater usage in the Tucson metro area requires 781 kWh/AF to pump from the underlying aquifer. EPRI (2003) estimates that average national groundwater pumping energy intensity range between 200 and 600 kWh/AF suggesting that the groundwater pumping energy intensity in the Tucson metro area are greater than the national average. In the Tucson metro area, the energy intensity of primary extraction and delivery is 1,579kWh/AF. For comparison, the energy intensity of primary extraction and delivery in southern California ranges between 1,876 and 2,900 kWh/AF (Klein, et al., 2005; Wilkinson, 2000). In total, electricity used during the primary extraction and delivery stage accounts for 76% of total electricity use for water and wastewater service. This is slightly less than the 77% electricity used for primary extraction and delivery in southern California.

The primary water extraction and delivery stage for the city of Phoenix includes CAP, local groundwater and SRP water. The CAP has an energy intensity of 1,525 kWh/AF, which is 50% of the energy intensity required to move water Tucson. Compared to the SWP in California, the CAP energy intensity for Phoenix is approximately 50%. The energy intensity for conveying surface water to Phoenix is less than other areas in Arizona and less than other large-scale water projects such as the SWP. Local groundwater use in Phoenix has a per-unit energy intensity of 919 kWh/AF, which exceeds both Tucson and the national average. Phoenix also has access to SRP water with no energy intensity due to the gravity flow design of the conveyance system.

Combining the energy intensity values of CAP water, groundwater and SRP water for the city of Phoenix results in a weighted energy intensity for primary extraction and delivery of 673 kWh/AF. The energy intensity for primary extraction and delivery of water in Phoenix is lower than Tucson, and southern California. Electricity use for primary extraction and delivery in Phoenix accounts for 45% of total electricity use, which is lower than in Tucson (76%) and lower than the average for southern California (77%). The primary reason for reduced electricity use is the SRP, which supplies 53% of the city of Phoenix's water supply without using electricity. The primary extraction and delivery stage is one of two components of water service and the energy intensity of water treatment and distribution is necessary to assess the energy intensity of water service.

Water treatment and distribution

Water treatment and distribution in the Tucson metro area has an energy intensity of 253 kWh/AF. This exceeds the treatment and distribution energy intensity for southern California which is 219 kWh/AF (Wilkinson, 2000). Water treatment in the Tucson metropolitan area has an energy intensity of 155 kWh/AF. Klein et al. (2005) report an energy intensity range of 32-521 kWh/AF for water treatment in California which suggests that water treatment energy intensity in the Tucson metropolitan area is not unusually small or large. Electricity use for distribution of water in Tucson accounts for 10.4% of electricity use. In comparison, distribution of electricity in southern California accounts for approximately 9% of total electricity use. The energy intensity of water distribution in Tucson is 248 kWh/AF, which is within the range of energy intensity values for distribution reported by Klein et al. (2005). Therefore, compared to the average southern California water agency more electricity is used to distribute water in the Tucson area.

The average energy intensity of water treatment and distribution for the city of Phoenix is 390 kWh/AF, which is larger than the energy intensity for treatment and distribution in California. Water treatment and distribution uses 30.1 % of total electricity for water and wastewater service in the city of Phoenix. This is 21% larger than in southern California and 19.7% greater than Tucson.

Water service is a combination of the pervious two stages: primary water extraction and delivery; and, treatment and distribution. The first research question for this project addressed energy intensity of water service. In the Tucson metropolitan area, combination of the energy intensity values from primary extraction and delivery and treatment and distribution results in a water service energy intensity of 1,832 kWh/AF. Similarly, the energy intensity value for water service in California as reported by Wilkinson (2000) is 2,095 kWh/AF. For the city of Phoenix, the energy intensity of water service is 1,063 kWh/AF, which is 50% of the energy intensity in southern California and 769 kWh/AF less energy intensive than Tucson.

An important factor contributing to energy intensity difference between the Tucson metropolitan area and the city of Phoenix is geographic location. The largest energy input for water service in both cities is conveyance (i.e., CAP) and the energy intensity of moving CAP water to Phoenix is 50% less than moving water to Tucson.

Additionally, the SRP is an important electricity savings for water service in Phoenix. If the SRP system required uphill pumping similar to the CAP system, electricity use for water service would increase greatly and the overall energy intensity might be similar to values observed in Tucson or southern California. Therefore, the electricity implications of using a gravity fed system results in less electricity use and a lower energy intensity.

Wastewater collection and treatment

The results discussed in this section respond to the second research question regarding the energy intensity of wastewater collection and treatment. Results from this study suggest that the energy intensity of wastewater service is 329 kWh/AF, which is less than the national average of 517 kWh/AF for wastewater treatment and the southern California average of 629 kWh/AF (EPRI, 2002b; Wilkinson, 2000). The wastewater collection and treatment energy intensity is lower in the Tucson metropolitan area due to less energy intensive wastewater treatment methods such as biofiltration. The biofiltration treatment process relies on wastewater moving through an artificial media covered with microorganisms that consume organic matter (Pima County Regional Wastewater Reclamation Department, 2006). The two largest wastewater treatment plants in Tucson also use natural gas and biological methane, which reduce the energy intensity for electricity.

The wastewater treatment facilities operated by the city of Phoenix have an energy intensity of 519 kWh/AF. The Phoenix wastewater treatment plants use an activated sludge process, which uses fans to aerate wastewater enabling microorganisms to consume organic matter (EPRI, 2002b). The plants also have the capability of tertiary treatment including nitrification and denitrification, which requires more electricity use. Wastewater treatment in the city of Phoenix exceeds slightly the national average of 517 kWh/AF (EPRI, 2002b); however, wastewater treatment in southern California has an energy intensity of 652 kWh/AF which exceeds the city of Phoenix.

Reclaimed water

In the Tucson metropolitan area, the treatment and distribution of reclaimed water has a calculated energy intensity of 1,530 kWh/AF. Reclaimed water is less energy intensive than potable water, a finding that addresses the third research question. Local groundwater requires less electricity to pump than reclaimed water; however, the current water supply in the Tucson metropolitan area also consists of CAP water. The energy intensity of water service is 1,832 kWh/AF and in comparison the energy intensity of reclaimed water is 1,530 kWh/AF. The finding that reclaimed water use saves energy in light of more energy intensive alternatives such as importation of surface water confirms the findings of other researchers (Sala & Serra, 2004; Wilkinson, 2000). Sala & Sera (2004) investigated reclaimed water use in Spain and identified energy savings associated with reclaimed water use, especially when compared to desalination costs, deep groundwater pumping and long distance conveyance of water. Wilkinson (2000) identified an energy intensity of 400 kWh/AF for supply of reclaimed water to users in California. While this value does not include distribution energy intensity it is much lower than the energy intensity for importing water via the SWP.

The city of Phoenix also reuses treated wastewater. The energy intensity of reclaimed water in the city of Phoenix is 2,984 kWh/AF. In Phoenix the calculated energy intensity for reclaimed water is approximately three times as large as the energy intensity of water service. One reason for the larger energy intensity value is that reclaimed water undergoes tertiary treatment at a reclamation facility, which is more energy expensive. Unlike Tucson and other locations such as California, reclaimed water use in Phoenix represents potential energy savings when compared to water conveyance. For comparison, in Tucson nearly 50% of the water is recharged and recovered requiring much less energy than treatment at a reclamation facility. The lower overall energy intensity is a result of recharge and recovery of effluent in addition to treatment at reclamation facilities.

Impact of Anticipated Water Demand on Electricity Use

The results discussed in this section answer the fourth research question regarding projected electricity use in the Tucson metropolitan area and city of Phoenix by 2030. For Tucson, I estimated electricity usage for four different water supply scenarios: A, B, C and D.

Table 10: Summary of water demand scenarios for Tucson, 2030

Scenario	Description
A	Tucson Water will serve approximately 900,000 people in the Tucson area. Investment will be made to reduce per capita water demand by 10%.
B	Tucson Water will serve approximately 900,000 people. No investment will be made to reduce per capita water demand.
C	Tucson Water will serve approximately 1.1 million people. Investment will be made to reduce per capita water demand by 10%.
D	Tucson Water will serve approximately 1.1 million people. No investment is made to reduce per capita water demand.

The electricity projections for water and wastewater service in the Tucson metropolitan area are based on water demand projections developed by Tucson Water which are illustrated in the above table. The demand scenarios assume a 2030 Tucson metropolitan area population of approximately 1.6 million. Scenarios A and C project water demand with a 10% per capita decrease in potable water consumption from 163 gallons per capita per day (GPCD) to approximately 147 GPCD. Scenarios B and D assume that the current per capita water rate, 163 GPCD, remains steady until at least 2030 (Tucson Water, 2008). Water providers will use CAP and groundwater to meet demand. Recharged CAP, natural aquifer recharge and reclaimed water use levels will be insufficient to meet water demand for scenarios B, C and D. As a result, additional water will be needed and two potential sources are local groundwater and reclaimed water. We evaluated the impact of using local groundwater or reclaimed water as the additional water source needed to meet demand for scenarios B, C and D. For all scenarios we assumed that the population served by water providers other than Tucson Water relied primary on groundwater and some CAP water.

In the Tucson metropolitan area, the percentage rate increase in total water demand will be less than the percentage rate of electricity increase due to the large energy intensity of imported surface water via the CAP. For all scenarios, electricity use for water and wastewater service more than doubles from estimated 2007 electricity usage. Even the most conservative scenario (i.e., Scenario A) projects a water demand increase of 61% and electricity demand increase of 110%. Scenario D has a water demand increase of 101% and an electricity demand increase of 131%. For comparison, statewide electricity demand growth is expected to be approximately 85% between 2008 and 2032 (Arizona Investment Council, 2008). Therefore, the growth rate of electricity use for the Tucson metropolitan area is larger than the expected electricity growth rate for the state of Arizona. For each analyzed water demand scenario, conveyance (i.e., the CAP) will account for more than 50% of the total electricity used for water and wastewater service in the Tucson area.

As previously mentioned, Tucson Water will require an additional water source by 2030 for scenarios B, C and D. We projected electricity demand of using either groundwater or reclaimed water as the additional water source. For scenarios B, C and D an electricity difference of 0.9-2.1% between local groundwater use and reclaimed water was calculated. The scenario that used reclaimed water rather than groundwater consistently used more electricity to meet water demand.

In addition to using different water sources, technology choices will impact energy intensities for water uses and therefore overall electricity use. The sensitivity analysis was designed to illustrate how moderate changes in energy intensity will impact overall electricity use. Energy intensity values were altered for three stages: water treatment, wastewater treatment and reclaimed water. The range of electricity use varied between 2.5 and 4.3% of the electricity values for each scenario as presented in Table 5. The largest observed increase occurs for water supply scenario D, which assumes the largest volume of reclaimed water use. The sensitivity analysis illustrates that moderate changes to treatment, wastewater treatment or reclaimed water energy intensity values have a small impact on overall electricity use.

For the city of Phoenix we evaluated two growth scenarios: a general growth plan and high-density growth plan. The general growth plans targets specific areas outside of downtown Phoenix for future growth (City of Phoenix, 2001). The high-density plan anticipates growth in the downtown Phoenix area (City of Phoenix Water Services Department, 2005). For each growth scenario, the city of Phoenix projected expected water demand. Additionally, the city investigated potential supply availability scenarios for the major water sources such as the CAP and SRP. The city of Phoenix evaluated three different supply availability scenarios: normal, moderate shortage and severe shortage. Shortage results from inadequate water storage due to drought and the probability of a moderate shortage between 2005 and 2055 ranging from 10-40%. Table 11 summarizes supply availability for both the CAP and SRP. I projected electricity demand for both the general plan and high-density growth plan in the context of four different water supply scenarios. This study investigates the electricity impact of four supply scenarios: CAP normal and SRP normal; CAP moderate, SRP moderate; CAP severe and SRP moderate; and, CAP severe and SRP severe. The table below illustrates supply availability by source.

Table 11: Supply availability for CAP and SRP systems

Supply Scenario	CAP	SRP
Normal	Total CAP delivery is 1.5 million AF, full delivery of CAP allocation	Each acre of land served by the SRP is allocated 3 AF
Moderate	Total CAP delivery is 1.0 million AF, Partial delivery of CAP allocation	Allocation per acre is reduced one-third
Severe	Total CAP delivery is 600,000 AF, Major reductions in CAP delivery	Allocation per acre is reduced two-thirds

Normal supply conditions on the CAP and SRP result in electricity use between 722 and 774 GWh annually, a difference of 7%. For both scenarios electricity use decreases as shortages occur. If moderate shortages occur on both the CAP and SRP electricity is reduced 100 GWh for the general growth plan and 140 GWh for the high-density plan. If severe shortages occur on both the CAP and SRP electricity use is reduced to 452.2 GWh for both scenarios. Supply availability directly impacts electricity use for service, and the electricity projections detail electricity variation among the supply and growth scenarios.

The sensitivity analysis for the city of Phoenix water supply and growth scenarios indicated more variation in overall electricity use. For the high-density growth scenario, total electricity demand will increase as much as 8.2% which is approximately two times greater than any increase observed through the Tucson area sensitivity analysis. The greater variability in electricity is a result of large water volumes undergoing water treatment and wastewater treatment. Based on the sensitivity analyses, the city of Phoenix water system could experience more electricity use variability than the Tucson metropolitan area water supply resulting from greater sensitivity to technology choices and augmentation of energy intensity.

CONCLUSIONS

As presented in the introduction of this study, gaps exist in the knowledge base concerning electricity for water services in Arizona; knowledge important to making informed water-energy nexus related policy decisions. The study of electricity for water services in the Tucson area and city of Phoenix resulted in advancing the knowledge base for each water use stage:

Primary extraction and delivery

- Long-distance conveyance (i.e., the Central Arizona Project) is the largest electricity user in both the city of Phoenix and Tucson metropolitan area
- In the Tucson metropolitan area, the energy intensity of CAP water is two times the energy intensity of reclaimed water

Water treatment and distribution

- Water treatment in the Tucson metropolitan area requires approximately 155 kilowatt-hours per acre-foot (kWh/AF) which is three times higher than water treatment energy intensity in the city of Phoenix

Wastewater collection and treatment

- Wastewater treatment and collection in the city of Phoenix is near the national average of 517 kWh/AF; however, wastewater collection and treatment in the Tucson metropolitan area is much lower with an energy intensity of 329 kWh/AF.

Reclaimed water

- In Phoenix reclaimed water has an energy intensity of 2,984 kWh/AF, which is nearly twice as high as the energy intensity for reclaimed water in Tucson

Projected electricity use by 2030

- In the Tucson metropolitan area, the growth rate of electricity is projected to range between 110 and 131% which will exceed the expected statewide electricity growth of 85% between 2008 and 2032 (Arizona Investment Council, 2008)
- In contrast, the projected electricity growth in Phoenix will nearly equal the expected state wide electricity growth of 85%

Overall electricity demand

- Currently, electricity use for water and wastewater service in the Tucson metropolitan area and city of Phoenix accounts for 1.2% of statewide electricity consumption for 2005 (Energy Information Administration, 2007)
- Projected electricity demand for Tucson and the city of Phoenix will equal approximately 1.1% of statewide electricity demand by 2030
- Electricity use for water and wastewater service in the Tucson metropolitan area accounts for approximately 5% of total residential, commercial and industrial electricity use in the metropolitan area (Hayes, Dickerson, Comrie, & Cotty, 2008)

Nationally, 3-4% of electricity is used for water and wastewater service (EPRI, 2002b). The city of Phoenix and Tucson metropolitan area consumption of electricity for water and wastewater service amounts to less than 2% of statewide total electricity. The 2% electricity use number represents a portion of total electricity for water use statewide due to the study's focus on Phoenix and Tucson. In the Tucson metropolitan area, electricity use for water and wastewater service accounts for approximately 5% of metro area total electricity consumption. Therefore, the Tucson metropolitan area uses slightly more electricity for water and wastewater service than the national average.

Additionally, there exist several other aspects of water use in the state beyond the scope of this study. For example, electricity use for water and wastewater service was limited to the study of the city of Phoenix rather than the Phoenix metropolitan area. Also this study evaluated water and wastewater service for approximately two and a half million people while the Arizona state population is nearly seven million. Furthermore, the scope of this study was limited to CAP deliveries to the city of Phoenix and the Tucson metropolitan area, which account for only 20% of total CAP water delivery. This research was also limited to urban water use, and therefore agricultural electricity use for water is an area for further study. Collectively, along with results from this study, as the other elements of electricity use for water service in Arizona are quantified more comprehensive perspectives of the water-energy nexus will emerge.

As stated, the results of this study suggest that electricity use for water and wastewater service in the Tucson metropolitan area and city of Phoenix is a small percentage (i.e., less than 2%) of overall electricity use in Arizona. Furthermore, projections suggest that electricity use for these two areas will remain less than 2% of statewide electricity use despite population growth and increasing water demand through 2030. This highly desirable and minimal overall electricity use reflects current supply and management decisions. However, as water shortages occur and population continues to grow there exists an opportunity and/or need to invest in alternative water resources such as brackish groundwater, which could result in increasing electricity use. Also, the need exists to investigate end use electricity consumption in Arizona, which in other states such as California, has been shown to be an important component for total electricity use for water and wastewater services. Quantification of end use electricity consumption will impact the 2% value calculated for water and wastewater service in the city of Phoenix and Tucson metropolitan area.

While overall electricity use in the Tucson metropolitan area and city of Phoenix are currently low, water and wastewater agencies are approaching a decisions crossroads. Future water management choices regarding water supply and treatment techniques may also result in an increase in overall electricity use. Simultaneous consideration of water and electricity resources will be necessary to maintain the current low overall electricity use for water and wastewater services. When considering the low overall electricity use in the Tucson metropolitan area and city of Phoenix for water and wastewater service, continued management of the water-energy nexus may require a greater focus on water for energy production as well as continued efforts to maintain current electricity use intensities. Future research should also investigate the electricity use of the 1.3 million AF of CAP water delivered outside of the city of Phoenix and Tucson metropolitan area, which represents 80% of CAP delivery. Also, there exists a need to determine electricity use of other major water providers in Arizona as well as smaller water providers around the state. As previously mentioned, additional research is needed to determine end use electricity consumption in the residential, commercial and industrial sectors as well as the magnitude of electricity use by the agriculture sector in Arizona. Overall, results from studies on the aforementioned research topics will complement results form this project to ascertain a more comprehensive view of the water-energy nexus in Arizona.

ACKNOWLEDGEMENTS

Funding for this project was provided by the Arizona Water Institute.

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