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Feasibility, and Resiliency, and Economic Impacts of Energy Storage in Urban Water Systems: Case Study of Cleveland, Tennessee

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To the Graduate Council:

I am submitting herewith a dissertation written by Susanna Hannah Sutherland entitled "Feasibility, and Resiliency, and Economic Impacts of Energy Storage in Urban Water Systems: Case Study of Cleveland, Tennessee." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Energy Science and Engineering.

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**Feasibility, and Resiliency, and Economic Impacts of Energy Storage in Urban Water
Systems: Case Study of Cleveland, Tennessee**

**A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville**

**Susanna Hannah Sutherland
December 2017**

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ABSTRACT

This research reduces the knowledge gap around how the water-energy nexus can be applied at the urban level, clarifying how a city water distribution system might be used to offset community energy consumption. The created methodology includes 3 research objectives. First, model scenarios are developed to determine opportunities for energy storage in urban water systems. Then, how increased energy storage capacity impacts water system resiliency is examined. Finally, the financial implications of scenarios are calculated.

A closed-loop water system model (EPANET2) simulates Cleveland, Tennessee's water distribution system, resolved to the neighborhood scale. Sectoral aggregated hourly energy use data provides a comparison baseline for storage scenarios. Storage is injected into the water model in concentrated and distributed configurations to understand which is more effective at shaving peak energy demands, and which is more effective at increasing water system resiliency. Configurations are assigned costs, to understand how feasible it is to increase energy storage in water systems over local utility planning and financing horizons.

Key findings include: (1) concentrated water storage configurations can generate significantly more electricity than distributed storage configurations, because they can be designed primarily for energy generation, not primarily to meet demand and to maintain pressure; (2) distributed water storage configurations can be more resilient to the chronic stress of population growth, because increasing storage throughout the water system is more effective at maintaining water system pressures and meeting increasing demand; and (3) neither concentrated nor distributed water storage configurations are cost effective within local utility planning and financing horizons, because the payback periods far exceed that 20-year timeframe.

This research fills a knowledge gap around the scale at which small pumped hydro-generation systems can be effective at reducing community electrical demands. It clarifies the impacts of various storage configurations on water system resiliency, and how fiscally solvent using the water system to store energy might be. It concludes that small-scale hydro in an urban water system is viable at the micro-scale on a case by case basis, but not fiscally feasible as a tool to shave peak community energy demands.

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INTRODUCTION

Exploring the Water-Energy Nexus at the Local Level

Water and energy system interdependencies and their separate management structures are becoming more prominent as water and energy resources are increasingly stressed. The interaction and interconnection among water and energy supply and use is often referred to as the water-energy nexus (Baker & Behn, 2013). There is an ever-increasing push for the integration of water and energy management at the local level to achieve long-term system sustainability, while balancing conflicting economic, environmental, and social priorities. Local energy and water system managers are aware of the interdependence between energy and water systems. However, often national, state, and local jurisdictions promote a silo approach to water and energy management, thus restricting their ability to integrate decision-making processes (Halstead et al., 2014).

Understanding the Water-Energy Nexus

The vulnerability of urban water and energy systems to variables such as terrorism, extreme weather, and market volatility, and their inextricable linkages to one another prioritize much of the current urban water-energy research (DOE, 2014). Ready availability and reliability of energy and water supplies determine how well a society thrives economically and environmentally. They are at times competing resources, out of balance with each other, but critical to maintaining and growing quality of life in urban centers. Policymakers face complex challenges, requiring integrated policy and management strategies and solutions often impeded by jurisdictional and information barriers (Goldstein et al., 2008). Ultimately, it is at the local level that urban water and energy system changes can be tested, implemented, and potentially scaled. Putting digestible knowledge and usable tools in the hands of local decision makers are key components needed to move towards widespread systematic operational and infrastructure changes.

Water and energy are resource drivers in urban areas, and the ability of their supply to meet local demand directly impacts the economic, environmental, and social prosperity of individual communities (Pate et al., 2007). Some urban centers already have water and energy use rapidly approaching or exceeding economic, environmental, and social demands (Hoekstra et al., 2012). They are striving now to change water and energy system operations and system investments to stay viable. Responsible management of both resources in the face of climate change, population shifts, and technology development is one of this generation's greatest challenges (Johansson et al., 2012).

Water-Energy Nexus Barriers Summary. The rising awareness of the importance of water-energy nexus means the amount of literature is steadily growing. Water-energy linkages have been examined from many angles (Desai & Klanecky, 2011; Gerbens-Leenes et al., 2009; Grubert et al., 2012; Sattler et al., 2012; Schnoor, 2011). A variety of researchers and some government agencies have worked to synthesize existing information and define knowledge gaps. They are finding, among other things, that obtaining useful data to understand causal relationships is difficult. There is a lack of methodological frameworks, and resistance to holistic standardization of water and energy systems. These constitute major barriers that stand in the way of robust, scientific investigations into the urban water-energy nexus (U.S. Department of Energy, 2014; Glassman et al., 2011; Kenway et al., 2011; McMahon & Price, 2011; Nair et al., 2014; Pate et al., 2007; U.S. Global Change Research Program, 2015).

Resilience as an Emerging Water-Energy Nexus Practice. Often, energy and water systems are discussed in terms of reliability. The target is maintaining perfect operation over time. Resiliency is a newer lens that addresses the ability of local infrastructure systems to recover from certain types of failure, while remaining functional from the customer's perspective. Operations may not in reality be perfect, but the customer is unaware, and delivered services minimize inconveniences.

Improved water system resilience means that a community is better prepared to respond to and minimize disruptions such as fluctuation in population, not that it can neutralize all risk. Urban water systems are more than their engineered parts. They involve highly complex interactions between human, technological, and environmental components. This research uses the U.S. Department of Energy's (DOE) definition of resiliency, which is "the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience" (Moniz, 2014).

In this research, resilience focuses on vulnerability and capacity to cope in the face of chronic stressors, because those are the elements of risk a community can best control. Chronic stress is the response to system pressure experienced over a prolonged period. This research does not focus on the acute hazards themselves. This portion of the research defines chronic stresses scenarios, and measures resiliency in terms of depth of failure. It examines how the addition of energy storage capacity in urban water distribution systems can be simulated to buffer impacts in the face of certain risks. Steps in this research process: (1) determined the most likely chronic stress scenario (population growth) that the case study area may face; (2) measure the ability of the water system to meet demand in this scenario using unused

tank storage capacity not already being used to meet demand; and (3) compare scenario outcomes with and without energy storage capacity.

Literature Summary. The present state of knowledge around the water-energy nexus calls for system integration at all levels. Published work around energy storage in urban water systems is very limited both in theory and in practice. Energy storage contributions to system resiliency are understood through the limited lens of a general evolution towards flexibility in a hard infrastructure system. Benefits and costs are poorly defined.

While many studies examine the interconnections between water and energy systems, little work has been done yet to investigate the impacts of the management options associated with both resources together, particularly at the local level (Hussey & Pittock, 2012). Though discussed together in the water-energy nexus frame, water and energy are still primarily managed and funded separately due to jurisdictional constraints. Understanding the financial impacts of various energy storage scenarios in urban water systems plays a tremendous role in the uptake of any proposed action in local government, because the reality is that working across departmental structures requires a well-documented win for multiple decision makers.

One set of water and energy interdependencies exists at the local level, and deals with the storage of energy in urban water systems. This research addresses this aspect of the water-energy nexus, examining literature that addresses water and energy interconnections in municipal settings. Specifically, literature of importance frames methods for storage of energy in urban water systems, provides examples of methodologies that can be used for financial analysis of energy and water system upgrades (such as additional storage), and explains how to evaluate water system resiliency. Key findings for each topic include:

- Literature surrounding the water-energy nexus is vague when it comes to the specifics of integrating water and energy systems. It identifies a host of obstacles to system integration, including the lack of availability of standardized data sets and tools. It also identifies fragmentation between management processes and structures. These both impact local level implementation, showing a knowledge gap to address, and calling out impeding processes.
- Using water to store energy (hydro-generation) at a large scale is a mature field, and is still one of the most efficient energy storage methods available. Implementing small-scale hydro-generation

is somewhat newer, especially at the microgrid level. Small-scale hydro is proving viable in some locales, and is being explored with greater frequency in the literature.

- Some integrated modeling efforts dealing with both water and energy systems are published. They are rare, however, and very few of these examples use actual city case studies to test their algorithms, operational conditions, and integration point theories.
- Many different modeling, mapping, and statistical analysis tools can be paired in almost any number of ways to answer interdisciplinary and cross-system questions. There is no standardization of types of tools to combine, types of data that local utilities should collect, or clear methods for how to use synchronous tools for system integration decision-making.

Moving Towards Urban Water and Energy System Integration

U.S. water and energy futures are uncertain, in part due to insufficient mechanisms to integrate the economic, environmental, and social variables that influence both systems. Lack of authority to manage resources, which display erratic distributions in time and space, undermine integrated water and energy management (Biswas, 2004). Increasingly, local water and energy managers realize that addressing the two resources comprehensively is a key to making progress towards system sustainability (Pate et al., 2007). This research provides them with useful tools towards that end.

There are three primary insights surrounding water and energy interactions in urban systems. First, energy needs will increasingly become a problem for water systems as they face higher costs, carbon reduction pressures, and source reliability concerns. Second, maximizing energy resources efficiently is a whole-system challenge (demand, management, technology, etc.), but structurally these systems are fragmented and not very collaborative. Third, technology is particularly important to maximize energy conservation and production (small-scale generation of hydropower, for example) and minimize regulatory action (thermoelectric cooling systems gaining more EPA attention, for example).

Energy is an essential part of water supply, purification, transfer, and utilization, and its consumption continues to grow (Apergis & Payne, 2012). In the U.S., 13% of electricity consumption is associated with water use, and this use contributes to over 290 million tons, or 5%, of annual U.S. carbon (CO₂) emission each year (Griffiths-Sattenspiel & Wilson, 2009). Water also plays an integral role in energy extraction, production, conversion, distribution, and use (Spang et al., 2014). Kenway et al. (2011), while stating that there is a rudimentary understanding of the complex and pervasive connections between water and energy in cities, visually show their basic causal relationships within urban settings. Figure 1 is

adapted from this summary. It essentially points out that one cannot be produced for human use without the other. All figures and tables referenced in this Introduction are placed in in Appendix I, in the order they are mentioned in this text.

Thermoelectric power is the largest water user for energy creation in the U.S., accounting for 49 percent of the country's total water withdrawal (Barber, 2009). Globally, the energy sector contributes the largest amount of greenhouse gas (GHG) emissions. It is commonly accepted that these emissions contribute significantly to climate change, which brings with it the hazards of increased intensity and frequency of extreme weather (Raupach et al., 2007).

Water plays a huge role in the effects of climate change. It can compromise urban systems through scarcity and intrusion, and can be compromised in quality and quantity by various natural disasters attributed to climate instability. The drought of 2012 impacted over a third of the U.S., limiting water availability and constraining power plant operations. Hurricane Sandy hit vital water infrastructure and energy facilities in the States of New Jersey and New York later that same year, resulting in billions spent on restoration efforts (Hsiang et al., 2017). Most local governments aren't prepared for investments of this magnitude, and are increasingly interested in proactive measures to insure system stability. Specifically, they need methods that contribute to system resiliency that also make economic sense.

Understanding Sustainable Urban Water Systems

In urban settings within the United States (U.S.), local practitioners broadly understand “sustainability” as a three-pillar concept: responsible economic, social, and environmental management. If asked to explain it, many simply say that sustainability meets the needs of the current generation without compromising future generations. To maintain consistency with the U.S. national scope of this study, this proposal adheres to the definition of sustainability from the 2009 Executive Order 13514 “Federal Leadership in Environmental, Energy, and Economic Performance”, where it is defined as: “to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations” (p. 14).

Sustainable Innovations in Urban Water Systems. For a municipal water system, sustainability means that it is capable of reactively meeting existing community needs while proactively anticipating future community needs. Urban water systems are increasingly integral to cities' sustainability goals. They: (1) impact carbon mitigation efforts through system energy use; (2) impact community climate resilience

through infrastructure and system performance; (3) impact cities' economic development by removing constraints on business and population growth; and (4) face new management challenges of performance, costs, and rates that affect a broad set of stakeholders and ratepayers (Hellström et al., 2000).

Many innovations for sustainability in urban water systems exist. There is only modest convergence on best practices, and change is still bifurcated and crisis-driven. Outdated regulations, uncertainties about new technologies, unclear management practices, and a lack of communication among management structures are critical barriers to water system developments.

There are 5 reoccurring themes cities cite as categories needing innovation in urban water systems: (1) a healthy water supply is needed for economic security and social stability, and optimizing water supply is increasingly important; (2) utilities and municipalities are struggling with rising operating costs, and centralized water distribution systems are vulnerable to single-point failures; (3) capital investment is heavily subsidized by government, and water rates do not reflect externalized costs of water withdrawal, pollutant discharge, and other community impacts; (4) despite shared resource points and the potential to leverage infrastructure, water and energy systems generally conduct planning independently; and (5) regulatory and disciplinary silos impede the collaboration among water and energy resource managers (Cosens et al., 2014).

Sustainable Urban Water Systems Measurement. Measuring the innovation trends and success towards sustainability goals in urban water systems is difficult, because it is not yet standardized. Sustainable water system goals include items shown in Table 1. Tables 1 and 2 summarize relevant findings from 2013-14 original and interactive research led by the Innovation Network for Communities with 14 U.S. cities, to understand the current state of sustainability in urban water systems.

Scorecards and frameworks are becoming more common for urban water managers to track progress towards key performance indicators (KPIs). A common issue with score cards is that use of them is not standardized across water utilities, so it is difficult to compare the same metrics between systems (Hellström et al., 2000). An example of a municipal urban water principle, milestone, and indicators is shown in Table 2. The brevity and lack of detail is normal for scorecards. It is up to the water utility to quantify progress against whatever set of KPIs they adopt internally.

There are 3 direct ways to influence urban water systems towards sustainability. First, systems can adopt performance goals and targets for water system sustainability and hold the systems accountable publicly. Second, water systems can undertake climate adaptation and resilience planning, which includes the sustainability of the system and engagement of stakeholders. Third, water systems can reinvent their business and financing models and raise capital needed to meet sustainability goals.

Sustainable Urban Water System Drivers. Major drivers of sustainable change within urban water systems can be put into two broad categories. First, the underlying dynamics of the water market (demand and supply) are shifting in ways that increase the power of market forces. Four large, discernible trends are changing the U.S. water market: (1) overall water use is declining (Hilaire et al., 2008); (2) new market niches are developing, like tradable supply and pollution rights and markets; (3) the price of water is rising (Walton, 2010); and (4) the economic value of water is increasing. Secondly, drivers of change (the economy, climate variability, and energy consumption, for instance) are growing in importance.

Long-term, three relatively new factors will increase the demand for water system sustainability: (1) the economy needs sustainable water; (2) climate change is creating conditions and uncertainties that require new solutions; and (3) the water-energy nexus is a driver in determining water system costs (B. Chen & S. Chen, 2016). These drivers support 10 new factors for urban water management (Brown et al., 2009): (1) Climate adaptation / resilience: Use of climate impact / system vulnerability analyses; (2) Standards for sustainability: External performance assessments by investors and stakeholders; (3) Carbon reduction (energy use / source): Carbon mitigation strategies applied to water systems; (4) Urban economic development: Business development and siting impacted by water availability; (5) Water stress: Severe, prolonged water scarcity resulting in policymakers changing allocation; (6) Demand management: Supporting consumer efforts to conserve water through behavior change; (7) Non-revenue water: Loss of delivered water due to leakage in pipes or unmetered use; (8) Business model disruption: Energy costs, loss of revenue due to conservation, financing of sustainable infrastructure projects, increasing investor expectations; (9) Watershed stakeholders: Increased necessity to align stakeholders to consolidate approaches; and (10) New revenue services: Utilities invent services to make up for revenue lost to conservation (footprint analysis for companies, insurance against water disaster, etc.).

Case Study: Cleveland, TN Water and Electric Utilities

While many studies do not use actual city water and energy system data, this research employs both. Data sets are used to understand orders of magnitude between community energy consumption and water

system storage capabilities. Modeled data is used to test where energy storage could be located, and in what configurations. This section examines the case study's energy and water systems.

Cleveland Utilities Profile. The City of Cleveland owns its own water and electric utility. According to the Cleveland Utility (CU) website, Cleveland Water Works began operation in 1895. The City of Cleveland bought the Tennessee Electric Power Company in 1939, and formed Cleveland Electric System.

In 1976, the Cleveland Water System and Cleveland Electric System merged operations, forming CU. A 5-member Public Utilities Board was established in 1981; it is appointed by the City of Cleveland mayor and directs a Chief Executive Officer (CEO). CU now serves approximately 39,754 electric customers, 30,417 water customers, and 18,026 sewer customers, both within Cleveland city limits and throughout much of Bradley County (Cleveland Utilities, 2017).

Though CU is a municipal utility, it is not housed within the city as a department, but is instead a separate entity. The Hiwassee Utility Commission (HUC) is also serviced by CU staff, sharing the same board, but HUC services the cities of Athens, TN and Riceville, TN. The mission of CU's electric division is to provide their customers with *“excellent and reliable water, wastewater, electric, and supporting services through innovative business practices, a process of continual improvement, and a demonstrated commitment to our community and Core Principles”*. Core principles include: community, continual improvement, ethical standards, excellence, inclusiveness, innovation, reliability, responsibility, safety, and stewardship. CU aspires to collaboratively and responsibly meet evolving utility needs (Cleveland Utilities, 2017).

Data Collection

Data was collected from CU, including water and energy demands, GIS shape files, a model export of the CU water distribution system, and planning documents to understand projected population growth patterns. Lessons learned about how to be a good communicator include: how to make the case when data is requested, how to obtain research buy-in, who to coordinate data transfer with, and when to ask for it. These lessons are summarized in Figure 2.

Water Data Collection Challenges and Outcomes. The CU Engineering Department approved the research concepts, provided water system background, and introductions to Jacobs Engineering Group –

their water system modeling consultant. After an initial meeting, Jacobs provided an .inp file export of Cleveland's water system model from H2OMap, a software designed by Innovyze (Wallingford Systems Limited, Broomfield, CO). They also provided pump and tank files in .dbf, .shp, and .shx, to spatially orient in ArcGIS (Environmental Systems Research Institute, Redlands, CA). In H2OMap, Jacobs has demand patterns created within the model from Cleveland's 2015 water billing data. These patterns use demands assigned to geo-referenced nodes in the water model. Each node has at least 2 base demands, which the model uses to calculate 5-minute time step demand data for 72 hours (most patterns).

Jacobs also provided the base data set they used to create Cleveland's water demand patterns: 2015 monthly water consumption data by meter and sector type. Addresses and names are stripped from files – no customer identifiers are used in this work. The monthly water meter data for the 2015 data set contains current and previous month readings, and total water usage readings by: (1) sector (commercial, large commercial, small commercial, industrial, and residential); and (2) meter ID. The 2015 water demand dataset also contains monthly totals by water source (produced and purchased water), monthly totals by commercial and residential sector (gallons and percent), and total loss by percent and volume.

Jacobs confirmed water model data inputs, answered water system behavior questions, and shared their 2015 CU calibration report. Several meetings occurred with them and CU personnel throughout the course of this research, including a windshield tour of the CU service territory. Discussions clarified preferred water system operating conditions, water model calibration methodology, and how the model is used to inform system planning for informed infrastructure decisions. Overall, the water data collection was a smooth process.

The learning challenge came when trying to understand what normal operation looked like within the model, so the model transfer between software could be verified in preparation for scenario development. Another barrier encountered is that energy calculating capabilities within the water system model are not executed by model time step. The only representation of energy consumption within the model are calculated averages of distribution pump energy consumption. Integration of energy consumption data at a community level within the water model was not possible, meaning that energy comparisons to water system storage capacity had to be calculated manually in Excel-based spreadsheets.

The existing water model proved to be intensely complicated, especially for a small city. CU is a webbed water system unconfined by city limits. The southern service territory is farm land, serviced by ground

water wells and not connected to the piping network. Figure 3 shows Cleveland's 20-year growth boundary, planning boundary, and water system network orientation.

Electrical Data Collection Challenges and Outcomes. Electrical data was more difficult to obtain. Collection attempts spanned 10 months and included several phone and in-person meetings with CU staff. Five overarching challenges were overcome: (1) A shared understanding was reached that customer identifiers are not needed to conduct the study - a non-disclosure agreement was also signed to insure any data provided is kept private; (2) Staff turnover in the Information Technology (IT) department changed who would ultimately provide the data and on what timeframe; (3) A shared understanding was developed over time on the data request components – this was finally accomplished by comparing the data request to the structures of the existing CU databases, and reaching a compromise on what can easily be provided in light of that structure; (4) A shared understanding was developed between the perceived and actual time required to export and transmit datasets; and (5) A compromise was reached on what the data set should include, to enable data transfer to finally occur.

Data gathering challenges are not specific to CU. Utilities across the U.S. are being asked to share water and energy consumption data that will allow urban sustainability to advance. Big data sets like these provide the ability for local authorities to make smarter decisions concerning updating codes for building retrofits and new construction, for example. Utilities are often reluctant to share data because of the staff time it can require fielding requests, customer data privacy concerns, and the implications of public knowledge of utility revenue models. This results in significant opportunity costs for communities. It stunts growth in the energy field by placing data needed to make transformational changes out of reach, and forces non-utility parties such as cities, researchers, and planners to develop work-arounds, and to make assumptions that would be unnecessary if data were scrubbed of customer identifiers and released in aggregate sets (Stimmel, 2014).

Another challenge is that even within a single electric utility, databases often do not interface with each other. ElectSolve (Shreveport, LA) is used as CU's meter data management system (MDMS), providing an integration platform for smart meter reading by the 15 electrical substations within CU's service territory. Another system is used for customer management and billing (CMB), and neither of these interface with GIS (for circuit mapping overlays), or with each other. In sum, CU has 13 databases with over 36,000 meter records. Each IT data manager specializes in a system, and most do not have working knowledge of the other systems, making data compilations and comparisons more difficult.

For communities that want to examine water and energy system integrations, the ideal data gathering scenario to reveal seasonal used patterns would be to obtain at least 1 year of electric demand data. Ideally, this data would be hourly for 12 months, to understand the demand shapes of a 7-day week (168 hrs.), month (720 hrs.), or year (8,760 hrs.), resulting in a data file of 280,320,000 records. CU does not have the capability of uploading such large data files to their FTP site for sharing.

In the first attempt to collect CU electrical consumption data, the CU Electric Division provided 2015 monthly energy consumption data by meter and sector type, as well as hourly electric meter readings for 1 month for 11 sector codes. The 2015 monthly electric meter dataset provided current and previous month readings, and total water usage readings by: (1) sector (commercial, large commercial, small commercial, and industrial, but no residential); and (2) meter ID. The U.S. Energy Information Administration's (EIA) utility data was also collected for Volunteer Energy Cooperative (VEC, all counties), as was their data for CU electric sales by sector.

In this first dataset, a consumption multiplier is used to compute consumption and peak demand. There are 12 meter readings (1 for each month) for most meters, but not all. Total electric usage is calculated within the dataset as the difference between current and previous electrical meter readings (in kWh). The first data set does provide hourly readings for 11 sector classes for 31 days in July 2016. The data comes in 60-minute intervals over 24 hours for a month. Meter names are un-descriptive of customer sector, and no spatial identifiers are provided. Most meters have hourly readings, though some hours are missing throughout the dataset.

However, after further negotiations with the utility, an electric consumption data set was delivered that contained hourly energy consumption (in kWh) by substation (16 total) and sector classes (11 total) for 4 months in 2016: January, April, July, and November – representing the 4 seasons in east TN. Like the water demand dataset, addresses and names are stripped from files; no customer identifiers are used. Because there are no customer identifiers, the best way to spatially locate electric demand is by electrical substation.

Substation identifiers were provided in the dataset, as was a substation and circuit zone map for import into ArcGIS. There are two 69 kV (medium voltage, commercial / industrial) substations, one in south and one in east Cleveland. The remaining are 13 KV (medium voltage - residential) substations zones. Due to the challenges of data availability and gathering, it must be assumed that electricity can be consistently

delivered throughout the electrical system, and that there are no weak spots in distribution within the CU electrical distribution system. Research questions can be adequately answered despite this assumption, because the methodology focuses on the water system, not the electrical system.

Once the electrical data was in hand, it became quickly evident that hourly data in such magnitude had to be restructured and formatted so it could be manipulated into the comparison calculations the research required. This process took at 1 month of careful translation of utility codes into discernable identifiers, through back and forth dialogue with the utility. Ultimately, it required a complete spreadsheet restructuring so that data could be visualized by sector, month, and hour. Because this process was manual, it had to be checked and re-checked to insure data transfer did not compromise the data set itself.

Water System Overview

Cleveland takes most of its water from the Hiwassee River, located just north of city limits. The Hiwassee is impounded and operated by TVA at an authorized channel depth of 10 feet. The river serves as a boundary between Bradley and McMinn Counties. It also connects the region to the Tennessee River, which is approximately 22 miles west.

Two filter plants are located roughly 0.5 miles apart on the Hiwassee: (1) the Cleveland Utilities (CU) filter plant, which services the City of Cleveland and parts of Bradley County; and (2) the Hiwassee Utilities Commission (HUC) filter plant, which services the cities of Riceville and Athens, TN, as well as parts of Bradley and McMinn Counties. Source withdrawals aren't monitored or limited by regulation. Pipe size does impose a daily withdrawal limit, however. CU's wastewater treatment plant (WWTP) can process and finish up to 12 million gallons per day (MGD) due to the 20" diameter pipe lines. The filter plant could accommodate up to 21.6 MGD if pipe size were increased. Projected demand scenarios considered for the WWTP in the Bradley County 2035 Strategic Plan (2013) indicate that the current WWTP capacity is adequate for anticipated growth if the system is consistently well maintained.

There are secondary water sources in addition to the Hiwassee River: Waterville Spring can provide up to 1.5 MGD. CU can purchase water from Savannah Valley Utility District to service the small Misty Valley subdivision on the northeastern boundary of the CU service territory. CU can also purchase or sell water to the Ocoee Utility District and the Eastside Utility District (EUD), servicing parts of the adjacent Hamilton County. These are small sales of around 1 to 2 MGD.

Urban water systems may be considered “closed loop” in water system modeling terminology, but as with any other water system, interconnections and interactions are unique to watershed conditions, supply or processing limitations, and service territories. Figure 4, taken from the City of Cleveland Comprehensive Plan (2013) shows Cleveland color coded by water utility service areas. Population is most dense in the northern portion of the service territory; this area was once its own utility district. A new industrial park is planned on the southeast side of town. If implemented, CU will likely have more interaction with EUD. On the southern end of the city, the city uses roughly 22,000 gal. per day from Clearwells Spring. CU does not service White Oak Mountain, located in the western portion of the service territory (Figure 4).

Water Demand. CU measures water production in terms of “finished water”. Finished water has had solids removed, has been treated for bacteria, augmented with liquid chlorine, lime, and fluoride, and is considered potable and suitable for human consumption. Finished water that is put into a municipal water system but is not accounted for in billing records is called non-revenue water (NRW). Water systems around the world share this issue, and is an opportunity to realize better water system efficiencies (Frauendorfer & Liemberger, 2010). In the CU system, metered and billed finished water is on average 1 to 2 MGD less than finished water produced. NRW represents around 20% of CU’s finished water production.

The CU water system currently bills around 31,000 customer meters, including users inside and outside Cleveland city limits. CU assumes there are 2 to 4 people in each household. Some of their industrial and commercial customers require significant amounts of water, depending on their product. For instance, a bottling plant has a much greater water footprint than a sock factory. Some water use is prompted by seasonal temperature changes. For example, in January, residents may drip pipes to keep them from freezing. In July, many will irrigate lawns to keep plants alive when heat is most intense in the southeastern U.S. In seasons of maximum daily demand (July and August, for example) the CU filter plant produces between 9 and 10 MGD of finished water, while in seasonal periods of average daily demand (November, for example), the filter plant will produce between 7 and 8 MGD of finished water.

Metering and Budget Considerations. In the past, CU meter technicians read the water meters at different times each month, resulting in system-wide estimated demand at any given time. This method is changing, as CU has completed installation of mobile advanced metering infrastructure (AMI) in both water and electric systems. This is a fiber mesh network governed by a gatekeeper, allowing on-demand

connections with endpoint meters in real-time. A truck drives routes to wake up meters for automated meter readings (AMR).

The Federal Energy Regulatory Committee (FERC) defines AMI as “a metering system that records customer consumption hourly or more frequently and that provides for daily or more frequent transmittal of measurements over a communication network to a central collection point” (AMR vs AMI, 2008). AMR is defined by the Demand Response and Advanced Metering Coalition as a “system where aggregated kWh usage, and in some cases demand, is retrieved via an automatic means such as a drive-by vehicle or walk-by handheld system.” The data available from each system differentiates AMR and AMI, and they both can be categorized as “smart” metering (Huang et al., 2015).

Smart meters can provide utilities with a substantial amount of end-use information. Electric utilities can obtain: daily, cumulative, and time-of-use kWh consumption; peak kW and last interval demand; load and voltage profiles (including sag and swell events, and electricity phase information); outage counts and logs; tamper notification; and power factors (Depuru et al., 2011). Smart metering allows CU customers to be billed based on actual consumption, as opposed to manual meter reads or estimations based on past consumption patterns of the customer or building. It can translate into more effective management: water utilities that have access to incremental demand data find it easier to target leaks, and locate outlets for NRW.

Considering Cleveland’s growth projections, CU anticipates steady additions to the number of metered customers. While an increasing population means an increasing utility revenue base, it also means installation and maintenance costs for new equipment, as well as necessary upgrades. CU performs facility upgrades as part of an annually updated 10-year capital plan. CU coordinates with other city planning mechanisms to ensure service can be provided within the urban growth boundary.

CU budgets up to \$100,000 each year to install water system connections within subdivisions or commercial and industrial developments throughout Bradley county. CU pays up to 50% of new water system connection installations below \$12,500 in Bradley County. In county areas where the sanitary sewer service is available, connection to the sewer system is not required nor billed for unless connected. If connected, current billing rates for customers outside city limits are approximately 150% of the inside city limits rate. Inside the city, sanitary sewer rates apply, regardless of whether a customer is connected to the sewer system or has an on-site septic system. Peak stormwater flows, or inflow from storm events

into the sewer system, present current and future capacity challenges (Cleveland Comprehensive Plan, 2013).

Operating Preferences. CU adheres to AWWA water quality parameters and operating standards. The CU Supervisory Control and Data Acquisition (SCADA) system controls the system at the Cleveland Filter Plant (CFP) and communicates with the Hiawassee Utility Commission (HUC) SCADA system. Demand varies constantly, and real-time data can be pulled from the SCADA system as needed. CU mainly uses the water system model created and maintained by Jacobs Engineering to help anticipate future demand in development scenarios. This model is periodically calibrated with real-time system pressure readings and SCADA data. Tank operating behavior can be observed in SCADA (real-time) or within the calibrated water model over the course of a 72-hour model time period in 5-minute time steps.

CU has a significant amount of storage: 21 million gallons in total. Needed Fire Flow (NFF) storage is included in this storage capacity. CU prefers to operate with 1 day of peak water demand in storage at all times, which would ideally also be able to handle 1 large local fire. Tanks are constantly recharging and mixing as they meet demand, day and night. Pressure valves are off when tanks are recharging. Supply pumps are on when it is time to deliver demand and refill the tanks. There are 2 pipes connecting each tank to the water distribution system: an incoming pipe, set by overflow, and an outgoing pipe, located at the bottom of each tank. Because of this design, the water in the tank is always mixing.

By AWWA standards, water is in danger of having higher than allowable chlorine levels in roughly 1 week, though it depends on the amount of chlorine residual within the tanks themselves. Because mixing is occurring regularly within the tanks, CU notes that water age isn't a prevalent concern for them. Tanks drop to meet user demand, and water mixes during the peaks and valleys of this demand.

Like most urban water systems, CU uses their storage for three main functions: (1) to be prepared for development as it occurs; (2) to maintain sufficient pressure across the systems; and (3) to meet existing demands, even if a large fire is occurring somewhere in the service territory. Current and future storage scenarios should be designed to not interfere with these operating preferences. New developments must have adequate pressures and water supply for daily demand, as well as the capacity for fire suppression.

Water Tanks and Reservoirs. CU stores water in cylindrical tanks ranging from 500,000 to 3,750,000 gal., for a total of 21,050,000 gal of nominal volume. Actual volumes vary at any given point in time.

Water storage tanks are distributed throughout the CU service territory, with Eldridge and the Candies Creek tanks having the largest storage capacity.

Table 3 provides the bottom bowl elevation, operating depth, diameter, and nominal volume for each tank, by name. HUC Clearwells is the main water treatment facility, and CFP is at full capacity during peak demand. Filter plants storage is measured as a combined storage calculation, so their volumes do not belong to individual tanks. Altitude valves at McDonald, Eldridge, Sunset, Candies Creek and Weeks tanks are typically operated manually by CU staff. Altitude valves are closed at each tank's maximum water level, preventing overflow. They are opened to refill the tanks, when the preset minimum water level is reached.

CU also has 12 reservoirs identified in their water model. Reservoirs are considered "infinite" sources of water. They can be a plant drawing and treating raw water from a water body, or they can be a connection to another water system, where water is bought and / or sold between utility territories. Three of these reservoirs pump from or return water to the Hiwassee River: the CU Filter Treatment Plant, the HUC Treatment Plant, and the Waterville Springs Waste Treatment Plant. As of 2016, there are no AMI meters to measure energy load on the main treatment plants.

In addition to these source reservoirs, there are 9 metered connections of the CU system to water neighboring distribution systems: Savannah, Tunnel Hill, Leadmine, Bluesprings, McDonald, Old Alabama, Highway 11, Ocoee, and Pine Hill. These kinds of inter-utility system connections can be used in place of a tank: for instance, CU reservoir Savannah only services Misty Valley subdivision, and adjusts otherwise low pressures in that area alone. In May 2012, CU bid a 500,000-gallon tank and booster station for this location, but funding for the lowest bid of \$525,450 did not materialize at that time. They will request proposals again in 2017, this time budgeting \$550,000.

Water Pressure and Pumps. The city lies across a series of low ridges and valleys. This topography results in changing elevations, so pressure must be maintained by tanks positioned on ridgetops to maintain a minimum of > 20 pounds per square inch (psi, calculated by dividing elevation by 2.3). The CU water system has a significant amount of high pressure areas (>100 psi). Highest pressure zones are in the westerly half of the system. The main pressure zone is an industrial site. Figure 5 depicts the pressure at a peak demand hour of 6 p.m. Eastern Standard Time (EST). If a tank is providing dual pressure at multiple points in the system, the water model shows that tank elevation as a flat line. Figure 5 shows

color coded water system network pressures at each node during peak demand. There are 5 main pressure zones, described in Table 4. Abbreviations in the table are as follows: Hiawassee Utility Commission (HUC); Cleveland Filter Plant (CFP); Eastside Utilities (EUD).

In addition to the 5 main pressure zones, there are 22 smaller pressure zones across the CU water distribution system. While some of the production facilities contain booster pumps (at HUC, for example), there is also an associated booster pump station in each small pressure zone to maintain pressure levels. At least 5 of the small pressure zones also have bladder tanks, which do not provide significant storage capacity: Ashlin Ridge, Bennett Place, Fair Lawn, Mt. Zion, and Quail Run. They control pump operations during high demand, and reduce residential “water hammer”, which is a term to describe a knocking noise in a water pipe occurring when water flow ceases inside a structure. Cleveland residences each have Pressure Reducing Valves (PRV), also designed to control water hammer within each home. The CU water system also has 6 pumping stations containing production facility high service pumps (HSP), and 29 booster stations containing pressure-boosting pumps, some with variable frequency drives (VFD).

Water Pipes. The CU water system is comprised of 6,547 pipes totaling over 718 miles. Pipe sizes range from less than 6 to 36 inches in diameter. CU has a mix of pipe materials and thus a range of roughness coefficients, or Hazen-Williams C-values. C-values are used in the Hazen-Williams equation, which is as follows (Equation 1):

$$f = 0.2083 (100 / c)^{1.852} q^{1.852} / d_h^{4.8655}, \text{ where}$$

f = friction head loss in feet of water per 100 feet of pipe ($ft_{h20}/100 \text{ ft. pipe}$)

c = Hazen-Williams roughness constant (based on pipe material type and sometimes pipe age)

q = volume flow (gal/min)

d_h = inside hydraulic diameter (inches, used to calculate pressure loss in inches in ducts or pipes)

New PVC pipe with C-values ranging from 140 - 150 exist within the CU system. There are also old cast iron pipes from the mid 1950’s, with C-values of 54 - 83. Jacobs Engineering uses a roughness coefficient of 130 throughout the model, due to recent pipe upgrades throughout the distribution system. CU’s distribution system now has 20” piping infrastructure in place, and this is reflected in the modeled pipeline from the northern to the southern ends. This relatively high C-value value is an average of the old and new pipe flows, and is based on pressure and flow data. For example, when lines are upgraded from

the HUC pump station to the HUC filter plant, pipe hydraulics are calculated through the pipeline for 3-4 miles. The roughness coefficient can be adjusted down from 130 as needed when modeling, to slow flow.

CU budgets \$200,000 per year for pipe upgrades. Estimating pipe size for growth is difficult. Oversizing can cause negative pressures throughout the water distribution system. Under-sizing pipes can result in the need for costly upgrades, if population growth results in more flow requirements than the existing pipes can accommodate.

Energy System Overview

CU is a municipally owned distributor within the VEC service territory, which includes 15 TN counties. VEC purchases power from the Tennessee Valley Authority (TVA), which has the following energy portfolio: 12,400 MW from coal combustion; 10,000 MW from natural gas (combined cycle, combustion turbine, and diesels); 6,700 MW from nuclear reactors; 5,800 MW from hydro (pumped storage and conventional hydropower facilities); 1,620 MW from renewables (wind and solar); and 1,300 MW in avoided capacity (Tennessee Valley Authority Integrated Resource Plan, 2015).

During mild weather, TVA primarily relies on its hydroelectric dams, coal, and nuclear units to meet electricity demand. In times of temperature extremes, TVA meets demand by using its natural gas-fired power plants and by purchasing power from other electrical generators. According to EIA datasets, CU's total 2014 utility bundled retail sales to 30,441 customers total 1,090,636 MWh (Annual Electric Power Industry Report EIA-861 data file, 2017). Total bundled retail sales in 2015 were very similar, totaling 1,080,631 MWh. Both years are in Figure 6.

Operating Challenges. According to the National Rural Electric Cooperatives (NREC) website (2017) smaller and more rural utilities face many challenges, including: growing a portfolio of distributed energy resources, offering competitive employee benefits to retain talent, meeting environmental permitting requirements, having strong and diverse financing options for maintenance and upgrades, meeting standard operating procedures at all times, having a robust power supply, and maintaining the reliability of a system secured against cyber-attacks. In short, small utilities can function much like large utilities, only with less resources, more direct customer interaction, and smaller profit margins. According to CU's website, safe and reliable energy delivery are the primary goal and responsibility of the CU electric division (Cleveland Utilities, 2017).

One of the primary issues VEC faces is how to keep electric rates low. Electric cooperatives face challenges that municipal electric systems do not. The rising cost to supply electricity is a constant concern. VEC maintains over 9,000 miles of electric line, while averaging roughly 10 members per mile of line. A typical municipality can average around 50 customers per mile of line, while maintaining a significantly smaller system. VEC's system cost is high and membership is low, meaning that the cost to member ratio is consistently difficult to manage.

Unlike independently owned utilities (IOU) and municipalities, a cooperative is nonprofit, with no investors or owners. It is designed to keep costs low by being member-owned, with each member bearing the cost of maintaining the electric system together. All revenue cooperatives collects is used for the operation and maintenance of the electric system, which helps keep costs down. However, there are other factors that influence the cost of electricity.

The Tennessee Valley Authority (TVA) was set up by Congress in the 1930's to act as a power generator and regulator for the electric service industry inside of the Tennessee Valley. TVA applies a wholesale electric rate valley-wide. This rate is applied to every local power company (VEC, for example) to cover the cost of electricity purchased from TVA. It does not reduce to allow for operational margins or for maintenance of the local electric grid. So, local distributors augment the wholesale electric rate. The amount they charge, plus TVA's wholesale electric rate is the retail rate, or cost that is applied to each member's electric bill. This billing structure allows TVA to increase wholesale rates with little or no consideration of local electric system operation and maintenance (O&M).

Demand Management Programs. The current TVA wholesale rate incorporates several components, including charges for energy consumed and levels of power demand during system peaks. VEC offers options to members to help manage the costs of these components. For residential members, eScore, a free in-home energy evaluation, is offered. Anyone participating in the eScore program may also qualify to receive financial rebates to help pay for energy efficiency (EE) upgrades. For commercial and industrial members, Energy Right Solutions for Business and Industry (ERSB and ERSI) is offered. These programs provide technical assistance and financial rebates to help members implement EE upgrades (Volunteer Energy Cooperative, 2017).

In addition to offering EE programs, VEC maintains a demand control program, to further manage incurred costs. The VEC Load Reduction Pilot is currently available to commercial and industrial

members. Members of this pilot program can contribute an elected monthly allotment of interruptible load. Depending on need, VEC may call for load curtailment 1 - 2 times per month. Participation in the program is free, so there is no penalty for non-contribution. There is a credit given to any member that contributes during a curtailment call. The credit is seasonal, between \$2.80 and \$4.50 per kW reduced. VEC can save an average of 6 dollars per month for each kW reduced. Participating commercial members can potentially save several thousand dollars per month, while the cooperative can potentially save several tens of thousands of dollars per month. Savings are used to help maintain the cooperatives rates, as well as their electric system (Volunteer Energy Cooperative, 2017).

This VEC model matches the seasonal TVA demand charges. TVA charges customers a higher rate in the summer (June through September) and winter (December through March) when there are increases in customer usage. Rates are lower during transitional months (April, May, October, and November). TVA has a time-of-use rate for customers consuming 1,000 kW or above, and an interest in peak demand management. CU's system electric load at peak is between 158 MW and 220 MW. Industrial areas account for 10 MW. There is no interval metering on the plants right now, though VEC has undergone a conversion of traditional meters to AMI – currently, 900 megahertz (MHz) of data are transmitted over the fiber network. Community electric peaks are occurring simultaneously with water demand peaks.

Electric Distribution Network. Of the 15 substations in the CU electric service territory, TVA delivers purchased power at 161,000 volts at two delivery point substations: East Cleveland and South Cleveland Substations. This power is transmitted through a network of subtransmission lines, distribution stations and distribution feeders until it is delivered to each customer. Because the primary focus of this study is CU's water system, this study does not delve as deeply into the electric system as it does the water system. It assumes no areas of transmission weakness within each zone.

Research Need and Intent

Urban water and energy managers can fortify water and energy systems by taking an integrated approach to managing them. While energy storage in urban water systems is just one item in a portfolio of integration options, it is the focus of this research. The original work is an in-depth analysis of energy storage capacity in urban water systems, and the financial and resiliency impacts of increased storage. The research contribution builds on the existing water-energy nexus literature by specifically exploring the benefits and drawbacks of using urban water systems to store energy.

While various interactions between energy and water have been explored at length, this research seeks to specifically serve urban water and energy system managers, planners, and local policy decision makers. By going deeply into the why, how, risks, and rewards of increasing energy storage in urban water systems, this research presents a methodology for urban water system managers to use when evaluating future maintenance efforts, expansions, and long-term resiliency.

Research Rationale

This new research is motivated by knowledge gaps existing in 3 categories, chosen based on relevance to decision making in the fields of urban water and energy management. Research advances local decision-making knowledge and confidence around: (1) how water systems can be designed to accommodate additional storage for energy; (2) how the addition of energy storage in urban water systems can fortify water system resiliency in the face of chronic stressors; and (3) the fiscal implications of increased storage capacity in urban water systems. Based on the review of definitive literature, this has not yet been done. Without presenting energy storage in urban water systems as a realistic, logical means to achieve local sustainability goals, there is little chance it will be widely implemented in existing water systems.

Research Objectives

Using data from an urban case study, objectives of this research include: (1) assess the potential for energy storage in water systems; (2) demonstrate how the addition of storage can ultimately aid in long-term system resiliency and overall sustainability; and (3) evaluate the economic drivers that influence storage capacity decisions. Water and energy interactions are not bound by jurisdiction. They represent more than just transporting, converting, and treatment infrastructure. Therefore, this research also considers variables like population, source water treatment capacity, pump capacity, and peak electrical demands.

Anticipated Use

It results in a methodology that can be applied in urban settings to assess the theoretical and practical ramifications of increasing energy storage in urban water systems. This methodology can aid decision makers and energy and water system managers in understanding the options, risks, rewards, and long-term impacts of energy storage in the urban water system. This study is interdisciplinary in nature, and employs modeling, Geographical Information System use, and creation of Excel-based tools that theoretically integrate the complex systems of urban water and energy. Research outcomes have the potential to benefit society and contribute to the achievement of sustainable municipal outcomes, by

providing in-depth research, analysis, and methodology creation around assessment of energy storage in urban water systems to offset community electrical demands.

Research Category 1. Energy Storage Opportunities in Urban Water Systems

This research step explores how opportunities for energy storage in urban water systems are best measured. It examines possible locations for additional storage. It examines various storage configurations to maximize potential energy generation.

Energy Storage Feasibility Hypothesis

The hypothesis is that there are untapped opportunities for energy storage within urban water systems. This is due to a lack of water and energy system integration at the local level. Modeling a closed loop urban water system and augmenting its storage capacity to test energy generation capabilities against community energy consumption during peak demand times can help identify these opportunities.

Energy Storage Feasibility Methodology

Testing this hypothesis includes developing a proof-of-concept for determining individual water system energy storage capabilities, after delivery to meet water demands and water system operating conditions. The methodology is validated with data from Cleveland, TN, a mid-sized city in the Tennessee Valley Authority (TVA) service territory. Steps in this process include: (1) obtain data: water system, energy demand, population, budget, and planning cycles; (2) develop and validate a water system hydraulics model; (3) evaluate energy demand to determine storage value; and (4) compare various storage configurations for potential energy output against peak community electrical demand. The metric of success of this step is assessing how well model outcomes compare to actual operations data. This is measured by the verification and validation process, and builds confidence in the outcomes of additional energy storage scenarios.

Examples of integrating a water system model outputs with energy data exists in the literature, but no work published to date is designed to readily answer the guiding research questions, or to test the accompanying hypotheses. The U.S. Environmental Protection Agency (EPA) has created software that models pressurized, closed-water distribution-piping systems, which include pipes, nodes (junctions), pumps, valves, and storage tanks or reservoirs. EPANET2 is free and publically available as an open-source toolkit, which is an important component to allow for ease of replicating of this study's

methodologies in municipal water systems. The associated EPANET Programmer's Toolkit is a dynamic link library of functions that allows for customization of the model to individual research needs.

Capabilities applicable to this study include determining pump energy usage, creating time-series graphs, and pumping and energy costs. This model provides the baseline for water system behaviors, and its outputs are paired with external data throughout the research process, to produce answers in each research question. Approaches outlined in the literature review reinforce the development of this proof of concept.

The Cleveland Utilities (CU) water system model is transferred from H2OMap software and modeled in EPANET2 to understand its capacity to store water for energy, where the best options for storage are, and how to do it. Water system data inputs required to build the model comes from Jacobs Engineering, which provides consulting services to CU. This dataset includes: water system components (links and nodes), time-series (5-minute time steps) demand patterns for the local water system. Demand is aggregated within the model. Demand is not matched to individual residences, but instead each node represents multiple users. Localized parameters like geography, current and projected populations, local plans and budgets, and water and energy rate schedules are obtained through online searches.

All necessary steps are taken in this research to insure proper model function and execution within set parameters, to be able to defend the methodology with confidence. To validate the EPANET model, the accuracy of a model's representation of the physical water system is proven. The verification and validation of the EPANET model begins when initial model integration is complete. Of the many approaches that can be used to validate a computer model, the following are used: (1) Model inputs and outputs are compared to the H2OMap calibrated model and to the Jacob's calibration report, to ensure tanks and pumps are behaving in the same ways between models and between models and water system data; (2) Functional water system specifications and operating preferences are confirmed, through data checks and interviews CU staff; (3) The model is tested and modified with EPANET experts to find and correct any errors in model execution; (4) Model run periods are increased, to insure tank behaviors are consistent over time; (5) Various fire patterns are run in multiple locations throughout the model to insure the system can respond to acute stress, while still maintaining pressures and meeting water delivery requirements over space and time.

Local aggregated hourly energy demand data is obtained from the local electric utility's Information Technology Department for 4 months, representing the 4 seasons of east TN. This allows for an

understanding of when the energy system could call upon the water system for energy generation from the stored reserves. Water system model outputs are compared to aggregated energy demand to determine how managers of any water system can input these localized data sets and learn how much energy in kilowatt hours (kWh) can be stored after user needs are met.

This analysis indicates how much flexibility is in the water system. Scenarios are developed within the water model to test increasing storage capacity in concentrated and distributed storage situations in various locations throughout the water system. Local hourly energy use datasets are compared to outputs from the water model scenarios, to better understand power flows, demand curves, and how variation between demand peaks can be reduced with the introduction of energy storage into the water system.

Ultimately, working with the water system model is an adaptive learning process. The model is used as a foundation with which to answer each research question and test each hypothesis. The methodology is simple enough so that other cities can collect and input localized water and energy data and assess their own systems for storage capacity opportunities, regardless of what software they use to model their water systems.

Energy Storage Feasibility Outcomes

This research step generates a better understanding of how changes in energy storage ideally enhance, or at least do not degrade, water system reliability and value. Methodologies mirror reality and produce high-confidence outcomes, showing research success. Methodologies developed from this research can be used to simulate local water systems in various regions.

It is important to keep in mind that modeled scenarios are only as good as the model parameters and the quality of the data that is inputted. Even when well designed and with very detailed data inputs, they are simply tools to enable possibilities to be explored. Because of the localized nature of this study, existing data is highly detailed. The water data sets virtually recreate Cleveland's physical water system as accurately as possible.

The primary finding of this research step is that concentrated water storage configurations can generate significantly more electricity than distributed storage configurations can. This is because they can be designed primarily for energy generation, not to also meet demand and maintain water system pressure. In

the concentrated storage scenario, 10% of peak community electrical demand could be generated by discharging storage tanks during peak electrical demand times.

Research Category 2. Resilience in Urban Water Systems from Energy Storage

This research step examines if increased energy storage capacity can aid in water system resiliency. It is designed to test how additional water storage responds to a doubling population. It also examines if energy generation capabilities are still in place.

Resiliency Analysis Hypothesis

The hypothesis is that the addition of water storage capacity can make water systems more flexible and resilient. This flexibility will enable a water system to respond to a doubling population. Tradeoffs will be made, however, and energy generation may be one of them.

Resiliency Analysis Methods

The concentrated and distributed storage models are assessed to understand if the water system is more flexible and resilient in the face of a doubled population. Change scenarios are chosen based on existing data sets that project local growth and resource use patterns. Today's water demand is extrapolated to find tomorrow's water demand, based on population projections. Each model includes physical and non-physical components and considerations. Physical components include geographical constraints and the engineered parameters of the water system. Non-physical components include the variable population shifts.

Demand at each node in both models is doubled, and the models are tested for the response of each storage configuration. How well model outputs respond to increased population, as well as how the storage originally added for energy generation in the water system is now utilized in this stressed condition, is assessed.

Resiliency Analysis Outcomes

Increased storage capacity can minimize system disruption in the distributed scenario. Distributed water storage configurations can be more resilient to the chronic stress of population growth, because increasing storage throughout the water system is more effective at maintaining water system pressures and meeting increasing water demands over time.

Research Category 3. Financial Analysis of Energy Storage in Urban Water Systems

This research step explores the fiscal implications of various energy storage enhancements. It examines key financial factors and levers that can impact energy storage decisions. It explores payback periods in terms of local planning and financing horizons.

Fiscal Analysis Hypothesis

The hypothesis is that energy storage enhancements in urban water systems have financial variables that include localized energy and water costs. These costs can be analyzed to determine fiscal scenarios and feasibility. Understanding costs will also address the scale at which this methodology should be tested.

Fiscal Analysis Methods

Comparing costs data to water model scenario outputs allows for a basic understanding of economic triggers and costs by storage scenario. How well model outputs can be assigned realistic cost data builds confidence in fiscal planning for additional energy storage scenarios. To understand the fiscal implications of increased energy storage capacity in urban water systems, CU budgets are explored, electrical rate schedules are understood, costs are assigned to model scenario components, and potential purchase prices are examined for renewable energy generation schemes.

Water model concentrated and distributed storage scenarios are assigned implementation cost data through cross-comparison of catalogues and other available pricing resources for the components of small-scale hydro generation. Storage costs are collected through secondary research, and assumptions are stated. This allows for the comparison of additional storage capacity to the value of the stored energy, determining the fiscal attractiveness of increasing energy storage investment within the urban water system.

The Excel-based calculator created for this analysis includes direct and indirect capital costs, as well as annual operating and maintenance costs to the water system, brought on by additional energy storage capacity. It assigns value to the potential energy generation, and outlines return on investment and payback periods. The employed methods are honed to address the quantitative metrics a local decision maker might require during budgeting processes, and based on a 20-year amortization of municipal bonds and power purchase agreement life-spans.

Fiscal Analysis Outcomes

The key finding from the financial analysis of concentrated and distributed storage scenario is that neither concentrated nor distributed water storage configurations are cost effective within local utility planning and financing horizons, because the payback periods far exceed the 20-years typically used for planning of infrastructure upgrades, bonds, and power purchase agreements.

Summary Discussion

The concentrated storage scenario proves better than the distributed storage scenario in terms of energy generation. However, it is weaker than a distributed storage scenario in terms of resiliency. Neither scenario can continue to generate electricity in the face of a doubled population, which requires the additional storage to meet new water demands. While both storage scenarios are feasible to construct, they are not cost effective in terms of local government planning and budgeting horizons.

Outcomes from each research step are corroborated by what little literature exists around the use of urban water systems for energy storage. However, the lack of knowledge around this topic is of note, especially among the known experts in the emerging field of energy and water system integration. A significant body of work needs to be added to this one, which contributes only a small piece of solving the water-energy nexus equation in urban water systems. Learning what not to do is equally as important as learning what to do, and this knowledge can only be gained by continuing to test various modeled designs for energy and water demand response, and continuing to factor in pricing implications.

While not a measurable metric of success, local decision makers can ultimately use this methodology to make informed energy storage decisions, and positively impact the resiliency and sustainability of their water systems. They can use it to determine what upgrades can be feasible and beneficial at the micro-scale within their water and energy systems. They can use it to understand the widely varying scales of magnitude between local water system capacity and community energy use. They can use it to determine what energy storage within the water system could be a good investment, and what is not worth pursuing.

References

- Apergis, N., & Payne, J. E. (2012). Renewable and non-renewable energy consumption-growth nexus: Evidence from a panel error correction model. *Energy Economics*, 34(3), 733-738.
- Annual Electric Power Industry Report (EIA-861 data file). (2017). Retrieved data from forms EIA-861, schedules 4A & 4D and EIA-861S on September 3, 2017, from <https://www.eia.gov/electricity/data/eia861/>
- Baker, K. A. C., & Behn, S. C. (2013). Law and water--the water-energy nexus: Recent federal actions and their potential impacts (PDF). *Journal-American Water Works Association*, 105(2), 28-30.
- Barber, N. L. (2009). *Summary of estimated water use in the United States in 2005*. US Department of the Interior, US Geological Survey, Norcross, GA.
- Biswas, A. K. (2004). Integrated water resources management: a reassessment: a water forum contribution. *Water international*, 29(2), 248-256.
- Bradley County 2035 Strategic Plan. (2013). Retrieved from <http://www.bradleyco.net/resources/5/BradleyCountyComprehensivePlan-Revised-8-20-13.pdf>
- Brown, R. R., Keath, N., & Wong, T. H. F. (2009). Urban water management in cities: historical, current and future regimes. *Water Science & Technology*, 59(5), 847-855.
- Chen, S., & Chen, B. (2016). Urban energy–water nexus: A network perspective. *Applied Energy*, 184, 905-914.
- Cosens, B. A., Gunderson, L., & Chaffin, B. C. (2014). The adaptive water governance project: Assessing law, resilience and governance in regional socio-ecological water systems facing a changing climate.
- City of Cleveland Comprehensive Plan. (2013). Cleveland, TN. Retrieved April 2015 from <http://clevelandtn.gov/index.aspx?NID=267>
- Cleveland Utilities. (2017). About CU. Retrieved August 30, 2015 from <http://www.clevelandutilities.com/about.htm>
- Depuru, S. S. S. R., Wang, L., & Devabhaktuni, V. (2011). Smart meters for power grid: Challenges, issues, advantages and status. *Renewable and sustainable energy reviews*, 15(6), 2736-2742.
- Desai, S., & Klanecky, D. A. (2011). Meeting the needs of the water-energy nexus. *Chemical Engineering Progress*, 107(4), 22-27.
- Executive Order 13514. 3 C.F.R (2009). *Federal leadership in environmental, energy, and economic performance*. Washington, DC: Author. Retrieved July 31, 2014 from http://www.whitehouse.gov/assets/documents/2009fedleader_eo_rel.pdf
- Fraundorfer, R., & Liemberger, R. (2010). *The issues and challenges of reducing non-revenue water*. Asian Development Bank.
- Gerbens-Leenes, W.; Hoekstra, A. Y.; van der Meer, T. H. (2009). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences of the United States of America* 2009, 106 (25), 10219-10223.
- Glassman, D., Wucker, M., Isaacman, T., & Champilou, C. (2011). The water-energy nexus: Adding water to the energy agenda. *World Policy Institute*, 1.

- Goldstein, N. C., Newmark, R. L., Whitehead, C. D., Burton, E., McMahon, J., Ghatikar, G., & May, D. (2008). The Energy-Water Nexus and information exchange: Challenges and opportunities. *International Journal of Water*, 4(1-2), 5-24.
- Griffiths-Sattenspiel, B., & Wilson, W. (2009). The carbon footprint of water. *River Network, Portland*.
- Grubert, E. A., Beach, F. C., & Webber, M. E. (2012). Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal-and natural gas-fired electricity. *Environmental Research Letters*, 7(4), 045801.
- Halstead, M., Kober, T., & van der Zwaan, B. (2014). Understanding the energy-water nexus. *Petter: ECN*.
- Hellström, D., Jeppsson, U., & Kärrman, E. (2000). A framework for systems analysis of sustainable urban water management. *Environmental Impact Assessment Review*, 20(3), 311-321.
- Hilaire, R. S., Arnold, M. A., Wilkerson, D. C., Devitt, D. A., Hurd, B. H., Lesikar, B. J., ... & Pittenger, D. R. (2008). Efficient water use in residential urban landscapes. *HortScience*, 43(7), 2081-2092.
- Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., & Richter, B. D. (2012). Global monthly water scarcity: Blue water footprints versus blue water availability. *PLoS One*, 7(2), e32688.
- Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., ... & Larsen, K. (2017). Estimating economic damage from climate change in the United States. *Science*, 356(6345), 1362-1369.
- Huang, Q., Jing, S., Yi, J., & Zhen, W. (2015). *Innovative testing and measurement solutions for smart grid*. John Wiley & Sons.
- Hussey, K., & Pittock, J. (2012). The energy–water nexus: Managing the links between energy and water for a sustainable future. *Ecology and Society*, 17(1), 31.
- Johansson, T. B., Patwardhan, A. P., Nakićenović, N., & Gomez-Echeverri, L. (Eds.). (2012). *Global energy assessment: toward a sustainable future*. Cambridge University Press, New York City, NY.
- Kenway, S. J., Lant, P. A., Priestley, A., & Daniels, P. (2011). The connection between water and energy in cities: A review. *Water Science & Technology*, 63(9), 1983-1990.
- McMahon, J. E., & Price, S. K. (2011). Water and energy interactions. *Annual Review of Environment and Resources*, 36, 163-191.
- Moniz, E. (2014, June 18). Ensuring the Resiliency of Our Future Water and Energy Systems (Energy.gov). Retrieved August 18, 2015 from <http://www.energy.gov/articles/ensuring-resiliency-our-future-water-and-energy-systems>
- Nair, S., George, B., Malano, H. M., Arora, M., & Nawarathna, B. (2014). Water–energy–greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. *Resources, Conservation and Recycling*, 89, 1-10.
- National Rural Electric Cooperatives. (2017). On the Issues. Retrieved August 15, 2016 from <https://www.electric.coop>
- Pate, R. C., Hightower, M. M., Cameron, C. P., & Einfeld, W. (2007). *Overview of Energy-Water Interdependencies and the Emerging Energy Demands on Water Resources* (No. SAND2007-1349C). Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States).

- Raupach, M. R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J. G., Klepper, G., & Field, C. B. (2007). Global and regional drivers of accelerating CO₂ emissions. *Proceedings of the National Academy of Sciences*, 104(24), 10288-10293.
- Sattler, S., Macknick, J., Yates, D., Flores-Lopez, F., Lopez, A., & Rogers, J. (2012). Linking electricity and water models to assess electricity choices at water-relevant scales. *Environmental Research Letters*, 7(4), 045804.
- Spang, E. S., Moomaw, W. R., Gallagher, K. S., Kirshen, P. H., & Marks, D. H. (2014). The water consumption of energy production: an international comparison. *Environmental Research Letters*, 9(10), 105002.
- Schnoor, J. L. (2011). Water–energy nexus. *Environmental Science & Technology*, 45(12), 5065.
- Stimmel, C. L. (2014). *Big data analytics strategies for the smart grid*. CRC Press.
- Sustainable Urban Water Systems. (2014). Innovation Network for Communities. Retrieved August 16, 2015 from <http://www.saenv.com/portfolio/urban-water/>
- U.S. Department of Energy. 2014. *The Water-Energy Nexus: Challenges and Opportunities*. Washington, DC: US Department of Energy. <http://energy.gov/downloads/water-energy-nexus-challenges-and-opportunities>
- U.S. Energy Information Administration. (2013). Monthly Energy Review. Retrieved August 26, 2015 from <http://www.eia.gov/todayinenergy/detail.cfm?id=16051>
- U.S. Global Change Research Program. 2015. *Our Changing Planet: The U.S. Global Change Research Program for Fiscal Year 2016*. Washington, DC, USA.
- Volunteer Energy Cooperative. (2017). Retrieved August 25, 3017 from <https://vec.org>
- Walton, B. (2010). The price of water: a comparison of water rates, usage in 30 US Cities. *Circle of Blue*, 26.

Appendix I

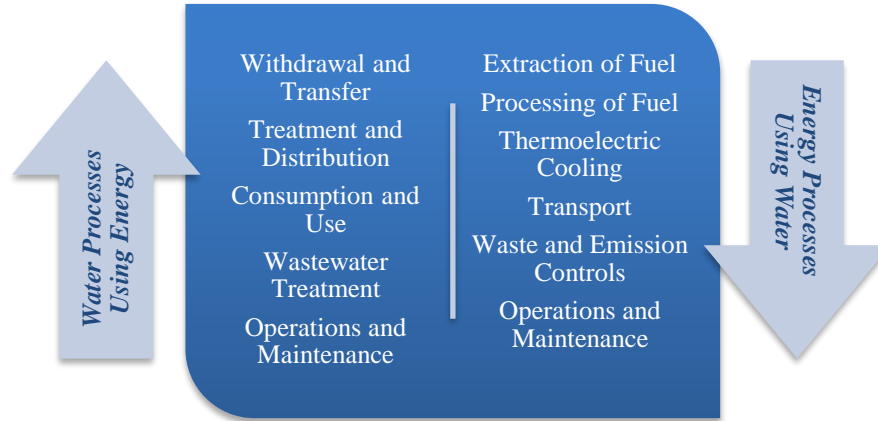


Figure 1. Basic Causal Relationships Between Water and Energy in Urban Settings.

Table 1. Sustainable Water Management Goals

Goal*	Description
Efficient	The system values water conservation and using the least amount of water possible for the desired use.
Resilient	The system can withstand variations in water availability and quality caused by aging of infrastructure, population growth, climate change, and other factors.
Regenerative	The system manages water use to maintain the natural system’s “water budget” at its regenerative capacity.
Clean and Safe	The system delivers water that is safe for its intended use and meets regulatory standards.
Equitable	The system provides all segments of the population with fair and equal access to water supply and services needed for health and life, while offering non-discriminatory opportunities to use water for economic gain.

* Adapted from content presented by the 2014 Sustainable Urban Water Systems study, performed by the Innovation Network for Communities with 14 U.S. cities.

Table 2. Urban Water Systems Scorecard Example.

Principle*	Milestone	Indicator
Water Conservation and Efficiency	Promote water conservation	Change in total volume of water produced annually, and volume of water consumed per household / entity per day.
	Install water meters	Percentage of users on water meters.
	Set the right price	Progress towards full cost accounting and recovery, and total costs / total water rate revenues.
	Minimize water loss	Percentage of water loss in distribution system, and non-revenue water produced and stored.
	Water reuse and recycling	Estimate of total reused or recycled water through municipal initiatives.

* Adapted from content presented by the 2014 Sustainable Urban Water Systems study, performed by the Innovation Network for Communities with 14 U.S. cities.

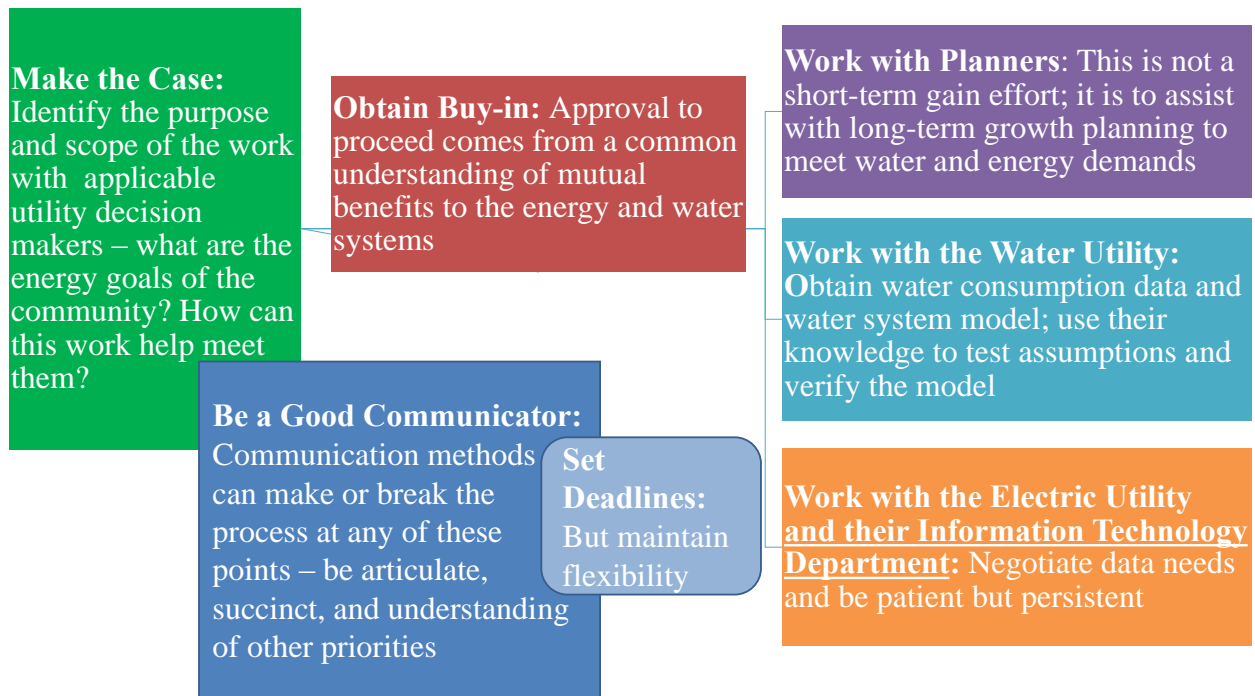


Figure 2. A Transferrable Method for Obtaining Case Study Data.

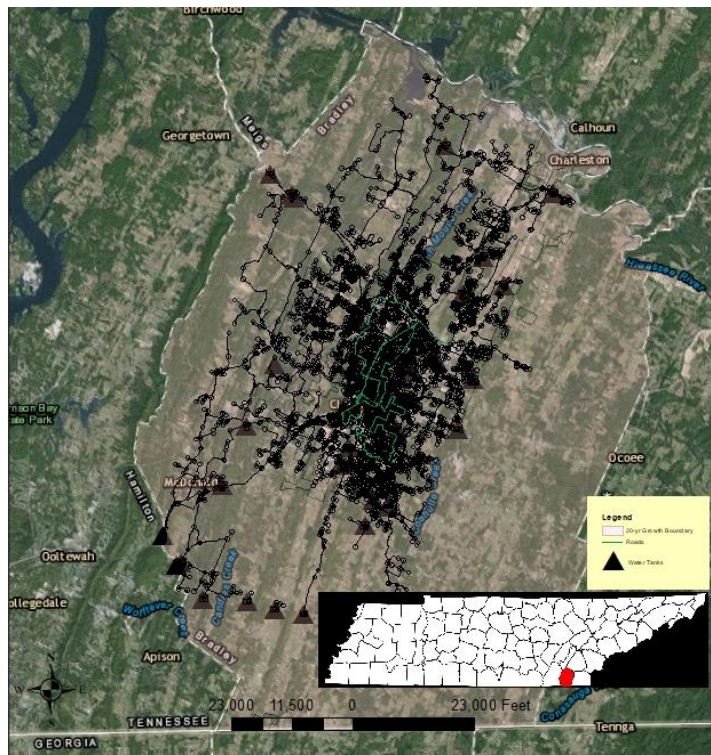


Figure 3. Cleveland 20-Year Growth Boundary, Roads, and Water System Network.

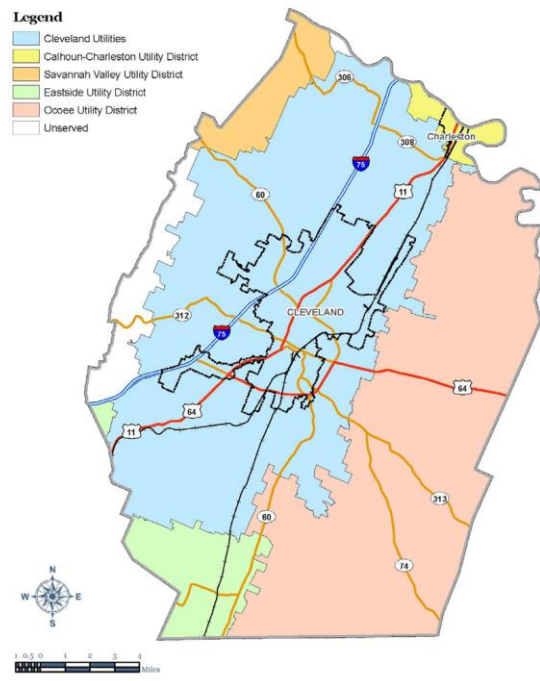


Figure 4. Cleveland Water Service Area Map

Table 3. Cleveland Utilities Water Storage Tanks

Tank Name	Bottom Bowl Elevation*	Operating Depth (ft.)	Diameter (ft.)	Nominal Volume (gal.)
Blythe Ferry	1,104.00	32	50	500,000
Bryant Drive	1,120.00	77	47	1,000,000
Candies Creek	1,022.70	30.33	75	1,000,000
Crown Colony	1,090.00	32	50	500,000
Eldridge	1,006.00	36.5	125	3,500,000
Johnson	1,051.00	63.5	36	500,000
McDonald	1,012.20	30	53	500,000
Sunset	1,000.00	42.5	115	3,300,000
Waterville	1,016.00	50	70	1,500,000
Weeks	1,011.00	31.5	127	3,000,000
CFP Clearwells (2 tanks)	820	13.5	158.8**	2,000,000
HUC Clearwells (2 tanks)	808	16	199.7**	3,750,000
Total: 12				21,050,000

**Measured in feet (ft.) at mean sea level (MSL); ** Equivalent Diameter*

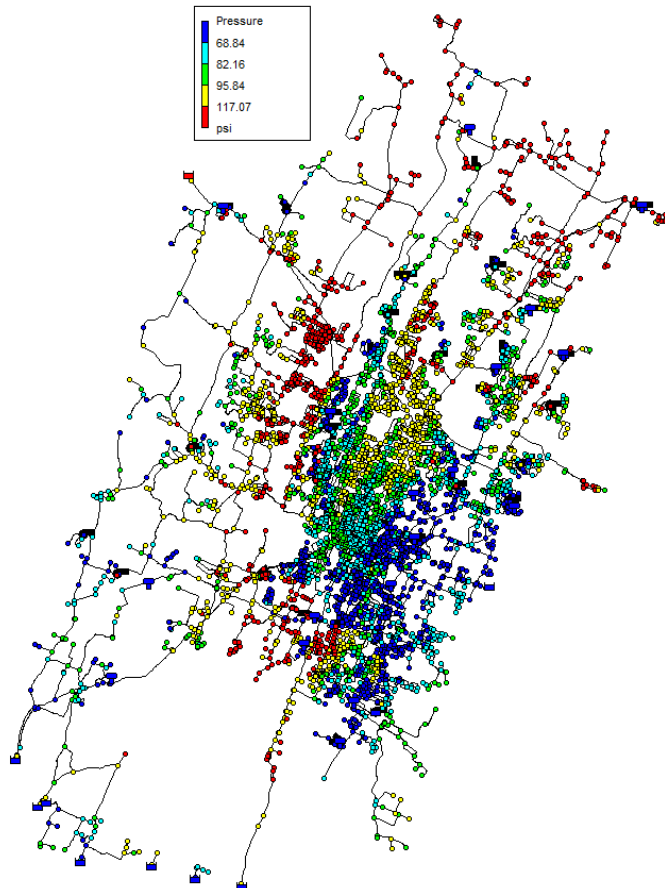


Figure 5. CU Water System Pressure Model at a Peak Demand Time.

Table 4. Cleveland Utilities Water System Pressure Zones

#	Pressure Zone Name	Servicing Area and / or Pump Name
1	Main*	HUC, CFP, and Waterville treatment facilities, and the EUD Highway 11/64 metered connection
2	Johnson	Sunset Trail Booster Pump Station
3	Blythe Ferry*	Blythe Ferry Booster Pump Station
4	Crown Colony Tank*	Adkisson Drive Booster Pump Station
5	Bryant*	North Street and Spring Brook Booster Pump Stations
	Note: A small portion (Misty Valley subdivision) of the system is served by a metered connection to Savannah Utilities, and there are 6 additional connections to EUD serving a small amount of CU customers.	

**Has an individual demand pattern based on SCADA demand data from June 2012 and Nov. 2013*

City of Cleveland Total MWh Sold by Sector, 2014 City of Cleveland Total MWh Sold by Sector, 2015

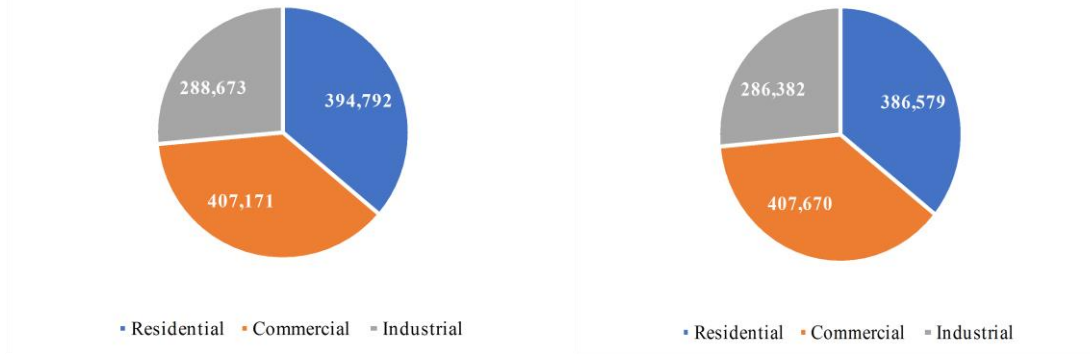


Figure 6. Cleveland Electricity Sold by Sector, 2014 and 2015 (EIA).

CHAPTER 1
FEASIBILITY OF WATER STORAGE FOR ENERGY IN URBAN WATER SYSTEMS

Abstract

The objective of this study is to explore if urban water systems can be used to generate enough electricity to reduce peak community electrical demand. It explores generation potential from concentrated and distributed storage configurations in a model of Cleveland, Tennessee's water distribution system. Cleveland's hourly electrical data is also obtained, aggregated, and compared to unused water storage within the water system. A comparison of water system storage and energy consumption data show that peak electrical shaving is a more realistic goal than peak leveling, due to the differences in scales between available water system storage and the electrical load for an entire community. If concentrated, tanks designed purely for energy generation purposes can shave just over 10% of community peak electrical demand, while the distributed storage scenario only produces 5%. Research outcomes imply that, should a community be inclined to add additional storage for energy generation over time, it is best be done by adding new tanks in 1 location, as opposed to increasing the sizes of existing tanks. Future studies examining the integrating of water and energy system operations in urban settings should explore small hydro-generation applications within urban water system at smaller scales. Narrowing the focus will further reduce the knowledge barrier as to the practical application of creating a water energy nexus between urban water and electrical distribution systems.

1.1 Introduction to Energy Storage in Urban Water Systems

Cities are systems of systems operating simultaneously and yet often separate and apart from each other. Systems integration is a generally desirable concept in municipal settings, because synchronous operation theoretically means considering multiple drivers for better operational practices (Rotmans & Van Asselt, 2000). Cities can use technology to gather operational data from multiple systems, analyze it, and turn it into actionable intelligence, thereby increasing decision-making capacity with less strain on human resources. It is no surprise that literature surrounding the water-energy nexus consistently calls for water and energy system integration.

The Challenges of System Integration

Barriers to integration are well defined, and are explored in the literature review. They primarily include: (1) fragmentation between management processes and structures; and (2) lack of availability of standardized data sets and tools. Perhaps more influential than separate management structures and disparate data sets, however, is that the water energy nexus remains a somewhat frustrating and evasive concept, and has yet to be presented: (1) with a case for engaging in system integration that speaks

directly to factors that motivate both water and electric utilities; and (2) in tangible frameworks, so it is clear what actions utility managers can or should take to begin an integration process.

The high-level water-energy nexus conversation often ignores internal utility drivers for change, when it should instead start with them. For instance, an electric utility may lack the motivation to engage or integrate with an urban water system, when traditionally they interact with the water system through larger hydropower facilities that they often own, and view water utilities as a customer. Or, a water utility may not be motivated to produce more energy than they can use to offset their own electric consumption, when reducing their own utility bill is more of a priority than supporting the electrical system.

Once the case can be made for engaging both electric and water utilities at the local level, the process for integration can be presented as a suite of options. There is no single path that will achieve “integration”. Not all utilities and cities can or will utilize all available options. Contextual situations and drivers will vary. Energy markets and regulation will remain primary utility motivators. It is not enough to say that water and energy systems should be integrated. A case needs to be made for it, using primary motivators as the starting point. Then, options need to be presented as a menu, so utilities can make their own actionable roadmaps towards system integration once they see it is in their best interests.

With the case-making context in mind, and understanding no two utilities will follow exactly the same water and energy systems integration pathway, this research explores only this one aspect of making the water-energy nexus tangible in a practical setting. Although additional phases of this research address the costs and resiliency impacts of energy storage within an urban water system, this research does not create a comprehensive framework for water and energy system integration at the local level. It delves deeply into only one integration angle, and the possible motivators for implementing it.

Water System Dynamics in Cities

There are four primary components in urban water systems: (1) the original water source; (2) a built system designed for the creation and transport of clean (potable) water; (3) a built system for the transport and treatment of black (sewer) water, and; (4) a built system that deals with runoff (stormwater) inputs. In addition to insuring that reservoirs, groundwater wells, and aqueducts can supply water needed to meet the varied demands from an urban area, there is also the component of operation and maintenance of water treatment plants and water distribution systems that transport water (with specific pressures) to users. Once the water is used, wastewater must be collected and transported for treatment and discharge

(Loucks et al., 2005). Additionally, the urban stormwater drainage system has mandated separation from the potable and sewer infrastructure, and overflows can be costly and dangerous. It is a vastly complicated system that is difficult to model, operate, and maintain, even before considering any energy system interactions.

Urban water systems rely on engineered components to provide water supply, transport, and treatment. There are above- or below-ground collection points from watershed sources; above- or below-ground water transfer mechanisms (aqueducts, tunnels or pipes); treatment facilities; underground water transfer pipes; storage facilities such as reservoirs, tanks, and towers; and an extensive piping system that transfers clean water to buildings, black water from buildings, and gray water from storm runoff. The piping network also services outlets around urban areas, such as fire hydrants, and industrial facilities that require significant water inputs for operations (Loucks et al., 2005).

Water constantly moves through city piping networks. If viewed as a form of potential energy generation, both the various uses it is destined for, and the stages it may be in (potable, black, gray) are secondary. Portland, OR is currently replacing a gravity fed potable water pipeline with one that contains 42-inch turbines connected to an external generator. The turbines do not slow the water enough to impact the rate of pipeline delivery, and the usable energy to be generated is estimated at 1,100 megawatt hours (MWh) each year. This could cover the on-going energy needs of roughly 150 homes (Electronic Engineering Journal, 2015). Over the next 20 years, it is estimated that the system will produce 2 million dollars in electricity sales.

Storage of energy in the urban water systems typically manifests itself in water tanks and pressurizing systems used to obtain the right amount of flow in specific situations, not necessarily to generate electricity that is transferred to the electrical grid for use. Smaller urban water systems often store water in cisterns or pressurized containers. Taller structures frequently feature rooftop or on-site storage to insure high water pressure on upper floors. In lower elevations, communities may also add pressurizing components, like pumping stations, at above- or below-ground water intakes (Loucks et al., 2005). When searching a local water system for energy storage opportunities, space for tanks may pose site-specific issues.

In general, tanks are located throughout a water system to: (1) equalize flow and minimize diurnal (or daily) demand curves; (2) to equalize pressure throughout the system over the course of a day; and (3) to

increase water system resilience to acute (i.e., fire) and chronic (i.e., drought) stresses. There are several different classifications of storage tanks: (1) surface or ground, which is at or below ground level; (2) standpipe, which is also at ground level and can be used in place of overhead storage on hilltops – with only the upper portion as adequately pressurized storage - as the lower portion is structural; (3) elevated or overhead storage; and (4) pressure or bladder tanks, which offer little to no storage, and function as a demand buffer so pumps aren't coming on and shutting off as frequently (Loucks et al., 2005).

Tools to Predict Urban Water System Demand. Now that the components of an urban water system are understood, the challenges can be explored. One decision-making driver in cities is being able to accurately predict municipal water demand. This is critically important so that growth in utility assets and infrastructure can be planned for and budgeted. It is essential to evaluate each component of a water system and its function as it relates to the capability of the water delivery system to meet required consumer and fire protection water demands (Hickey, 2008).

The ability to meet demand is a direct function of the rate of water consumption. Three historical or predicted water demand rates are involved in meeting consumer demand and fire protection. First, the average daily demand, or average of total water consumed each day over the course of a year. Second, the maximum daily demand, or the maximum total amount of water used during one 24-hour day. Third, the maximum hourly demand, or the most water used in any single hour of any 24-hour day – usually calculated in gallons per day by multiplying the actual peak hour by 24 hours (Hickey, 2008).

In addition to analyzing historical and predicted demand rates, accurately predicting growth scenarios means maintaining a forecasting model that can simultaneously compute outcomes under a variety of factors associated with chronic stresses, such as economic development, population growth, human behavioral patterns, and climate change. Traditional forecasting models (time series analysis and multivariate regression, for example), and even more advanced modeling techniques (artificial intelligence programming, like neural networks or expert systems), are frequently used to predict short and long-term water demand (Khatri & Vairavamoorthy, 2009).

Models can consider water supply: freshwater withdrawals, groundwater withdrawals, imported water, and treated wastewater, for instance. Potential sources of water demand, such as commercial or industrial growth, can be added. Some models incorporate management tools: water reuse and recycling, inter-basin transfer, conservation, or pricing, for instance (Zarghami & Akbariyeh, 2012). The Dynamic Urban Water

Simulation Model (DUWSiM) is one such tool that links urban water with a land use dynamics model (MOLAND) and the climate model (LARS-WG). Merging these models creates a water-cycle planning platform to balance supply and demand (Willuweit & O’Sullivan, 2013). However, limitations within modeling structures mean that they are fallible tools at best. Models are only as good as their inputs and computation capabilities, and many cities – small and large alike - lack lengthy and continuous historical water demand records, to say nothing of data describing the circumstantial and dependent variables of water demand (Qi & Chang, 2011).

Challenges Driving Development of City Water Systems. Factors like urbanization driven by population growth, as well as changing natural systems driven by climate change, put significant pressures on urban water resources and systems. These pressures require water managers to consider management options that can expand to account for economic, social and environmental factors. The American Water Works Association (AWWA) published a 2013 list of the 13 biggest challenges facing the water industry (Westerling, 2013). Included are: the condition of water and wastewater infrastructure; lack of accurate valuation of water; lack of capital funding; water supply scarcity / drought; a retiring workforce; customer and community relations; service cost recovery; government regulations, emergency planning and response; energy usage and costs; risk and resiliency associated with climate change; and terrorism: contamination or cyber-attacks.

The following are barriers to integrating water systems with the energy system, regardless of city size or regional location: (1) political boundaries or jurisdictions are wide and varied; (2) systems are planned, funded, operated, and measured for performance in isolation; (3) integrated system standards haven’t yet emerged; and (4) different methods of collecting and storing data contribute to uncoordinated reporting (Liu et al., 2015). Innovation inhibitors include: infrastructure repair and rehabilitation needs, rate control, regulatory demands, procurement laws, climate change impacts on water resources / water scarcity, customer resistance to rate increases, lack of any unified framework for evaluating innovations or consistent guidance on what innovative actions to implement, and the current workforce’s education level (Frantzeskaki & Loorbach, 2010).

While some of these challenges seem daunting, they can also be catalysts and drivers of new and better methods of operating urban municipal and investor-owned utilities. In short, urban water systems of all shapes and sizes are faced with a myriad of challenges, and are incredibly dynamic on their own.

Factoring in the energy system adds a significant layer of complexity that most civil servants and utility workers are unprepared to address.

Electrical System Dynamics in Cities

To fully understand water and energy integration challenges in cities, the electrical system must also be understood on a basic level. Before examining at a high level the risks faced by the electrical industry, it is important to clarify what the electrical system is composed of, how it is structured, and at what scale. In general, an electric utility system is made up of four main components: (1) generation; (2) transmission; (3) subtransmission; and (4) distribution.

Scaling up: Generation to Transmission. In developed areas, electricity is created at a generating site from a fossil or renewable fuel. Long distance transmission enables remote renewable energy resources that can displace fossil fuel use in electricity creation. Hydro, wind, and sometimes solar generating sources are usually removed from urban areas, often because the cost of siting is less in more remote areas. Connection costs play a large role in determining whether a renewable alternative is economically viable. Single-wire ground return is a transmission method comprised of a single wire supplying electrical power to remote areas at relatively low cost. While typically used to connect rural areas to the grid, single-wire ground return can also be used for larger or more isolated loads, like energy generated from water pumps (Blaabjerg et al., 2004).

To transmit electricity, an initial form of energy is converted into electricity by spinning a magnet of coiled electrical conductors. Switchyard transformers increase voltage from around 69,000 volts (V) to 230,000 V (or even more, if it is extra or ultra-high voltage) in preparation for transmission. Electricity is put onto the transmission system and moved by voltage conductors using direct current (DC) or alternating current (AC) through interconnecting power lines, or transmission networks (Electric Utility System Operation, 1997).

While DC is still used in some locations where the generating station is close to the consumer, AC is more common because it can move electricity over long distances with less energy loss than DC can. The transmitted electricity is sent to substations near populated areas at a frequency of either 50 or 60 hertz (Hz). In transmission, it mingles with electricity produced at other generating sites. Large industries or commercial consumers sometimes are connected at the primary distribution level and receive distribution voltages delivered as three phase power in high voltages (Electric Utility System Operation, 1997).

Scaling Down: Transmission to Subtransmission. Subtransmission moves the electricity from substations to distribution substations inside populated areas. Substations have circuit breakers that allow for disconnection from the transmission grid or distribution lines. Medium industries can take power directly from the subtransmission system. For most consumers, however, the subtransmission system is connected to distribution substations that use transformers to lower the transmission voltage and deliver as single phase electric power. Medium voltage circuits can typically accommodate as low as 601 V and as high as 69,000 V. It is carried to distribution transformers via primary distribution lines near end users (Electric Utility System Operation, 1997).

Delivering: Subtransmission to Distribution. Voltages are stepped down by distribution transformers to a lower voltage secondary circuit for the appropriate user utilization level (around 120 or 240 V for household appliances in residential areas, for example). Electricity is sent by the distribution transformer to the busbar, which acts as an electricity conductor. The busbar sends the electricity to secondary distribution lines and then, to consumers. Service drops connect secondary distribution lines to building electrical meters, which deliver single phase power to the remaining electricity consumers (smaller industries, commercial establishments, and residential homes) at voltages below 600 V (Electric Utility System Operation, 1997).

Distribution systems, in many urban settings, have been systematically moved from overhead wires and placed underground by local electric utilities. This option, while costlier, creates less need for right of way, eliminates visibility and fly-over zone issues, and reduces storm damage potential. In these undergrounded conditions, distribution can occur in sub-surface utility ducts and face less service disruption from line damage, though disruptions can also be harder to locate when they do occur. Overhead transmission and distribution lines are still common, however, especially in suburban or rural areas. In addition to being less expensive to place, they are not as load-constrained due to thermal capacity as underground lines are (Johnson, 2006).

Radial distribution networks connect consumers to a single supply source. These are usually found in suburban or rural areas, and feature switchboards for re-routing during emergency situations. Network distribution is when several supply sources operate in tandem, servicing areas with highly concentrated demand. Distribution networks can be reconfigured for system optimization and to actively curb power loss (Baran & Wu, 1989).

System Management: The North American Power Grid. Combined transmission and distribution of electricity is referred to as the power grid. Large areas of synchronous grids moving AC at similar frequencies but in various phases are called interconnections, and there are four in North America: Western, Eastern, Quebec, and the Electric Reliability Council of Texas (ERCOT) Interconnections (Liu & Xie, 2004). AC power interchange is a function of the phase difference between any two nodes in the network. No power is interchanged with a zero-degree difference, and phase differences up to 90 degrees are considered stable (Electric Utility System Operation, 1997).

In North America, Interchange partners are responsible for maintaining a frequency of around 60 Hz, and insuring that the phase differences between any two nodes are less than 90 degrees. When 90 degrees is exceeded, systems are separated and adjusted before reconnecting them. Transmission systems are built with redundancy to avoid regional blackouts that can occur if the balance between generation and demand isn't maintained. Transmission and distribution lines used to be owned by the same entities. As the energy market is de-regulated, however, two business models have emerged - leading to the separation of line control (Christie et al., 2000).

Electric Grid Challenges. The U.S. electrical system is continually changing to meet demands of increasing populations, incorporate new technologies, and to adapt to shifting political and physical climates. In the 1990's, the electrical industry faced ownership reform. Restructuring of the industry occurred, through energy market deregulation to create a commercialized electricity market (Besanko et al., 2001).

In the early 2000's, renewable sources of energy for electricity generation began steadily gaining market share, due to a combination of: (1) increasing national concerns around energy security; (2) increasing local desire to decrease greenhouse gas (GHG) emission reduction; and (3) improving technologies with decreasing costs. While renewable energy sources are attractive for many reasons, they continue to create disruptive challenges for the industry to manage (Schleicher-Tappeser, 2012). Throughout it all, federal energy policy is conflicted and almost non-existent, making it difficult for utilities to plan for any potential future regulation (Stokes, 2015).

Traditional utility companies that deal with generation, transmission, and distribution in cities also face shifting landscapes in markets, technology, and energy policy. Challenges include: (1) aging electrical infrastructure's ability to meet peak demand reliably ("Rising Utility Construction Costs: Sources and

Impacts”, 2007); (2) planning for and budgeting electrical upgrades (Brown & Willis, 2006); (3) intermittency issues and storage needs for renewable energy and distributed generation systems (Lopes et al., 2007); and (4) adapting to “Smart Grid” technology and microgrid concepts (McDaniel & McLaughlin, 2009). The size and scale of electrical systems in cities may differ, but the overarching challenges are the same.

Opportunities for Energy Storage in Urban Water Systems

Untapped opportunities for storage of energy in urban water systems exist. First, how energy is stored within the electrical grid is explored. Production of electricity in the U.S. is still primarily centralized and produced from fossil fuel sources, though moving towards decentralization and the introduction of an increasing amount of renewable energy sources (U.S. Energy Information Administration, 2013). Decentralized electricity production and the sporadic introduction of fluctuating energy sources, like solar or wind, are often accused of increasing power grid instability, though this assumption is being disproved in more current literature (Amin & Wollenberg, 2005).

Daily electricity load projections are initially based on model predictions of need variability. When production from primary sources is insufficient due to an imbalance of supply and demand, reliability is often maintained from contribution of secondary sources - like hydroelectric and thermal plants. These plants also use stored energy: water for Pumped Hydroelectric Storage (PHS) plants, and fossil fuels for thermal plants (Dunn et al., 2011).

There is a body of work that looks at hypothetical scenarios of a decentralized grid that relies primarily on renewable energy sources. In those scenarios, it is sometimes predicted that underground pumped hydro will be the most viable storage method – though there are no facilities for this use currently in existence (Pickard et al., 2009). Studies like this point to the growing interest in scenario development for generating, transmitting, converting, and then storing energy for peak demands, which is increasingly attractive in the face of decentralization and diversified energy portfolios (Ibrahimov, 2013). Currently, the nation has about 24.6 gigawatt (GW) of electrical grid storage. This is approximately 2.3 percent of total electric production capacity (U.S. Department of Energy (DOE) Global Energy Storage Database, 2015). Today, energy storage can be difficult to add to a system, requiring additional physical space in an already built environment, significant capital budgets, and patience for time-consuming regulation.

Over 30 years ago, conversion methods other than PHS for the storage of AC power were costly, unreliable, and used sparingly. This and the mass production of electricity contributed to a prevailing belief that it cannot be cost-effectively stored. The introduction of high-performance, reasonably priced power electronics, able to handle high power levels, has changed this belief somewhat. Now electricity can be indirectly stored through methods other than pumped and stored water (Rogers et al., 2013). Viable methods for energy storage in the electricity grid now include technologies that use air, batteries (including exploration of storage in unused, but grid-connected electric vehicles), flywheels, hydrogen, superconducting magnetic energy, thermal, and hydro. Photovoltaic (PV) generators can have service reservoirs that act as energy storage for some systems (Đurin and Margeta, 2014). Other storage methods such as these are acknowledged as significant mechanisms advancing human-kinds' capacity to store electricity. However, this research focuses only on water systems that store energy.

PHS has been a staple storage method in the U.S. since 1929 (Baker & Collinson, 1999). It is an old technology used to store large volumes of water over short and long timeframes, with high efficiency and relatively low operating costs. The Electric Power Research Institute (EPRI) reports that PHS is the largest form of grid energy storage available globally (Ibrahim et al., 2008). This storage method represents over 200 facilities, and accounts for more than 99 percent of bulk energy storage capacity worldwide – or, about 127,000 megawatts (MW). Between 70 and 85 percent of the energy used to pump water to an upper reservoir can be regained through release to the lower reservoir. Of all existing electrical storage methods, PHS still represents the lowest energy loss (U.S. DOE Global Energy Storage Database, 2015).

PHS systems store energy by using the turbine and generator to pump water uphill or into an elevated storage area at non-peak energy times of day. The water is released during peak times when energy is in high demand. In its simplest form, PHS includes two reservoirs in different elevations and locations, the distance differences of which determine how much electricity a release from the upper reservoir will generate. A pump and intake waterway moves water from the lower reservoir to the upper to serve as potential energy ready for conversion into kinetic energy during peak hours. A turbine and generator create electricity as water returns to the lower elevation (Eyer & Corey, 2010).

In the past decade, investment in PHS has declined due to pressures from electrical system deregulation and increasing environmental regulation (Chen et al., 2009). This storage method requires a significant amount of land: enough for two reservoirs ideally spaced to maximize energy outputs. It can require

capital investment in hundreds of millions of U.S. dollars (USD), and environmental and regulatory permits that can take a decade or more to obtain. Conversely, interest in other energy storage systems is resurging, due to: (1) favorable conditions in the worldwide utility regulatory environment; (2) a growing reliance on electricity from industrial, commercial, and residential sectors; (3) power reliability and supply issues; and, (4) the growth of renewable energy sources as a major contributor to the electricity supply (Author, 2004).

Small-scale PHS systems are being developed, however, and while permitting is still a challenge, the footprints require less land and capital than traditional PHS does. In 2013, London's City Council approved a plan for a 50 MW capacity PHS facility, or 500 MWh of electricity generation. The facility is in a cluster of abandoned slate quarries in north Wales. The plan calls for a 12-hour-life gravity battery to store energy created by movement of 1.1 million tons of water (The Time is Right for Small Pumped Energy Storage, 2013). This is just one example of how the hydropower industry is adapting to resource reduction, by reclaiming brownfield lands and adjusting electricity production expectations.

In Greece, a stand-alone PV plant partially replaces battery storage with a small PHS system. The plant is installed on Donoussa Island to cover the energy needs of 13 homes. The solar array has 300 PV modules, and an 18-kilowatt (kW) total installed power. The small hydroelectric system consists of a 6-kilovolt (kV) pump, turbine, and a direct current (DC) generator of 7.5 kW. There are two water reservoirs 100 meter (m) apart in elevation, each with identical capacity (150 m³). The PV generator handles daytime capacity and directs any surplus to the pump. During the night, water is released to cover energy needs (a somewhat opposite structure from traditional PHS, which stores with off-peak generation and releases during peak hours). The system also has 186 battery cells to cover peak loads (Manolakos et al., 2004).

Small-scale PHS is being deployed in the U.S. as well. The Sacramento Municipal Utility District is building an \$800 million, 400 MW PHS project in El Dorado County, CA. The project, which federal regulators licensed in 2014, will give the utility more operating flexibility and allow it to add more energy from variable renewable sources, like wind and solar power. In Washington, Klickitat County Public Utility District is in the federal permitting process to develop a 1.2 GW PHS system, also to integrate more renewable energy in the Pacific Northwest (These Forces Changed the Energy Storage Game, 2014).

In addition to scaling down the size and reworking the functionality of PHS systems, exploration continues in the U.S. to understand how already constructed non-hydropower producing facilities can be retrofitted to store and produce electricity. There are around 80,000 impoundments on U.S. waterways that do not produce power, and about 2,500 dams providing 22 gigawatts (GW) of PHS and 78 GW of conventional power. Impoundments originally constructed to serve navigation or water supply needs can be retrofitted to provide power without the high construction costs, permitting requirements, or long timeframes that new dams require (Hadjerioua et al., 2012).

In 2014, the Oak Ridge National Laboratory (ORNL) on behalf of the U.S. Department of Energy (DOE) produced an in-depth study of “new stream reach”, which is the possibility of creating new hydropower facilities that store and generate electricity on undeveloped waterways. This study estimates that the resource capacity for new hydropower development (excluding protected areas like parks and scenic rivers) is 65.5 GW. This is very close to the existing U.S. hydropower capacity of 79.5 GW. Energy generation potential, should all new hydropower proposed in this study be realized, is estimated at 347.3 terawatt hours (TWh) per year (Kao et al., 2014).

In addition to small PHS and new hydro development studies, small hydropower applications are being explored. This is a technology that speaks to the microgrid concept, where small generation systems that account for specific site characteristics can be deployed to power portions of communities or industrial areas. Cost studies and technology research are being done in this growing area (Zhang et al., 2012). In 2011, ORNL worked with the private sector and DOE to develop a small hydropower machine that combines flow, turbine, and generator in one small package. This two-year project in Culver, Oregon assesses the technology from concept phase to testing, to understand strengths and weaknesses in performance, capacity, and readiness. Study results are favorable, and a phase-two proposal examines construction and implementation with an eye towards full-scale deployment (Hadjerioua et al., 2012).

Now that the challenges cities face with water and electric system integration is understood, as well as how energy is stored, what role PHS plays, and what work is ongoing in the realm of new hydropower development, it is important to understand what this means for metropolitan water and energy system managers. Often, they don't control energy generation portfolios, amounts, or rates. This next section explores practical work to date around the integration of water and energy system models.

Modeling Water and Energy Systems

Water and electrical systems are usually modeled and operated separately, and little published work has been done to explicitly link these two systems in either modeling or management processes. Modeling just the water system alone is complex, requiring careful accounting for many dynamic variables. These include: water and wastewater flows; pressure heads and quality in conveyance; treatment, distribution and collection systems; and demand fluctuations (House-Peters & Chang, 2011). Integrated modeling techniques and methodologies have been used for decades at the local level to deal with questions like determining low-cost design of water distribution systems.

Adding energy system considerations to water system models is even more complicated, and there are very few published examples of it being done at any scale. Life-cycle energy analysis is one example of water system modeling that addresses energy components. It can be performed to quantify energy expenditures on just the water-piping network alone. These models can allow for informed considerations of the fabrication, use, and end-of-life stages of the pipes in a water distribution system. A different methodology incorporates the EPANET2 hydraulic model, as well as a pipe-aging model to estimate possible energy recovery in each life stage. An exponential pipe-break model estimates energy required to repair pipe breaks during use. This methodology can be used to quantify energy expenditures in water-piping networks in varying timeframes, such as 10, 20, 50, and 100-year pipe replacements (Filion et al., 2004). Another study considers water system reliability by using EPANET2 to develop 1-hour incremental varying demand patterns as the dynamic variable, using MATLAB to model the EPANET outputs by time step (Shuang et al., 2014).

One study develops a model methodology comprised of three linked models, including a steady state simulation model, a reliability model, and an optimization model. The goal is to determine the optimal (least-cost) design of a water distribution system subject to continuity, energy conservation, nodal head bounds, and reliability constraints. The simulation model evaluates water system continuity and energy constraints. It is used in the reliability model to define failure components (or “cut-sets”). The reliability model, based on a minimum of cut-sets, determines values for consistent operations. The optimization model seeks best-case inputs to achieve realistic outputs from scenarios, and is based on a generalized reduced-gradient method that seeks least-cost-design options (Su et al., 1987).

A much more recent ORNL study models the impacts of solar distributed generation on U.S water resources. This work shows that increasing energy generation from rooftop solar PV can result in

decreased water withdrawals needed to meet overall energy demands (Omitaomu et al., 2015). The study builds on a previous effort that uses Lidar data to estimate the rooftop solar PV energy generation capacity of a case study area (Kodysh et al., 2013).

Another paper explains a methodology for assessing water withdrawals for power plant cooling under different electricity pathway scenarios, geographic criteria, and time scales that speak to both electricity and water management. This platform uses the National Renewable Energy Lab's (NREL) Regional Energy Deployment System (ReEDS) to generate inputs for the Water Evaluation and Planning (WEAP) water system management model. In WEAP, electricity use represents thermoelectric cooling water withdrawals and consumption within the water resource context. The results include water use by the electric sector at a watershed level, allowing examination of water resource implications for specific electricity pathways (Sattler et al., 2012). While the ReEDS and WEAP models function at a much larger watershed and utility district scale than is needed to answer the urban-scale questions in this research proposal, they are examples of integrated modeling of water and energy systems.

In developing countries, integrated modeling is used (infrequently) to determine how best to provide sufficient urban water services, while planning for population growth. One study in Port Vila, Vanuatu modeled 49 scenarios through 2050 using the Urban Volume and Quality (UVQ) model. The results are contrasted with outputs from a 2015 model based on water demand, current infrastructure, and climate patterns. Results demonstrate that consumption, waste, and contamination can be reduced with increased infrastructure capacity (Poustie & Deletic, 2014).

Choosing a closed-loop water system model that shows where and how a local water system can incorporate energy storage requires a basic understanding of what types of water models exist, and how they are used to answer specific questions. Models that optimize and simulate water system inputs and outputs are increasingly used to analyze a variety of design and operation problems involving urban water systems (Cunha & Sousa, 1999). The use of storage in existing urban infrastructure can be optimized in many cases, though typically this method is used to evaluate water storage for treatment, not energy production. Optimization of urban water systems searches for input and output balances in sewage systems, wastewater treatment plants, and surface water systems simultaneously. Though these methods for finding solutions are increasingly effective in the design and planning of urban infrastructure, they are challenged by the complexity and non-linearity of urban water distribution networks (Su et al., 1987).

Evolutionary search algorithms, or formulas that rearrange data to compute evolving scenarios, are also commonly used for the design and calibration of various highly non-linear urban system hydraulic models. They are particularly suited for answering questions in large and complex areas, like water treatment, storage and distribution networks (Van Zyl et al., 2004). They do not need complex mathematical matrix inversion methods, and they allow incorporation of additional calibration parameters and constraints into the optimization process. In addition to use in the calibration function, evolutionary search methods have been used extensively to find least-cost designs of water distribution systems (Savic & Walters, 1997).

Other applications include finding least-cost locations of water quality monitoring stations (Al-Zahrani & Moied, 2001), developing best-case replacement strategies for water mains (Dandy & Engelhardt, 2001), and calculating urban water system GHG emissions (Wu et al., 2009). These search methods are also used to develop master or capital improvement plans for water authorities. They are used to identify low-cost solutions for highly complex water distribution systems, which are subject to many constraints and loading conditions. Constraints on the system include maximum and minimum pressures, maximum velocities in pipes, tank refill conditions, and maximum and minimum tank levels (Duncker et al., 2005).

Dynamic simulation models are replacing steady-state models in the literature, and are used to analyze water pressure, quantity, and quality in collection and distribution networks. Dynamic models provide estimates of the time-variant behavior of water flows (and contaminants) in distribution networks. Time-series analysis represents flow, pressure, and quality variability throughout a system. It can increase understanding of transient conditions, like the passing of contaminants through a piping network. Dynamic simulation also allows for statistical analyses of risk. This methodology is practical for researchers and practitioners using readily available hardware and software (Nilsson et al., 2005). Models used to simulate a sequence of time periods must be capable of simulating systems that operate under highly variable conditions. Varying conditions include water supply availability, use patterns, demand changes, source dispatches, and weather patterns. Each of these are examples of variables that can affect flow quantities and direction within a water system (House-Peters & Chang, 2011).

To discover the foundational methodology of this research, many different types of energy system models are examined, in addition to the water models. These include energy planning models, energy supply and demand models, forecasting models, renewable energy models, emission reduction models, and energy optimization models (Jebaraj & Iniyar, 2006). These model types can assess many different aspects of

energy production and consumption, such as high-resolution residential electricity consumption (Morton et al., 2015). Linear power flow models representing less accurate DC systems, or nonlinear power flow models representing more accurate AC systems are used to analyze power grids.

These models show the energy flow through each transmission or distribution line through a nonlinear system. Power flow models can be simplified through several means, such as assuming steady state operation and system frequency. This does not account for changes in power flow or voltage, due to load or generation fluctuations. Sometimes, a per-unit system is used to represent all voltages, power flows, and demands. This allows scaling targeted system values to a baseline. A system one-line diagram is the basis to build a mathematical model of the electricity system components: generators, loads, busbars, and transmission lines), and their electrical capacity (Overbye et al., 2004).

Computer Aided Design (CAD) software can be used to design and simulate smaller electrical power systems - in buildings, for instance. Power system CAD tools provide a design foundation that allows power systems to be virtually created, and enable evaluation of the safety and integrity of the designs (Singh et al., 1995). Several different power system studies can be carried out on the same input model data. Geographic Information Systems (GIS) are also used to incorporate multiple criteria for decision-making. The Oak Ridge Siting Analysis for power Generation Expansion (OR-SAGE) tool uses inputs like population growth, water availability, environmental indicators, and tectonic and geological hazards to provide an analysis for power plant siting options. The tool can provide insight on land suitability based on specific inputs (Omitaomu et al., 2012).

Using the Water System for Energy Storage. While most storage capacity within the CU water system is used to maintain system pressure, meet demand, insure against fire, and maintain 1 full day of storage, there is some unused storage capacity in the tanks. Naturally, there are logistic challenges to the concepts of using existing water system storage for energy generation.

One of those challenges is that currently there is no TVA rate structure for local water systems to provide electricity to local distributing energy systems. Green Power Providers (GPP) is a program TVA and local power distributors offer to solar, wind, biomass and low-impact hydro generation systems across the Tennessee Valley. However, GPP targets residential and commercial customers who wish to install small-scale (50 kilowatts or less) renewable generation systems. GPP participants are paid for every kWh generated by their renewable energy system.

Research Motivation

This feasibility research explores where to put additional storage within an urban water system. It examines storage configurations that can optimize energy generation. It compares potential small-scale pumped hydropower from the urban water system against community energy consumption. Peak leveling and peak shaving potential is calculated.

The tested hypothesis assumes that energy storage enhancements in urban water systems can have potential impact on community peak energy consumption leveling, and that various storage configurations can be analyzed to determine the greatest energy storage potential. To answer the motivating research questions and test the hypothesis, concentrated and distributed storage scenarios are developed in a case study water system model. They are analyzed against aggregate community energy data to determine potential peak energy shaving possibilities.

1.2 Modeling the CU Water System

To answer the research questions of where to put additional storage capacity and in what configurations, this study uses a closed-loop water piping system model (EPANET2) that can be modified to integrate existing power flow and energy demand data. To build the CU water system model into the EPANET program, a file was exported from H2OMap Water Suite 9.6, a software designed by Innovyze (Wallingford Systems Limited, Broomfield, CO). When imported into EPANET2, the .inp becomes a .net file.

CU Model Calibration and Verification

Jacobs Engineering created the model of the CU water system. They performed the most recent model calibration and verification in 2014, to confirm that simulated results are consistent with peak-day demand and average-day demand conditions, and that the model can accurately replicate system performance. The verification process checks that the model inputs for incorporated pump operating times, system demands, and initial tank levels are correct. Model outputs are then compared to SCADA data for tank levels, pressure readings, and flow rates. Specific model elements are iteratively modified as necessary to match the model simulation results with the SCADA information. The verification process results in a model calibrated within an acceptable range of error when compared to water system performance. It is an effective evaluation tool to examine existing conditions and evaluate future system scenarios, which can help with risk analysis and growth investment planning.

For this calibration, SCADA data is obtained for the peak day demand period (June 2012) and average day demand period (November 2013). The peak water demand pattern (PD_MAIN) is built from the June water consumption data. The average-day water demand pattern (AD_MAIN) is built from the November water consumption data. Ultimately, 4 diurnal demand patterns that correspond to distinct pressure zones are developed: Main, Crown Colony Tank, Blythe Ferry, and Bryant.

The main diurnal pattern (PD_MAIN) is used for the entire service area, excepting the Crown Colony Tank, Blythe Ferry, and Bryant pressure zones. These patterns feature custom diurnal curves. To represent demand fluctuation, estimated plant production rates and storage tank levels are used to calculate hourly demand changes over a 72-hour timeframe. This is done for both average (November 19-21, 2013) and peak (June 27-29, 2012) demand scenarios. Resulting pattern curves represent demand fluctuations for peak-day and average-day demand conditions.

Jacobs uses demand disaggregation in their model, a data methodology that spatially assigns water demand values to nodes throughout the distribution model, based on their individual proximity to actual demand locations. The H2OMAP software has a demand allocator function that automatically assigns spatially located demand to the closest model node. The demand disaggregation used in the model is based on billing data from October 2011 - September 2013. During this 24-month period, average-day billed demand is 7.65 MGD.

Billed demand is electronically located in the model database using a combination of meter location, geocoding, and manual identification. When available from meter data provided by CU, Jacobs uses unique meter identifiers to join billing data to meter locations, using GIS software capabilities. When meter identifiers are not available, billing address data is used. Jacobs uses manual identification techniques to specifically locate demand associated with the top 25 largest water consumers within the CU system. These customers have unique nodes assigned in the model. Billed demand that could not be located using meters, addresses, or manual identification is evenly distributed to system nodes that did not have previous demand allocations. This includes NRW, estimated by pressure zone when possible, but otherwise evenly distributed and assigned to various nodes throughout the model.

To examine local system behavior, verify booster station operations, and calibrate the model, pressure data is gathered from 46 locations throughout the distribution system during the months of May and June of 2014. This data is gathered by placing pressure loggers on fire hydrants for real-time pressure readings.

CU staff deployed pressure loggers at hydrants on the discharge side of each pump station, and on hydrants located at booster pump stations. Pressure loggers are also placed on the discharge headers at the HUC and CFP treatment facilities, along with the suction and discharge piping headers for Waterville Springs and 5 of the major booster pump stations: Adkisson Drive, Blythe Ferry, North Street, Spring Brook, and Sunset Trail.

Pressure data is available for 20 of the 22 small pressure zones in the CU distribution system. The 2 small pressure zones in which data was not collected were Crown Colony Pump Station and Pleasant Grove. Pressure data collected for each of the remaining 20 small pressure zones was compared to model results from the November 19-21, 2013 verification scenario. Of the 20 small pressure zones with available pressure data, 19 mirrored to model outputs. During this process, adjustments are made in the model. These include: the opening or closing of valves to match status in the GIS file, adding pressure-regulating devices as confirmed by CU staff, and adding small piping connections to reduce flow and pressures.

CU water distribution GIS information is compared to data for water sources, pumps, tanks, pipes and control valves. Geometry and network connectivity in the model is compared to GIS information and updated. CU provided pump curves, drawings of the pump stations, and storage tank geometry to incorporate into the model. CU staff discussed pump station controls, pressure zone boundaries, and system operations with Jacobs staff for clarity as they adjusted the hydraulic model. These 2 groups also visited 7 pump stations to confirm pump sizes, pipe diameters, and fittings. The measurements are used to calculate minor losses at the pump stations. This collaborative approach allows for the incorporation of institutional and operational knowledge of the distribution system, and verifies that the model closely reflects actual system conditions.

During this calibration process, many changes were made by Jacobs staff to the model of the CU water system. Major and minor piping changes that have occurred since the previous model calibration process were incorporated into the model. Piping updates also include more detail of the piping layouts at each of the three CU water production facilities and at the 5 major booster pump stations. Pump curves, pump controls, valves, valve controls, and tank geometry are also updated in the model to match current data. Finally, flow control valves representing the production capacity at the HUC and CFP facilities are installed at each facility, so high service pumping can be examined during peak day demand times. This insures the capacity of the production facilities is not exceeded within the model (Jacobs Technical Memorandum, 2014).

Model Boundary Conditions

There are 2 general categories of data streams in simulated water models: measurements and boundaries. Measured operational data can be used to verify simulation results. Boundaries conditions include system performance settings, and are used actively to change pipe, pump, or valve statuses or settings within a model. This is a broad categorization, and there are nuances. Some data points can become either a measurement or a boundary, depending on other factors. For instance, the presence of a pressure sensor downstream of a regulating valve could be used as a regulator valve setting boundary, or as a measurement to compare against simulated pressure (U.S. EPA., 2014).

Boundary conditions are found at the edges of the active model area, and serve to define the physical boundaries and perimeter of a water system. They show conditions like “reservoirs”, which can be connection points to other systems or to natural water sources. Reservoirs are nodes that represent an infinite external source or body of water supplying the network. They are used to model such things as lakes, rivers, groundwater aquifers, and connections to other systems. The primary model input for a reservoir is hydraulic head. Because a reservoir is a boundary point for a water distribution network, its head cannot be affected by what happens within the network. Therefore, it has no computed outputs. However, its head can be made to vary over time by assigning a demand pattern (Brünger et al., 1984).

To differentiate, tanks are not reservoirs or boundary conditions (Fetter, 2000). Within a water model, they are nodes with storage capacity, where stored water volumes and elevations can vary throughout a simulation. Primary input properties for tanks are: (1) bottom elevation, where water level is zero; (2) diameter, if cylindrical; and (3) initial, minimum and maximum water levels. Primary tank outputs from a water model is a time series of its hydraulic head, or the water surface elevation within the tank. Tanks must operate within their minimum and maximum levels within EPANET, because it stops outflow if the minimum level is reached and stops inflow if the maximum level is met (Housner, 1963).

Because boundary conditions represent actual hydraulic conditions, they are necessary to ensure a water model can accurately reflect an entire water distribution system’s behaviors. In addition to providing valuable information on the reservoirs, boundary conditions include information on pump status, pressure control points, valve statuses, reservoir levels, water production, and demand by location. This information is required to perform steady-state analyses and to set initial conditions for extended-period simulations (Rossman, 2000). They are largely responsible for flow throughout the model, and are the

most common error sources during model simulations. Boundary conditions can be extracted from SCADA programs or measured in the field.

Measured operational data is gathered the same way: either measured in the field or taken from SCADA systems. Data required for input to a water distribution system model includes maximum and minimum tank levels; valve positions; flow rates; setting (open or closed) for pumps; valves; pipes; initial pump status; pump speed; and pump sequencing inside a pumping station. Measured operational data within a hydraulic model allows for simulated modification of water system performance.

A water system modeler uses boundary conditions and measured operational data in 2 ways. First, to embed initial boundary condition and system control data. System control data influences diurnal changes in boundary conditions throughout a model run, such as how pump or valve statuses can change over time and create variation in boundary condition water levels and pressures. These are the initial conditions. Second, the data can be used for model verification or as a reference dataset. Data (flow, pressures, and levels, for example) can be compared to model outputs to confirm that the model can represent actual operations (American Water Works Association, 2005).

When calibrated, a model needs to match the state of the system, including boundary conditions. System behavior occurring in the water system during calibration should be replicated in the model, meaning that if a pumping station contains pumps that are off at 12:00 a.m., the model should reflect that those specific pumps are set to off at 12:00 a.m. Valves (especially PRVs, which are designed to open in low flow conditions), pumps, and pipe settings should be mirror images between the actual water system and the modeled water system.

Tank water levels within the actual water system should match the tank levels within the model. The performance of any water model is largely a function of the initial boundary conditions applied when building the model. The quality and distribution of this data determine the effectiveness of the local implementations and the soundness of scenario manipulations. Table 5 outlines CU's initial boundary conditions after a successful model run. All figures and tables referenced in this Introduction are placed in Appendix 1, in the order they are mentioned in this text

Model Transfer Verification and Validation

When water distribution system models are transferred between software systems, compatibility issues can arise. The following inputs can be compared across models to insure system parameters transfer correctly:

- Facilities: the number of junctions (or “nodes”), pipes, tanks, pumps, valves, and reservoirs
- Pipes: total length of pipes, and their average C-values, and status (open or closed)
- Junctions: minimum, maximum, and any zero elevations – which will cause negative pressures
- Pumps: elevations, status (open or closed), and pump curves
- Valves: setting (open or closed), associated head curves, and valve type
- Controls: programmable logical controls (PLC's), including simple and rule-based controls, may have to be exported from the original model and added manually to the new model
- Patterns: total number of demand patterns present and their demand multipliers

A transferrable method for developing and verifying a water system model is outlined in Figure 7. Each of these steps is performed as part of the model transfer verification.

When the CU model is transferred between modeling software programs, the EPANET Status Report contains many errors after that initial model run that need to be resolved before the transfer can be validated. Some missing elements must be entered manually, including many of the simple and rule-based controls, which Jacobs supplied through screenshots of their model's inputs. Zero elevations at nodes are located and corrected to match surrounding elevations, to correct negative pressure warnings. Pump curves are extended in several locations to meet head requirements and stop the exceeding of maximum flow. Some pipe roughness coefficients are reduced from 130 to 100 to slow flows.

Finally, some smaller pipelines in the model are closed off, and demand represented at the nodes those pipes serviced is aggregated at the base node. Adding the sum of demands and closing pipes serves to somewhat simplify the model in a few locations. If there is no tank at the end of a pipeline, closing that small section does not significantly impact the system outputs. These additions and modifications allow the model to run successfully as a reference situation. The model remains stable during fire flow tests. In summary, all model adjustments performed to the base model are: 3 pumps are closed with demands aggregated to nodes below, 2 pump curves are extended to meet flows, 1 roughness coefficient is adjusted from 130 to 100 to increase friction and slow flow, and 1 node's elevation is slightly adjusted to resolve negative pressure. An example of extension of a pump curve at Sunset Trail is shown below, in Figure 8.

Exports from both the Jacobs CU model and the EPANET CU model are compared to ensure that initial inputs and boundary conditions align between models. Any condition that differed is resolved using input data from the H2OMap model to adjust the EPANET model. In addition to discussing model behaviors post-import with Jacobs Engineering staff, published EPANET experts Dr. Chris Cox and Dr. Bruce Robinson were consulted at length. Several hours were spent over the course of 2 days with each of them. They examined the model and discussed various behaviors of interest and acceptable modeling techniques that can be used to address any errors that may occur during model scenario development. A summary of model modifications is detailed in Table 6.

This process served to ensure that the methods with which model adjustment are made do not violate system flow balances and operating preferences. Ultimately, the EPANET CU model executed without errors, post software transfer. Figure 9 summarizes this verification and validation process. From EPANET, elevation time series are exported into Excel (Microsoft Corp, Redmond, WA) and graphed to compare against tank behavior graphs in the Jacobs Engineering calibration report. Figure 10 shows Bryant Drive Tank graphs from both models, as well as with SCADA data to visualize this comparison exercise. Tank elevations exhibit almost identical behaviors between models.

Finally, the EPANET model is stress-tested to insure it can meet normal demands as well as fire demands. In fire scenarios, 20 psi is the standard minimum pressure. A properly functioning model should be able to supply maximum, peak demands, as well as accommodated additional fire flows. The assumption is that market demand for water will stay the same during a fire, but that system pressures will decrease. Those not in a fire zone may experience reduced flows and therefore consume slightly less, because the reduced pressure won't allow them to use the same amounts. At time zero of the fire(s), nodes will still demand the same, motivating tanks to drain faster, and pumps to come on with more frequency.

To determine the maximum pressure available at a node when the flow demand is increased to suppress a fire, the fire flow is added to the node's normal demand through pattern application. The analysis is run, and the resulting node pressure decreases. In EPANET, to determine the maximum flow available at any pressure, the emitter coefficient at the node can be set to a larger value: 100 times the maximum expected flow, for instance. The required pressure head (2.3 times the pressure in psi) is added to the node's elevation. Post-analysis, available fire flow equals the actual demand reported for the node, minus any consumer demand already assigned to it.

To stress test the verified model, a fire flow pattern is run in the water model. Keeping base demand the same, additional fire demand is added at noon (starting at the 144-time step) for 1 hour. This new pattern (Fire_PD) is run at 4 areas in the model: (1) near a boundary condition: Savannah Reservoir; (2) near a tank: Bryant Tank; (3) at city center: high demand at 1 downtown node (large fire); and (4) city center: 1,641 Junctions in downtown area (small fires). Additionally, a conservative fire pattern is run at all nodes every 2 hours. After running these stress tests, 82 low pressure nodes (~20 psi) are found. This number corresponds to low pressures found in a PD_MAIN demand pattern run, so the fires are not causing any extraordinarily low or unusual pressures.

Though increased demand is reflected incrementally at the affected nodes, tanks do not drain or radically change in elevations – they respond instead to fire demand with slight changes in elevations. Figure 11 shows the flow system balance of the verified model during a fire flow run. The spikes in the green line show the model meeting fire demand every 2 hours, according to the conservatively designed fire flow pattern assigned to each node throughout the water model.

Once the model transfer is verified, patterns are extended to create a full week (with weekends) and month, to test the ability of the model to replicate run results beyond a 3-day (72-hour) period. The model should be able to run calculations indefinitely. Figure 12 outlines the steps of pattern extension, using a full week as an example.

These exercises work together to ensure that the EPANET CU water system model represents demand patterns, pressures, and flows in diurnal curves by 5-minute time step over the assigned run-time hours. It presents a holistic yet finite picture of how the actual water system will run similarly each day, though it is understood that the water system will never repeat any one day verbatim. For example, the pressure at any one location will vary each day over time, but will fall within an expected range. The model represents realistic demand patterns and simulates normal operations. The 3-day (72-hour) run time is used in scenarios.

Model Controls

Controls within the model drive system behavior. These are input statements designed to prescribe network operations over time. With controls, the status of identified links is specified as a function of time, tank water levels, and pressures at select points within the network. In EPANET, there are two categories of controls that can be used: simple and rule based.

Simple controls change link status or settings based on water level (the height above tank bottom, not elevation or total head) in a tank, junction pressure, time of day (1:00 p.m., for example), or specific time within a simulation (Hour 65, for example). Statements are expressed in 3 standard formats: (1) link [identifier] status [open/closed/speed/control valve setting] if Node [identifier] above/below [elevation]; (2) link [identifier] status [open/closed/speed/control valve setting] at time [clock time AM/PM]; and (3) link [identifier] status [open/closed/speed/control valve setting] at time [24-hour time]. Use of simple controls is not limited. Pressure controls used to open and close a link can cause the system to become unstable if the pressure settings are too close together. Rule-based controls can create more stability in this instance.

Rule-based controls accommodate link settings that need to be based on a more than 1 condition that might exist in the network after a model run is computed. These controls are formatted as if/then statements and can perform functions such as shutting down a pump and opening a by-pass link when tank level exceeds a specified value. The rule then does the opposite when the level is below another specified value. Both simple and rule-based controls can be set to govern reservoir behaviors. Rules assigned to reservoirs respond to what the system needs by ensuring that associated tank levels, node demand, or time of day trigger supporting links.

Supporting links include valves, variable frequency drives (VFDs), connected pipe flows, and pump status (open or closed). They are triggered as the system run is calculated in the model over a 72-hour period, responding to what the whole system is demanding. In some cases, time during the model run triggers link behaviors as well (a pump, link, or valve is set to closed or open at time 0, for instance). Table 7 shows simple and rule-based controls in the verified EPANET CU model. These are organized by pump and tank at each source location. Reservoirs that do not have controls are not listed.

Understanding Pump Curves. As described in the validation process with the CU model transfer between software, another governing feature the modeler controls to enhance system performance are the pump curves. Pump curves describe mathematically relationship between the head and the flow rate a pump can deliver at the nominal speed setting. “Head” is expressed in units of height (feet or meters), and is defined as the maximum height (or pressure) a pump can deliver. It is plotted on the vertical (Y) axis of the curve in feet. Flow rate is plotted on the horizontal (X) axis in flow units (GPM).

At the time of a model calibration exercise, these pump curves are verified by pump type at a specific location. When scenarios are run to test system response to demand increases, pump curves can be changed to make pumps more powerful. Changing pump curves essentially translates into increasing pump size, by increasing pump head to manage greater flows. In both model scenarios described in the following section, pump curves are adjusted throughout the system as needed, to deliver water at specified pressures with increased distributed or concentrated storage. Figures 13, 14, and 15 show the setup of each reservoir within the CU model.

1.4 Testing the Feasibility of Storage in Urban Water Systems

To test if a local water system can be used to store water that can then be generated into electricity to offset peak energy demand, 3 initial water and energy data analyses are undertaken. First, exports from the verified CU water distribution system model (running the peak demand pattern) are examined to determine the potential energy in existing tanks. Pumps are also examined for energy consumption requirements as they fill the tanks. Then, an energy value is assigned to unused storage in the water system. Next, Cleveland's peak energy consumption data is assessed against potential tank generation and pumping energy requirements to see if this unused storage could possibly impact community energy demand (Figure 16).

Calculating the Energy Value of Unused Storage

The following calculations are used in steps 1 – 3.

Step 1. Calculate potential energy for all tanks if they drained, and the pump energy required to fill them:

$$E(h) = \rho g \pi R^2 (h - h_{min}), \text{ where}$$

E = energy (kWh)

ρ = density of water (1,000 kg/m³)

R = radius

g = acceleration of gravity (9.8 m/sec²)

h – tank elevation

Table 8 shows calculations by tank. Elevation is the bottom of bowl elevation in feet MSL. Depth is the operating depth in feet minus the minimum tank level in the model. Diameter is the tank circumference in feet. Volume is nominal volume in gallons. Gallons to kilograms is measured by 1 gallon equaling 3.79

kg. Feet to meters is calculated by 1 foot equaling 0.3048 m. Joules are calculated by multiplying kg by the value for gravity (9.81) and by meters. A joule equals 0.001 kJ. One kJ equals 0.00027777 kWh. Pumps are assumed to have 70% efficiency.

According to these calculation methods, the 21,050,000-gallon existing tank capacity could generate 2,237 kWh if fully drained 1 time, and would require 3,190 kWh in pump energy to recharge from zero 1 time. Without higher peak electrical demand pricing per kWh, draining and recharging would not make sense from an energy generation versus consumption perspective.

Step 2. Calculate energy value of the total unused storage in the system:

$$E_{\text{unused storage}} = (T_{\text{height}}) (T_{\text{area}}) (\pi r^2) (T_{\text{diameter}}) (T_{\text{volume}}), \text{ where}$$

E = energy

T = tank

1 cubic foot = 7.48 gallons

Using this equation, 3 calculations are performed for each tank: (1) volume in cubic feet is converted to gallons; (2) gallons are multiplied by percent full; and (3) actual gallons are subtracted from total gallons to find unused gallon capacity (Figure 17).

According to this calculation method, there is anywhere from 1.1 to 5.3 MGD in unused storage capacity. From this, total unused storage capacity can be assigned a potential energy generation value in kWh (Figure 18). This assumes tanks are always 100% full and the additional filled storage capacity (or unused storage) is being used for energy generation only, not to meet demand or to maintain pressure.

There is anywhere from 8 to 20 kWh in potential energy represented by the unused storage capacity. Additionally, the potential energy generation value in kWh from normal tank draining patterns can be calculated (Figure 19). There is anywhere from 0.8 to 5.44 kWh in potential energy represented by normal tank drain patterns.

Step 3. Compare pump energy consumption to peak energy demand for the water sector:

$$HP = \frac{\Delta p Q}{1714}, \text{ where} \quad (4)$$

HP = horsepower

P = pressure (psi)

Q = flow in gallons per minute (GPM)

While EPANET does have a function that allows pump energy consumption to be viewed by pump, these graphics total each pump's energy consumption, as opposed to allowing a modeler to observe energy consumption by pump over time. Therefore, this must be calculated. Because pump flow can be calculated in gallons per minute, the change in pressure is multiplied by the demand flow, and then divided by the constant of 1714 (the hydraulic horsepower formula to calculate when flow is known). The answer can be divided by 70%, to account for the assumption of energy loss from the pumps. Pumps consume anywhere from 12.9 kWh to 95.4 kWh over a 72-hour model run (Figure 20).

Additionally, flow is aggregated and a total kWh value is calculated for each individual pump in the model. As expected, the Water Treatment Plants have the largest flows, followed by pump stations that are operating 2 or more pumps the same location. Pumps that operate at regular intervals to push relatively constant volumes of water (either at tanks or in high density areas) are the next highest users, followed by the lowest energy user group: pumps and boosters that supply residential areas throughout the distribution system.

Calculations for all CU tanks and pumps functioning in a peak-demand scenario are compared to July electric consumption for the Cleveland community. To give a sense of the vastly differing scales of magnitude, CU July electric demand ranges from average lows of 70,000 kWh to average highs of 230,000 kWh. Figure 21 is a graph of the total hourly July electric consumption data provided by CU. It represents meters from all sectors at hourly intervals. In short, electricity consumption for the community is more than 1,000 times what could be gained from generating electricity without significant water system modifications.

Finally, when the energy consumption of just the water and sewer sector is compared to pump energy consumption, it cannot be graphed in any meaningful way, due to this significant difference in scale.

Figure 22 shows this comparison over a 3-day period. Pump energy consumption is minimal when compared to peak energy demand for the water sector. An average of 56,744 kWh is consumed over a 3-day period (between 15 and 95 kWh at any given time) by the pumps. Water sector energy use is between 20,000-70,000 kWh at any given time.

In summary, these 3 exercises serve as due diligence to inform scenario development. From exporting, calculating, and observing charted outcomes, 3 findings are apparent. First, due to the higher energy requirements of the pumps to fill the tanks than what can be gained by draining the tanks to create energy (as seen in Step 1), the attractiveness of using the water system to offset electrical demand is energy-pricing dependent. This means that if the need to pump water at the peak electrical demand price point is reduced, then energy costs are also reduced. Pumping water to fill tanks during off-peak demand times instead of during peak times, and releasing water to generate electricity at peak demand when energy costs are higher could save energy costs for a utility over time.

Second, due to the difference in the value of unused water storage when compared to community electric consumption, there may be some peak-shaving value in adding storage in model scenarios, but it will not be able to level peak electricity demand peaks (as seen in Step 2). Third, the pump energy consumed in the water system is around 0.001% of the total energy consumed by the CU water sector (as seen in Step 3). This means that while pump energy consumption is a consideration, it is not a driving factor in the exercise of modifying a water distribution system to shave community peak electrical demand.

Designing Two Scenarios to Create Additional Water Storage for Energy Generation

Now that a baseline comparison between water distribution system behavior and community energy consumption is understood, two scenarios are undertaken within the water model. These are designed to understand what impact additional storage added for electricity generation (as opposed to meeting demand or maintaining pressure) can have on an entire community's peak energy demand. Designing, developing, and successfully running these scenarios allows comparison of various water model outputs to energy data, to understand how unused water energy at non-peak electrical demand times could be stored within the water system, and to understand how aggregated energy demand impacts storage demand. Essentially, utilizing local water and energy system data allows the testing of various locations for storage opportunities, and becomes a simulated peak electricity-shaving exercise using modeled water storage tanks.

First, it is helpful to visualize the water system from the overarching concepts of the conservation of water and energy flows, or the balancing of shifting energy and mass over time and space. In short, the balance is that water and energy flows must not be added to or subtracted from as they move throughout the system. Outlined in Figure 23, blue items represent the flow of water through water system: from the supply and water treatment side (including the source, water treatment facilities, and supply pumps), to the water distribution side system (including the piping network, valves, pumps, tanks), and finally to the consumer. Orange items represent the flow of energy through the electrical system, and test how potential energy could be extracted from tanks using an upper tank, a turbine, and a lower tank.

This visual is helpful when designing scenarios. It identifies assumptions (that energy and water demand are fixed, for instance), removing those items from the list of variables from which scenarios can be designed to manipulate. Several explorations occur both externally to the water distribution model and within it before a final design for the scenarios is decided upon. These analyses inform on the capacity of the water system to meet targeted energy reductions. They define: (1) peak energy demand for Cleveland; (2) how much energy is required to level peak electrical demand for the entire community; (3) how much energy is required to shave peak demand by 10%; (4) how many additional gallons of storage is required to meet this energy reduction target; (5) the best configuration for the upper and lower tanks; (6) height differential needed to produce the desired amount of electricity; and (7) desirable controls that can be built within the model to make it not only smartly respond to demands while maintaining system pressures, but to also be able to generate electricity while performing these essential functions.

Electricity demand is highest during certain hours of certain months. As demand rises, energy becomes more valuable. TVA defines peak electrical demand within its power system as the afternoons and evenings of summer (June-September) and early to mid-mornings of winter (December-March). In winter, peak demand times are the hours of 5 am to 11 am eastern standard time. In the summer months, peak demand times are the hours of 1 p.m. to 9 p.m. EST (TVA, 2015). Accordingly, CU aggregated peak electrical demand in kWh for July 12, 13, and 14 during the hours of 1 PM to 9 PM eastern standard time is isolated and summed. It totals 856,974 kWh (Table 9).

Assuming the lower reservoir, or tank, is at least 100 m (328 ft.) below the upper tank, gallons needed to generate this peak total can be calculated through simple conversion:

$$3.08(10^{12})j = x (9.81 \text{ m/s}^2) 100 \text{ m}$$

$$\underline{3.08(10^{12})} = 3,139,653,415 \text{ kg}$$

$$9.81 \text{ m/s}^2(100\text{m})$$

$$3,139,653,415 \text{ kg} / 3.79 = 828,404,594 \text{ gallons, where}$$

j = joules

x = kg

9.81 = gravity (m/s²)

According to this calculation, 828,404,595 gallons a day in unused storage is needed to completely level peaks. Because there is only an average of 3,861,027 gallons of unused storage in the CU system at any given time, this would require an additional 824,543,568 gallons of unused storage to be available. To store this amount of water, 236 3,500,000 gallon tanks – the largest water tank size in the CU system – would need to be added.

This calculation exercise provides baseline knowledge and sheds more light on the significant differences between community energy consumption and available storage in the CU system. However, because the goal of this research is to present a usable methodology as a long-term planning tool for water system operators, it is decided to stay within the realm of possibility when exploring how best to add additional storage to the water system for energy generation. Because the order of magnitude between what amount of electricity the water system can reasonably be expected to produce is so vastly different from the amount of electricity generation needed to level peak energy demand for an entire community, it is unrealistic to assume any water system manager would undertake such an investment without proof of a reasonable payback period. Therefore, the scenarios are designed to attempt to shave the daily peak electrical demands by 10%, or to produce around 85,697 kWh as a target best case. To be very clear, this is 10% of only the peak electrical demand, not 10% of the entire system's electrical load.

Two scenarios are designed to store – either in a distributed manner or in a concentrated location - and extract energy from the water system. They are both firmly rooted in the foundational concept that the water and energy system must maintain a flow balance, and represent the shifting of energy and mass over time. Scenarios are also based on the traditional hydropower generation design, assuming an upper reservoir, a turbine, a lower reservoir, and pump are needed to create and capture energy.

The design is tested conceptually to insure no water system rules are violated. For example, tanks are forced to drain to create energy by the addition of a timed operating valve, as opposed to adding additional demand that makes them drain. This is because demand in these scenarios is assumed to be fixed, and water traveling from an upper tank to a lower tank must be returned to the upper tank, as opposed to being consumed. The simple loop design is also tested in EPANET first, without using the verified CU water system as a base model. Isolating it in this way allows the tanks, links (including pumps, pipes valves), and nodes to be arranged in various ways to find the most efficient configuration, without also having to deal with the sensitivity of an entire water system during this learning process. The test model is modified until tank, pump, and valve behaviors are understood with the assignment of various pump curves, headloss curves, and controls. Once this knowledge is gained, inserting generating loops into a sensitive and complex water system is less daunting.

It is important to note that to simulate a turbine in EPANET, a general-purpose valve (GPV) is used. Each valve type in the model has a different setting that describes its operating point, as opposed to automatically being assigned one of EPANET's standard hydraulic formulas. For instance, PRVs require an assigned pressure setting. The setting that defines this link is a user-specified head loss and flow relationship. Like the concept of pump curves, GPVs have a headloss curve that describes the headloss (Y in feet) through the GPV as a function of flow rate (in GPM). However, a headloss curve goes in the opposite direction from a pump curve: the headloss curve shows decreasing head with increasing flow rate, whereas a pump curve shows how flow rate decreases with increasing head.

Once designed and tested, these scenarios are built into individual CU water models, using the verified model as a base. Once modifications are made and the system is adjusted to address and resolve any ensuing errors, the model is stress tested by running a fire pattern to insure demand is met and pressures maintained. Model outputs are analyzed to understand how the local water system can be modified to help reduce community energy demand curves. The following describes the methodology and model modifications used in each scenario.

Scenario A1 Methods: Concentrated Storage, Current Demand

The design steps, assumptions, and model modifications used to create the single-location baseline model under current demand constraints are as follows:

1. New tanks (called “tank farm” and then numbered in order 1-9) are modeled after the largest tank in the CU system, to achieve as much energy generation as possible, thus shaving peak energy

demand. Initially, seven 3,500,000 gallon tanks are placed in a row in the south side of the CU service territory. The location is zoned for industrial growth, and CU has modeled a possible tank addition in this location. Elevation changes (at least 328') needed to place the lower tanks for maximum energy generation are present along a primary water line. The location is also close to a 69-kV electrical substation, reducing potential energy loss in transfer. Later, two more tanks are added to the tank farm, once the potential energy generation of the original 7 tanks is understood, bringing the total to 9 tanks (Figure 24).

2. Because the tanks do not have to hold water that is needed to meet demand or to maintain system pressure, all of it can be used for energy generation. Therefore, lower tanks of the same size are placed at lower elevations, at least 328' below the upper tanks. It is assumed that the upper tank is 90% full and that the lower tank is 0% full at time zero of the model run.
3. A GPV valve is added as a link type between the upper and lower tanks to simulate a turbine within the model. It is sized at 36" and assigned a headloss curve. Controls to govern the GPV are written so that it comes on to generate energy only during peak electrical demand, opening at 1 PM and shutting off after 9 p.m. EST over the 3-day run.
4. A lower pump is added to return the water to the upper tank. It is assigned a pump curve powerful enough to refill the upper tank during off peak hours, as well as hourly controls that turn it off during on-peak hours, and on during on-peak hours (as seen in Table 10 for an example of employed tank farm pump controls).
5. Connecting links (pipes) are added to allow the GPV to draw from the upper tank and fill the lower tank. They are also added to allow the pump to drain the lower tank and fill the upper tank. Pipes in the upper and lower tank loop are tightly configured, to minimize the energy consumption of the pump.
6. After the addition of each tank, the model is run and any ensuing errors are corrected. These include locating and adjusting any areas exhibiting negative pressures and increasing pump curves for any pumps that are open, but which exceed maximum flow, throughout the system.
7. A Fire Flow pattern is run, to stress test the model and insure it can still meet demand, while accommodating additional fire flows.
8. Once the model modifications are complete, fire flows have stress-tested system operations, and any errors in the run-status report have been corrected, graphs of tank, GPV, and pump behaviors from a successful model run are examined for operational inconsistencies.
9. Energy in kWh is calculated for each tank, and total generation outputs from the tank farm are compared to energy data to understand peak leveling implications.

Each tank in the tank farm has the same specification and the same set of controls assigned to it, assigned to each by individual tank name. These hourly setting controls operate in tandem with the existing and verified model controls, which include various operating controls based on time of day, model run hour, flow, and tank elevation. Figure 25 shows the water system flow balance of the successful A1 scenario during a fire flow run. The spikes in the green line show the model meeting fire demand every 2 hours, according to the conservatively designed fire flow pattern.

Building a fully functioning Scenario A1 model took many iterations to resolve flow and pressures errors. As part of this process, the following modifications were made in the model to solve negative pressures throughout the system, and to adjust pumps that were open, but which exceeded maximum flow: Adkisson, Crown Colony, and Windcrest pump curves were increased. Eventually, after pump curve adjustments did not resolve the excessive-flow problem, the Windcrest pump was turned off. This is a 500 GPM pump with only 1 node above it, so that node's demand is added to the node below the pump.

Scenario B1 Methods: Distributed Storage, Current Demand

Scenario B1 explores the addition of distributed storage in existing tank locations throughout the water system. To attempt to generate 10% of peak electrical demand, additional tank capacity is added by doubling the size of existing tanks to accommodate energy generation. Scenario B1's design requires significant testing and adjustment to insure doubling tank capacity is done in the most efficient manner. A test tank (Blythe) is first doubled in diameter. In a companion model, the height of Blythe is doubled. Pump operations are examined and compared between both test structures, as is Blythe's behavior in the unmodified, verified model. Figure 26 visualizes this comparison exercise.

Using the verified model outputs as the baseline, as expected, the tank stays full, and elevations change slightly and consistently over time to accommodate demand. The associated pump uses 1,046.81 kWh over the 3-day model run. Expanding tank diameter to twice the tank's normal size moderates the changes in water elevations somewhat, so that head increases and decreases are less dramatic over time. The pump uses 968.82 kWh over the 3-day model run. Increasing tank height to accommodate twice the original water elevation also reduces the frequency of water elevation changes. Again, the tank remains full and elevations continue to change consistently over time. The pump uses 1,180.63 kWh over the 3-day model run. Therefore, it is evident that pumps will require slightly more energy in an expanded height scenario, but the differences are negligible between the 2 tank expansion designs. Making a tank taller also improves head, which is needed during hydraulic energy generation.

Following this exercise, the remaining existing tanks in the CU system are doubled in height in the B1 model. The model is run after each addition, to be able to catch and correct negative pressures or excessive pump flows. This method helps to contain and isolate errors according to the most recent model addition. Then, each location is spatially referenced in ArcGIS to aid in the design of the lower reservoir, or water holding tank.

The accompanying electricity-generating GPV and return pump are sized according to gallons the lower tank can receive, and the head required to return the water to the upper tank. Pump and headloss curves are assigned to each. For each unique tank, the accompanying generating system is specifically designed according to the height increases made within the EPANET model. The design steps, assumptions, and model modifications used to create the baseline-distribution-storage scenario under current demand constraints are as follows:

1. Each existing tank's capacity is enlarged by doubling the height of each one.
2. Existing tanks are located at the highest points in a water system to maintain water system pressures, so a lower tank is placed at least 328' (or 100 m) in elevation below each upper tank. Because the upper tanks must hold water that is needed to meet demand and maintain system pressure (unlike scenario A1, which did not need the tank farm to perform these services for the water distribution system), only half of it can be used for energy generation. Therefore, lower tanks are sized to hold half of the volume of water the upper tank can hold, now that it is enlarged. It is assumed that the upper tank is 90% full and lower tank is 0% full at time zero in the model, when the minimum and maximum tank water elevations are set (visualized in Figure 27).
3. A GPV valve is added as a link type between the upper and lower tanks to simulate a turbine within the model. It is sized at 36" and assigned a headloss curve. Controls to govern the GPV are written so that it comes on to generate energy only during peak electrical demand, opening at 1 p.m. and shutting off after 9 p.m. EST over the 3-day run.
4. A lower pump is added to return the water to the upper tank. It is assigned a pump curve powerful enough to refill the upper tank during off peak hours, as well as hourly controls that turn it off during on-peak hours and on during on-peak hours (as seen in Table 11).
5. Connecting links (pipes) are added to allow the GPV to draw from the upper tank and fill the lower tank. They are also added to allow the pump to drain the lower tank and fill the upper tank. Pipes in the upper and lower tank loop are tightly configured, to minimize the energy consumption of the pump.

6. After the addition of each tank, the model is run and any ensuing errors are corrected. These include locating and adjusting any areas exhibiting negative pressures and increasing pump curves for any pumps that are open but exceeding maximum, flow throughout the system.
7. Once the model has been adjusted enough to allow for a successful run, a fire flow pattern is run, to stress test the model and insure it can still meet demand while accommodating additional fire flows.
8. Once the model modifications are complete, the fire flows have stress-tested system operations, and any errors in the run-status report have been corrected, graphs of tank, GPV, and pump behaviors from a successful model run are examined for operational inconsistencies.
9. Energy in kWh is calculated for each tank, and total generation outputs from the distributed tanks are compared to energy data to understand peak leveling implications.

Each tank in the distributed model has different specifications, but the GPV and lower pumps share the same set of controls, though they are assigned to each by name. As in Scenario A1, these hourly setting controls operate in tandem with the existing and verified model controls. These include various operating controls based on time of day, model run hour, flow, and tank elevation. Figure 28 shows the water system flow balance of the successful B1 scenario during a fire flow run. The spikes in the green line show the model meeting fire demand every 2 hours, according the fire flow pattern.

Building the Scenario B1 model is much more complicated than building the A1 scenario model. This is because in A1, tanks are built in a consistent manner, using the same specifications for each as the tank farm is built out. They are in the same location, and do not have to meet demand, or maintain system pressures. In scenario B1, each tank is different, with its own unique circumstances of demands and pressures. Elevations vary. Supply pumps can be close or far away from the tank, depending on the system's configuration. Each tank and pump depends on the others, and a modification at one can prompt an error in another location – even if it is on the other side of the water system.

Weeks are spent adjusting controls, testing various curves, and hunting node by node for negative pressures. Once found, logic must be used to understand what the motivator of the error is, so that any changes to the model remain within reason, and do not violate system flows and energy balances. Finally, a model is produced that not only runs without error, but also can generate electricity, while meeting pressure and demand requirements. In the end, the following modifications are made in the model to solve

negative pressures throughout the system, as well as pumps that are open but exceeding maximum flow: Crown Colony and Waterville pump curves are increased to deliver new head requirements.

Now, it is time to examine energy generation results from both scenario configurations, to see where they each fall in relation to the goal of shaving 10% of peak electrical demand. To calculate generating potential for both scenarios, each tank's demand (GPM), head (ft.), pressure (psi), and maximum height (ft.) is exported into Excel in 5-minute time steps for a full 3 days. Elevations are graphed for each tank to insure the tank does in fact fill to maximum set levels during times of off-peak energy use, and empty to minimum set levels during times of peak energy use. Then, flow, velocity (ft./sec), unit head (ft./kg), friction factor, reaction rate, and status (open/closed) for the associated GPV is exported by 5-minute time step. Finally, horsepower is calculated for each GPV's hours of operation only (1 – 9 p.m. EST for each of the 3 days) using the following formula:

$$\text{Horsepower} = \frac{h_A Q (SG)}{3,956}, \text{ where}$$

$h_A = \text{head (ft.)}$

$Q = \text{flow (GPM)}$

$328' = \text{difference in elevation between the upper and lower tanks}$

$\text{Specific gravity (SG)} = 1$

This is converted into kW for each peak-hour 5-minute time step by multiplying H_A by 0.7457 (the conversion from H_A to kW), and then by converting kW to kWh by multiplying kW by 0.08 (representing the 5-minute time step).

1.5 Results

The methods for creating, specifying, and constraining the 2 models containing scenarios A1 and B2 are now understood. It is clear from an examination of controls, flow charts, tank behaviors, and fire tests that system flow balances have not been violated in the exercise of prompting tanks to generate electricity.

Before looking at electricity generation outcomes by scenario, it is important to understand how much capacity is added in terms of used and unused storage, just as is done for the verified, unmodified model. Figure 29 compares storage in both scenarios, providing a visual of how much more storage capacity the

tank farm has when compared to the distributed tanks with increased height. Both have significantly more storage capacity than the baseline verified model.

The system holds between 15 to 20 MGD in storage to meet demand and maintain pressures. It has between 1 and 5 MGD in unused storage. Scenario A1 (concentrated storage) has anywhere from 27 to 51 MGD in its tanks at any given time, and between 19 and 50 MGD in unused storage. Scenario B1 (distributed storage) has anywhere from 15 to 30 MGD in its tanks at any given time, and between 5 and 21 MGD in unused storage.

Scenario A1 Results: Concentrated Storage, Current Demand

Unsurprisingly given this examination of capacity, Scenario A1 is the better energy generating option. It can generate just over the full 10% of peak electrical demand (Table 12) over a 3-day period. Figure 30 shows the A1 GPV slightly reducing the peaks of the electrical demand curves. Figure 31 is a visualization of scenario A1 outcomes.

Scenario B1 Results: Distributed Storage, Current Demand

Scenario B1 can cover only half of the desired 10% peak shave, generating up to 44,704 kWh over a 3-day period (Table 13). Scenario B1 is the less attractive energy-generating option, generating 44,471 less kWh than A1. Figure 32 shows the GPV only slightly reducing the peaks of the electrical demand curves, barely enough to even differentiate from the peak electrical demand curve. Figure 33 is a visualization of scenario B1 outcomes.

1.6 Conclusions

This research reduces the knowledge gap within the water energy nexus by examining if local water systems can be used to reduce peak energy demands for entire communities. The findings create a greater understanding of how a local water system can potentially support the electrical system through storage and generation opportunities. To determine opportunities for energy storage and generation in urban water systems, relevant literature is explored. This baseline of existing knowledge is referenced to explain how urban water systems and electrical systems work. Best practices for modeling water systems are examined through the lens of integration strategies that can allow comparison of water and electrical systems together.

To determine how opportunities for energy storage in urban water systems are best measured, and where storage should be located to best help the local water system contribute to the reduction of community energy demand curves, a case study city's water system is modeled. The model represents an actual water system operated by Cleveland Utility in Cleveland, TN. It is a complicated system with thousands of links and nodes, 10 primary water tanks, two primary water treatment facilities, 6 production-facility water pumps, and 30 booster pumps. A calibrated water model is transferred between software programs and is verified in EPANET for the purposes of this research. The water system components and methodology are described in detail in Sections 1.2 and 1.3. Experts are consulted and a validated and verified baseline model is finalized, upon which to build 2 storage scenarios: concentrated (A1) and distributed (B1).

Community energy data for the City of Cleveland is obtained and compared to existing used and unused storage in the water model. When water model tank behaviors and its outputs are compared to aggregated community-wide electrical data, an order of magnitude is discovered that tempers expectations of peak electrical demand leveling, and focuses attention upon the possibilities for peak electrical demand shaving. Through this comparison exercise, it is learned that if a water system operates in a Business as Usual (BAU) scenario, it cannot level peak energy. The unused energy storage value is 2,240 kWh if all tanks drained at once. Over a 3-day run, there is anywhere between 10 – 20 kWh at any given point in unused storage space. This alone will not serve to level community electrical peaks, because peaks are anywhere from 200,000 – 240,000 kWh per day.

Thus, it is hypothesized that increasing tank sizes may allow the water system to contribute to the reduction of peak community electrical demand, but (1) that peak leveling is unrealistic, and (2) how storage is added within the water system matters to its energy generating potential. Peak electrical demand is defined as the hours of 1 – 9 p.m. EST, according to TVA guidelines. Ten percent of that peak – not 10% of the entire community energy demand - is isolated and calculated to total 85,697 kWh.

Two scenarios are designed to test the addition of concentrated and distributed water storage within the water model. The new storage can only be used to energy generation, not to also meet demand and maintain water system pressures. In both scenarios, multiple modifications are made within each one's baseline verified CU water model, to insure they can generate electricity without violating operational preferences. Each scenario model must still meet water demands and maintain system pressures – thus, preserving the balance of the shifting of water and energy throughout the system over time.

Scenario A1 concentrates water storage that can be used only for energy generation by modeling the addition of a tank farm. Nine 3,500,000 gallon tanks are added to the baseline verified model of the CU water system. Each has a lower tank of the same size to capture water that flows through a GPV to generate energy during times of peak electrical demand. Model controls are adjusted to insure the upper tanks drain with the GPV open during peak hours, and that the lower pump refills the upper tank after 9 p.m. EST each day. When tank farm energy generation is calculated, it totals just over 10% of the peak electrical demand, at 89,175 kWh.

Scenario B1 distributes water storage that can be used only for energy generation by increasing the size of existing tanks to double their original capacity. When existing tanks are doubled in diameter, peak leveling is still minimal and more head is needed to maximize energy generation potential. Thus, the height of each of the 10 primary tanks are doubled. Lower tanks at half the size (or, the original tank's size) are added, with a GPV to generate energy during times of peak electrical demand placed between the upper and lower tanks. Half of the upper tank is still reserved to meet demand and pressures required by the rest of the water system. A pump is added to return water from the lower tank to the upper tank. Model controls are adjusted to ensure that half of the upper tanks drain with the GPV open during peak hours, and that the lower pump refills the upper tank after 9 PM each day. When distributed energy generation is calculated, it totals just over half of 10% of the peak electrical demand, at 44,704 kWh.

Using an actual city's water system and electrical load as a case study serves to answer the motivating research questions and test the hypothesis: that there are untapped opportunities for energy storage within urban water systems due to a lack of water and energy system integration, and that there is value in examining data from both systems in an integrated and coordinated way to identify these opportunities. According to these tests, calculations, and results, opportunities for energy storage in urban water systems are best measured by understanding how much storage exists that is not being used to meet water consumer demand, fire flow requirements, and to maintain system pressure. Aggregate community electrical demand must be understood in terms of order of magnitude between what is required to shave community peak electrical demand, and how much unused storage an urban water system can offer to energy generation.

If energy generation is the goal, water storage for this purpose alone (not to meet demand or to maintain system pressures) should be concentrated. Urban water systems can be used to shave the peak energy demand in communities as they grow only if enough unused storage also added specifically for this

purpose. The tested hypothesis identified opportunities for system integration, but resiliency and cost implications still need to be explored. Additional research answers these two remaining research questions.

Future studies that examine the integration of water and energy system in urban settings should include the construction of a model that calculates energy consumption and generation by matching water system model time steps. This will allow multiple configurations to be tested with less time investment. It will further reduce the knowledge barrier that currently exists as to the practical application of creating a water energy nexus between local urban water and electrical systems.

References

- Al-Zahrani, M. A., & Moied, K. (2001). Locating optimum water quality monitoring stations in water distribution system. In *Proc., World Water and Environmental Resources Congress* (p. 393-402). Reston, Va.: ASCE.
- Amin, S. M., & Wollenberg, B. F. (2005). Toward a smart grid: power delivery for the 21st century. *IEEE power and energy magazine*, 3(5), 34-41.
- AMR vs AMI. (2008). Retrieved June 06, 2017, from http://www.elp.com/articles/powergrid_international/print/volume-13/issue-10/features/amr-vs-ami.html
- Annual Electric Power Industry Report (EIA-861 data file). (2017). Retrieved data from forms EIA-861, schedules 4A & 4D and EIA-861S on September 3, 2017, from <https://www.eia.gov/electricity/data/eia861/>
- American Water Works Association. (2005). *Computer Modeling of Water Distribution Systems* (Vol. 32). American Water Works Association.
- Author, N. (2004). Review of electrical energy storage technologies and systems and of their potential for the UK. *EA Technology*, 1, 34.
- Authority, T. V. (2015). Integrated Resource Plan: 2015 Final Report. *Tennessee Valley Authority, Knoxville, TN*.
- Baker, J. N., & Collinson, A. (1999). Electrical energy storage at the turn of the millennium. *Power Engineering Journal*, 13(3), 107-112.
- Baran, M. E., & Wu, F. F. (1989). Network reconfiguration in distribution systems for loss reduction and load balancing. *IEEE Transactions on Power Delivery*, 4(2), 1401-1407.
- Besanko, D., D'Souza, J., & Thiagarajan, S. R. (2001). The effect of wholesale market deregulation on shareholder wealth in the electric power industry. *Journal of Law and Economics*, 44(1), 65-88.
- Blaabjerg, F., Chen, Z., & Kjaer, S. B. (2004). Power electronics as efficient interface in dispersed power generation systems. *IEEE transactions on power electronics*, 19(5), 1184-1194.
- Brown, R. E., & Willis, H. L. (2006). The economics of aging infrastructure. *IEEE Power and Energy Magazine*, 4(3), 36-43.
- Brünger, A., Brooks, C. L., & Karplus, M. (1984). Stochastic boundary conditions for molecular dynamics simulations of ST2 water. *Chemical physics letters*, 105(5), 495-500.
- Dunn, B., Kamath, H., & Tarascon, J. M. (2011). Electrical energy storage for the grid: a battery of choices. *Science*, 334(6058), 928-935.
- Christie, R. D., Wollenberg, B. F., & Wangensteen, I. (2000). Transmission management in the deregulated environment. *Proceedings of the IEEE*, 88(2), 170-195.
- Cunha, M. D. C., & Sousa, J. (1999). Water distribution network design optimization: Simulated annealing approach. *Journal of Water Resources Planning and Management*, 125(4), 215-221.
- Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, 19(3), 291-312.

- Dandy, G. C., & Engelhardt, M. (2001). Optimal scheduling of water pipe replacement using genetic algorithms. *Journal of Water Resources Planning and Management*, 127(4), 214-223.
- Duncker, A. M., Simpson, A. R., & Wozniak, T. (2005). Staging of master planning of water distribution systems using genetic algorithm optimization. In *2005 World Water and Environmental Resources Congress, Anchorage, AK* (p. 48).
- Durin, B., & Margeta, J. (2014). Analysis of the possible use of solar photovoltaic energy in urban water supply systems. *Water*, 6(6), 1546-1561.
- Electronic Engineering Journal. (2015). Retrieved August 18, 2015, from <http://www.eejournal.com/archives/fresh-bytes/portland-to-generate-electricity-within-its-own-water-pipes>
- Electric Utility System Operation Manual, Professional Training Systems, INC, Portland. (1997).
- Eyer, J., & Corey, G. (2010). Energy storage for the electricity grid: Benefits and market potential assessment guide. *Sandia National Laboratories*, 69-73.
- Fetter, C. W. (2000). *Applied hydrogeology*. Prentice hall.
- Filion, Y. R., MacLean, H. L., & Karney, B. W. (2004). Life-cycle energy analysis of a water distribution system. *Journal of Infrastructure systems*.
- Frantzeskaki, N., & Loorbach, D. (2010). Towards governing infrasystem transitions: reinforcing lock-in or facilitating change?. *Technological Forecasting and Social Change*, 77(8), 1292-1301.
- Hadjerioua, B., Opsahl, E., Gordon, J., & Bishop, N. (2012). *New Small Hydropower Technology to be deployed in the United States*. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN.
- Hadjerioua, B., Wei, Y., & Kao, S. C. (2012). An assessment of energy potential at non-powered dams in the United States. *Prepared for the US Department of Energy, Wind and Water Power Program, Budget Activity Number ED, 19(07)*, 04.
- Hickey, H. E. (2008, October). Water Supply Systems and Evaluation Methods, Volume II: Water Supply Evaluation Methods [Scholarly project]. Retrieved October 12, 2016.
- House-Peters, L. A., & Chang, H. (2011). Urban water demand modeling: Review of concepts, methods, and organizing principles. *Water Resources Research*, 47(5).
- Housner, G. W. (1963). The dynamic behavior of water tanks. *Bulletin of the seismological society of America*, 53(2), 381-387.
- Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—characteristics and comparisons. *Renewable and Sustainable Energy Reviews*, 12(5), 1221-1250.
- Ibrahimov, M. (2013). Sustainable energy generation: what are the perspectives. *International Proceedings of Economics Development and Research*, 59, 149.
- Jacobs Engineering Technical Memorandum (2014). *Cleveland Utilities Distribution System Hydraulic Model Update and Calibration*. Knoxville, TN.
- Jebaraj, S., & Iniyar, S. (2006). A review of energy models. *Renewable and Sustainable Energy Reviews*, 10(4), 281-311.

- Johnson, B. W. (2006). *Out of Sight, Out of Mind?: A Study on the Costs and Benefits of Undergrounding Overhead Power Lines*. Edison Electric Institute.
- Kao, S. C., McManamay, R. A., Stewart, K. M., Samu, N. M., Hadjerioua, B., DeNeale, S. T., ... & Smith, B. T. (2014). *New stream-reach development: A comprehensive assessment of hydropower energy potential in the United States* (No. ORNL/TM-2013/514). Oak Ridge National Laboratory (ORNL).
- Khatri, K. B., & Vairavamoorthy, K. (2009, May). Water demand forecasting for the city of the future against the uncertainties and the global change pressures: case of Birmingham. In *EWRI/ASCE: 2009, Conference, Kansas, USA, (2009, May)* (p. 17-21).
- Kodysh, J. B., Omitaomu, O. A., Bhaduri, B. L., & Neish, B. S. (2013). Methodology for estimating solar potential on multiple building rooftops for photovoltaic systems. *Sustainable Cities and Society*, 8, 31-41.
- Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., ... & Li, S. (2015). Systems integration for global sustainability. *Science*, 347(6225), 1258832.
- Liu, Y. Q., & Xie, K. (2004). Analysis on blackout of interconnected North America power grid occurred on August 14, 2003 from the viewpoint of power system dispatching [J]. *Power System Technology*, 8, 10-15.
- Loucks, D. P., Van Beek, E., Stedinger, J. R., Dijkman, J. P., & Villars, M. T. (2005). *Water resources systems planning and management: An introduction to methods, models and applications*. Paris: UNESCO.
- Lopes, J. P., Hatziargyriou, N., Mutale, J., Djapic, P., & Jenkins, N. (2007). Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. *Electric power systems research*, 77(9), 1189-1203.
- Manolakos, D., Papadakis, G., Papantonis, D., & Kyritsis, S. (2004). A stand-alone photovoltaic power system for remote villages using pumped water energy storage. *Energy*, 29(1), 57-69.
- McDaniel, P., & McLaughlin, S. (2009). Security and privacy challenges in the smart grid. *IEEE Security and Privacy*, 7(3), 75-77.
- Morton, A., Nagle, N., Piburn, J., Stewart, R. N., & McManamay, R. (2017). A Hybrid Dasymmetric and Machine Learning Approach to High-Resolution Residential Electricity Consumption Modeling. In *Advances in Geocomputation* (pp. 47-58). Springer, Cham.
- Nilsson, K. A., Buchberger, S. G., & Clark, R. M. (2005). Simulating exposures to deliberate intrusions into water distribution systems. *Journal of Water Resources Planning and Management*, 131(3), 228-236.
- Omitaomu, O. A., Blevins, B. R., Jochem, W. C., Mays, G. T., Belles, R., Hadley, S. W., ... & Rose, A. N. (2012). Adapting a GIS-based multicriteria decision analysis approach for evaluating new power generating sites. *Applied Energy*, 96, 292-301.
- Omitaomu, O. A., Peck, J., and Smith, A. (2015, June). Modeling the Impacts of Solar Distributed Generation on U.S. Water Resources. Paper presented at the Proceedings of the ASME 2015 Power and Energy Conversion Conference: PowerEnergy 2015, San Diego CA, USA.
- Overbye, T. J., Cheng, X., & Sun, Y. (2004, January). A comparison of the AC and DC power flow models for LMP calculations. In *System Sciences, 2004. Proceedings of the 37th Annual Hawaii International Conference on* (p. 9-pp). IEEE.

- Pickard, W. F., Shen, A. Q., & Hansing, N. J. (2009). Parking the power: Strategies and physical limitations for bulk energy storage in supply–demand matching on a grid whose input power is provided by intermittent sources. *Renewable and Sustainable Energy Reviews*, 13(8), 1934-1945.
- Poustie, M. S., & Deletic, A. (2014). Modeling integrated urban water systems in developing countries: Case study of Port Vila, Vanuatu. *Ambio*, 43(8), 1093-1111.
- Qi, C., & Chang, N. B. (2011). System dynamics modeling for municipal water demand estimation in an urban region under uncertain economic impacts. *Journal of environmental management*, 92(6), 1628-1641.
- Rising Utility Construction Costs: Sources and Impacts. (2007). Retrieved August 24, 2016, from <http://www.edisonfoundation.net/iei/Documents/RisingUtilityConstructionCosts.pdf>
- Rogers, J., Averyt, K., Clemmer, S., Davis, M., Flores-Lopez, F., Frumhoff, P., ... & Yates, D. (2013). Water-smart power: Strengthening the US electricity system in a warming world. *Union of Concerned Scientists, Cambridge, MA*.
- Rossmann, L. A. (2000). Epanet 2 users manual, us environmental protection agency. *Water Supply and Water Resources Division, National Risk Management Research Laboratory, Cincinnati, OH*, 45268.
- Rotmans, J., & Van Asselt, M. B. (2000). Towards an integrated approach for sustainable city planning. *Journal of Multicriteria Decision Analysis*, 9(1-3), 110.
- Sattler, S., Macknick, J., Yates, D., Flores-Lopez, F., Lopez, A., & Rogers, J. (2012). Linking electricity and water models to assess electricity choices at water-relevant scales. *Environmental Research Letters*, 7(4), 045804.
- Savic, D. A., & Walters, G. A. (1997). Genetic algorithms for least-cost design of water distribution networks. *Journal of Water Resources Planning and Management*, 123(2), 67-77.
- Schleicher-Tappeser, R. (2012). How renewables will change electricity markets in the next five years. *Energy Policy*, 48, 64-75.
- Shuang, Q., Zhang, M., & Yuan, Y. (2014). Performance and reliability analysis of water distribution systems under cascading failures and the identification of crucial pipes. *PloS one*, 9(2), e88445.
- Singh, D., Rabaey, J. M., Pedram, M., Cathoor, F., Rajgopal, S., Sehgal, N., & Mozden, T. J. (1995). Power conscious CAD tools and methodologies: A perspective. *Proceedings of the IEEE*, 83(4), 570-594.
- Stokes, L. C. (2015). *Power politics: renewable energy policy change in US states* (Doctoral dissertation, Massachusetts Institute of Technology).
- Su, Y. C., Mays, L. W., Duan, N., & Lansey, K. E. (1987). Reliability-based optimization model for water distribution systems. *Journal of Hydraulic Engineering*, 113(12), 1539-1556.
- The Time is Right for Small Pumped Energy Storage, UK Hydropower Developer Says. (n.d.). Retrieved August 17, 2015, from <http://www.renewableenergyworld.com/articles/2013/09/the-time-is-right-for-small-pumped-storage-in-the-uk-developer-says.html>
- These Forces Changed the Energy Storage Game in 2014. (2014). Retrieved August 30, 2015, from <http://www.greenbiz.com/article/two-major-trends-changed-energy-storage-2014>
- Tennessee Valley Authority. (2015). The Price of Power. Retrieved August 23, 2016 from http://cemc.org/cemc_rate_change_video/articles/Time%20of%20use.pdf

- Van Zyl, J. E., Savic, D. A., & Walters, G. A. (2004). Operational optimization of water distribution systems using a hybrid genetic algorithm. *Journal of water resources planning and management*, 130(2), 160-170.
- U.S. Department of Energy (DOE) Global Energy Storage Database. (2015). Retrieved August 11, 2015 from <http://www.energystorageexchange.org>
- U.S. EPA. Water Utility Case Study of Real-Time Network Hydraulic and Water Quality Modeling Using EPANET-RTX Libraries. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/350, 2014.
- Westerling, Kevin. (2013). The 13 Biggest Challenges Facing The Water Industry. Retrieved October 2016 from <https://www.wateronline.com/doc/the-biggest-challenges-facing-the-water-industry-000>
- Willuweit, L., & O'Sullivan, J. J. (2013). A decision support tool for sustainable planning of urban water systems: Presenting the Dynamic Urban Water Simulation Model. *Water Research*, 47(20), 7206-7220.
- Wu, W., Simpson, A. R., & Maier, H. R. (2009). Accounting for greenhouse gas emissions in multiobjective genetic algorithm optimization of water distribution systems. *Journal of Water Resources Planning and Management*, 136(2), 146-155.
- Zarghami, M., & Akbariyeh, S. (2012). System dynamics modeling for complex urban water systems: Application to the city of Tabriz, Iran. *Resources, Conservation and Recycling*, 60, 99-106.
- Zhang, Q. F., Smith, B., & Zhang, W. (2012). Small hydropower cost reference model. *Oak Ridge National Laboratory. US Department Of Energy*.

Appendix 1

Table 5. Cleveland Reservoirs: Initial Boundary Conditions.

Reservoir Name	Total Head Post-Model Run	Net Inflow	Elevation
Waterville Springs	850	0	850
CU Filter Plant	999	-5,000	999
HUC WTP	999	-6,732	999
Savannah Meter	1	-28.75	1060.3
Eastside Tunnel Hill Meter	1,100	-0.037	1,100
Eastside Lead Mine Valley Road Meter	1,100	-1.79	1,100
Eastside Blue Springs Meter	1,100	0	1,100
Eastside McDonald Meter	1,100	-6.75	1,100
Eastside Old Alabama Meter	1,100	-24.77	1,100
Eastside South Lee Hwy (11&64) Meter	1,105	-1,286.95	1,105
Ocoee Meter	1,100	0	1,100
Eastside Pine Hill Road Meter	1,100	0	1,100

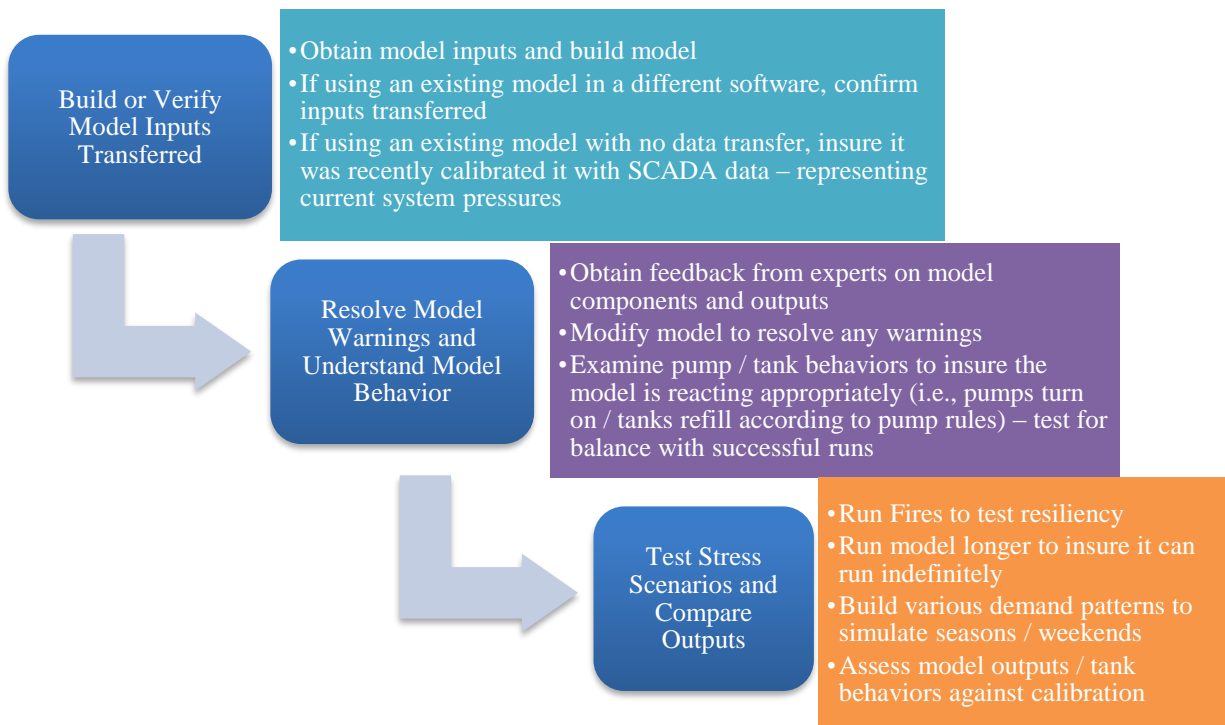


Figure 7. Develop and Verify a Water System Model: Visualization of a Transferable Method.

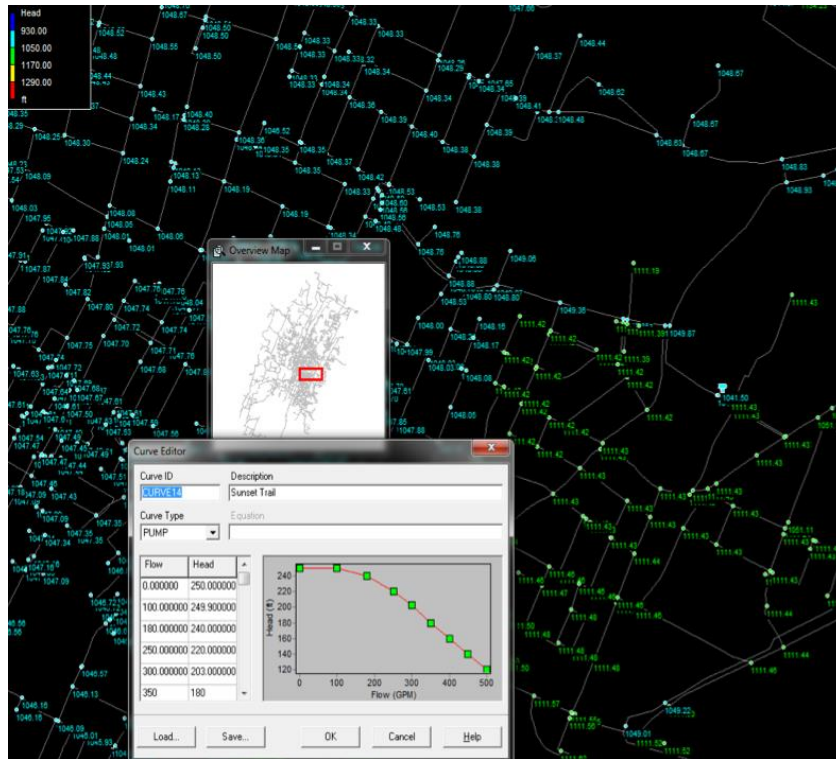


Figure 8. Example of a Model Error Correction: Sunset Trail Pump Curve Extension.

Table 6. Detailed Model Modifications Post-Software Transfer

Location and Description	Model Warning	Issue Resolve*
Benjamin Crest Pump: pump is below 5 nodes, a small subdivision	Open but exceeds maximum flow	Aggregated demand to node at the base of the loop, applied a zero pattern to nodes above the pump, disconnected pump and nodes above
Breckenridge Pump, pump is below 5 nodes, a small subdivision	Open but exceeds maximum flow	Aggregated demand to node at the base of the loop, applied a zero pattern to nodes above the pump, disconnected pump and nodes above
Oakwood Pump: pump is placed at more complicated system loop	Open but exceeds maximum flow	Aggregated demand to node at the base of the loop, applied a zero pattern to nodes above the pump, disconnected pump and nodes above.
White Oak Pump: pump is located along a main line, not a subdivision	Open but exceeds maximum flow	Changed roughness coefficient in pipe 61264 from 130 to 100 to increase friction and slow flow
Northstreet Pump: pump connects several lines, is important to the system	Pump curve not intersecting head curve	Bumped pump curve (to intersect head curve) by 10' (190 to 200). Added 10' to the pump curve
Sunset Trail Pump: pump services 1 node above but connects on either side, has an associated tank	Open but exceeds maximum flow, resulting in negative pressures	Pump curve goes to 300 GPM but flow goes to ~430 GPM (per report graph), so added to the pump curve
Node 51936: Fairlawn bladder tank is here	Negative Pressure	Elevation is 1,035', changed it to 1,000' to match surrounding elevations (~942'-1000')

*Conferred with EPANET experts Dr. Chris Cox and Dr. Bruce Robinson on these modifications.

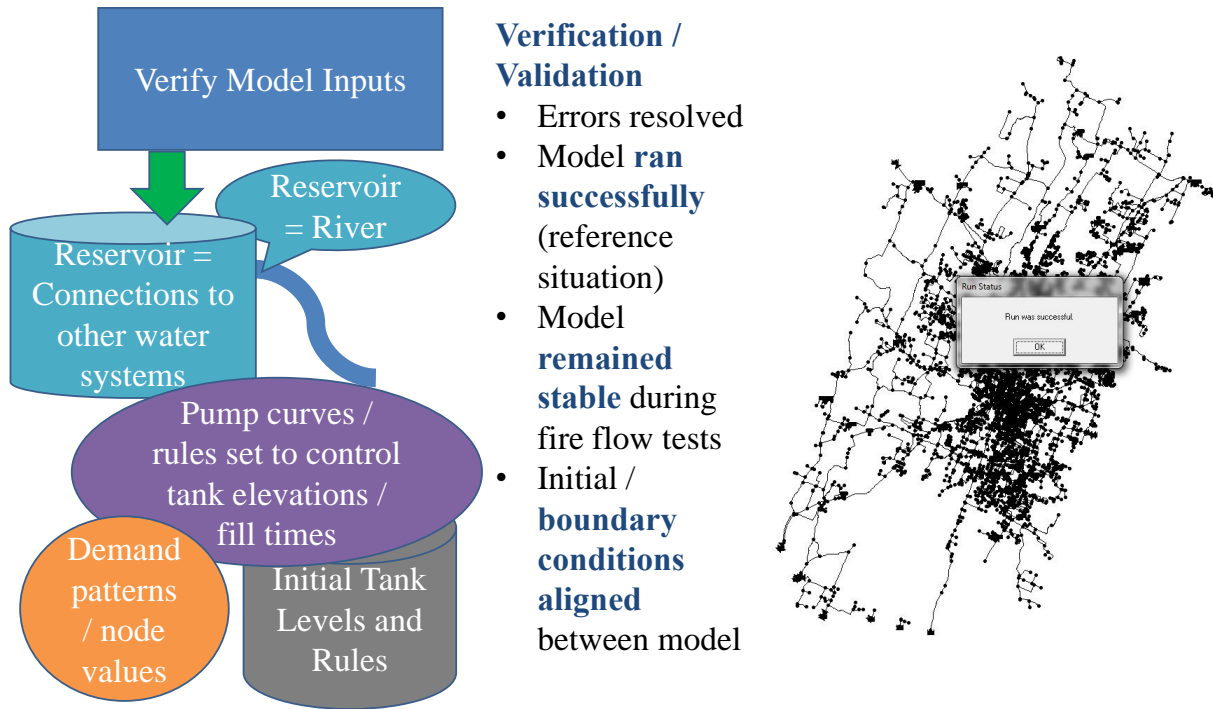


Figure 9. Verifying and Validation the CU Water Distribution System in EPANET.

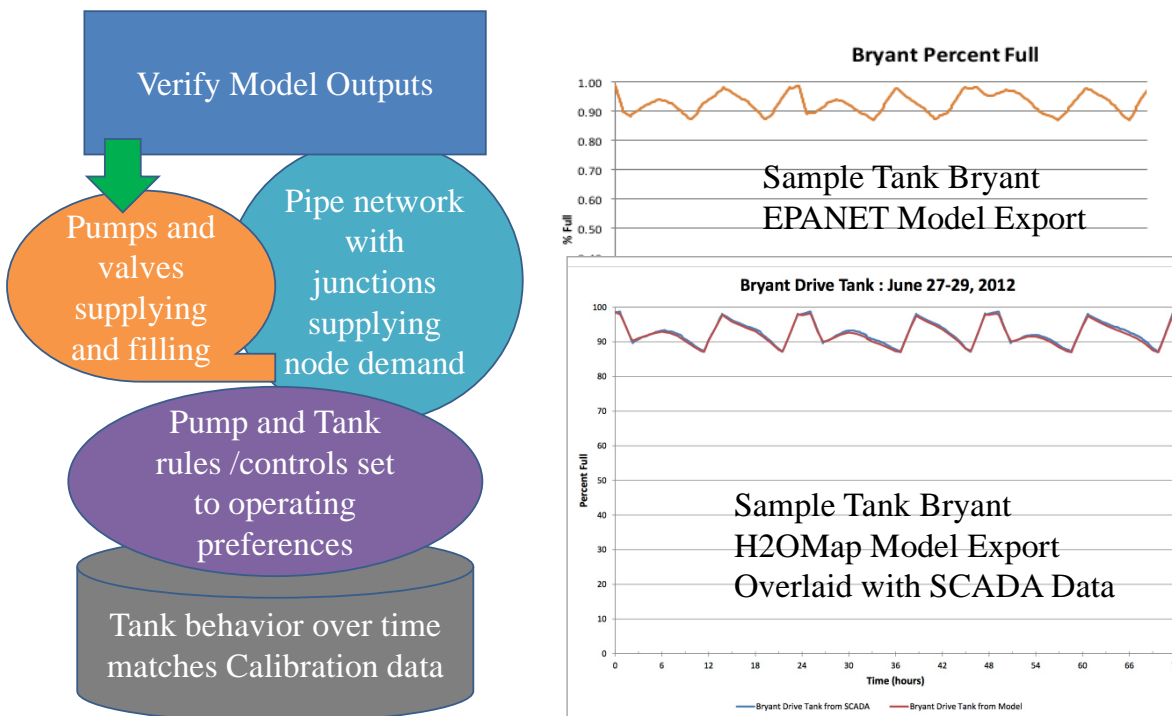


Figure 10. Confirming Matching Model Outputs: Bryant Drive Tank Behavior Example.

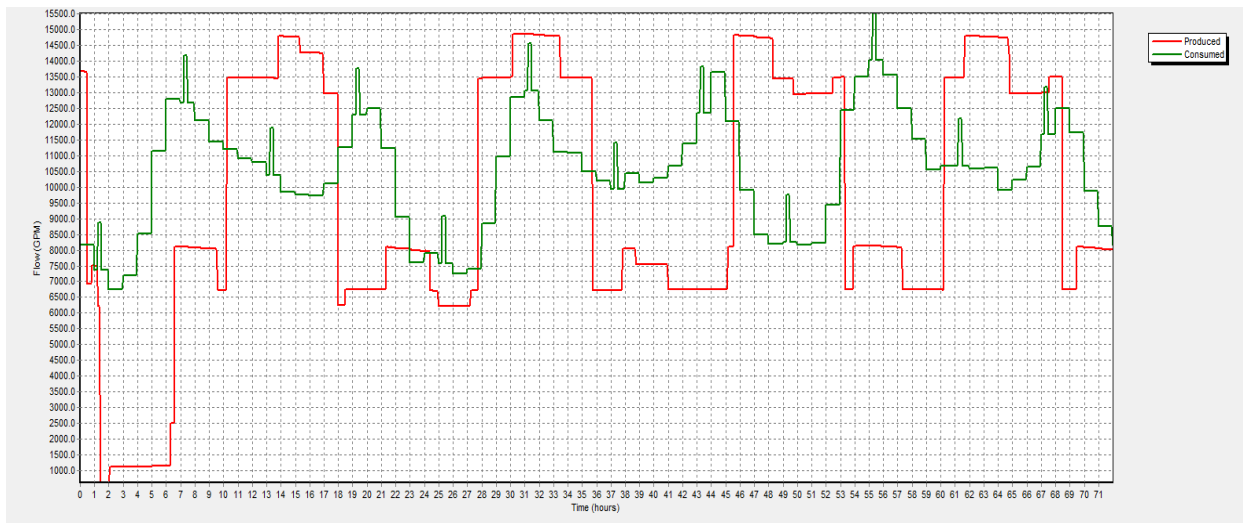
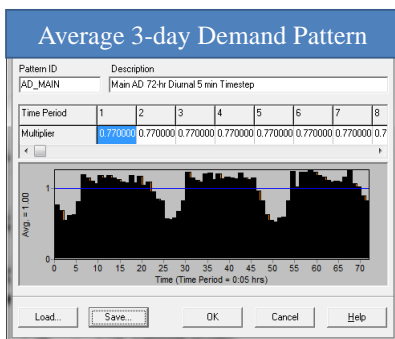
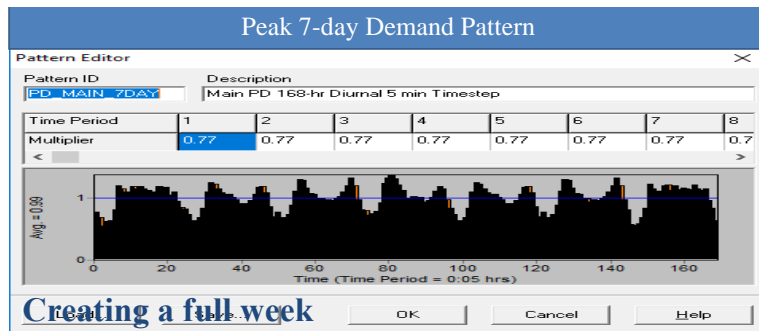
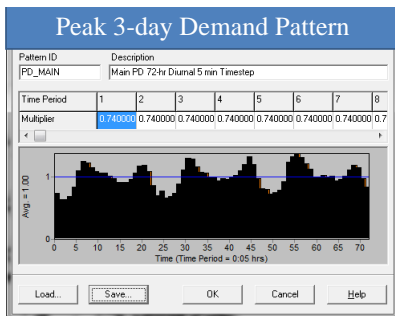


Figure 11. Confirming the Verified Model Accommodates Fire Flow.



Creating a full week

- Exported Peak Demand pattern into Excel (3 days / 72 hours)
- Added 4 more days
- Reloaded it as PD_MAIN
 - Rather than replacing manually at individual selected nodes, as was done for the Peak Demand Fire pattern
- Can extend this method and run model for months / years

Figure 12. Extending Patterns: Full Week with Weekend Pattern Example.

Table 7. Verified Model Controls

Location	Pumps / Tanks	Rules
HUC WTP	<p>Pumps: 4 on curve 9 (max Q – 3,675 GPM with 194’ head)</p> <p>Tanks: combined diameter = 200’, Initial Level = 15’, Max Level = 16’</p> <p>Demand: 0 at surrounding nodes, picks up at nodes that represent houses / users</p>	<p>Rule-based Controls: RULE LAUDERDALE_VALVE_CLOSED IF PIPE HUC_FLOW FLOW < 4000.0 AND TANK CANDIESCREEK LEVEL >= 24 AND SYSTEM CLOCKTIME > 1:00 AND SYSTEM CLOCKTIME < 4:00 THEN LINK LAUDERDALE_VALVE STATUS IS CLOSED RULE LAUDERDALE_VALVE_OPEN IF SYSTEM CLOCKTIME < 1:00 OR SYSTEM CLOCKTIME > 4:00 OR PIPE HUC_FLOW FLOW > 4000 THEN LINK LAUDERDALE_VALVE STATUS IS OPEN</p> <p>Simple Controls: LINK HUC_HSP_1 Open At Time 0 LINK HUC_HSP_2 Closed If Node ELDRIDGE Above 32 LINK HUC_HSP_2 Open If Node ELDRIDGE Below 30 LINK HUC_WTP_FCV Closed If Node HUC_CLEARWELLS Above 15 LINK HUC_WTP_FCV 6732.0 If Node HUC_CLEARWELLS Below 8 LINK HUC_HSP_1 Open At Time 0.0 LINK HUC_HSP_2 Closed If Node ELDRIDGE Above 32 LINK HUC_HSP_2 Open If Node ELDRIDGE Below 30 LINK HUC_WTP_FCV Closed If Node HUC_CLEARWELLS Above 15.5 LINK HUC_WTP_FCV 6732.0 If Node HUC_CLEARWELLS Below 8</p>
CU WTP	<p>Pumps: 7 on curve 6 (max Q – 8,100 GPM with 278’ head)</p> <p>Tanks: combined diameter = 158.5’, Initial Level = 12’, Max Level = 13.5’</p> <p>Demand: 0 at surrounding nodes</p>	<p>Rule-based Controls: RULE CU_VFD_120PSI_ON IF TANK ELDRIDGE LEVEL < 29 THEN PUMP CU_VFD_120PSI STATUS IS OPEN RULE CU_VFD_120PSI_OFF IF TANK ELDRIDGE LEVEL > 33 THEN PUMP CU_VFD_120PSI STATUS IS CLOSED RULE CU_VFD_105PSI_ON IF TANK ELDRIDGE LEVEL < 31 AND PUMP CU_VFD_120PSI STATUS IS CLOSED THEN PUMP CU_VFD_105PSI STATUS IS OPEN</p> <p>Simple Controls: LINK CFP_FCV Closed If Node CFP_CLEARWELL Above 13 LINK CFP_FCV 5600.0 If Node CFP_CLEARWELL Below 8</p>
Highway 11	Connection to non-CU system	<p>No associated pumps, McDonald is the nearest tank, with EUD rules. LINK EUD_CONTROL_VALVE Closed If Node MCDONALD Above 29 LINK EUD_CONTROL_VALVE Open If Node MCDONALD Below 22</p>

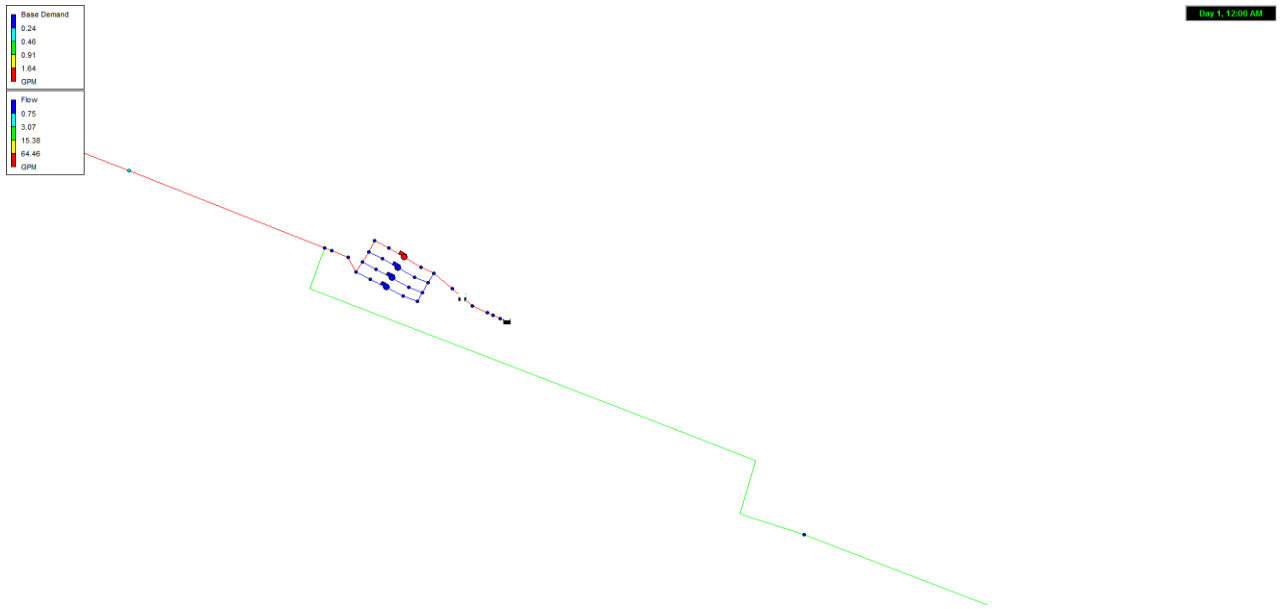


Figure 13. Hiawassee Utility Commission Water Treatment Plant (HUC WTP) Design.

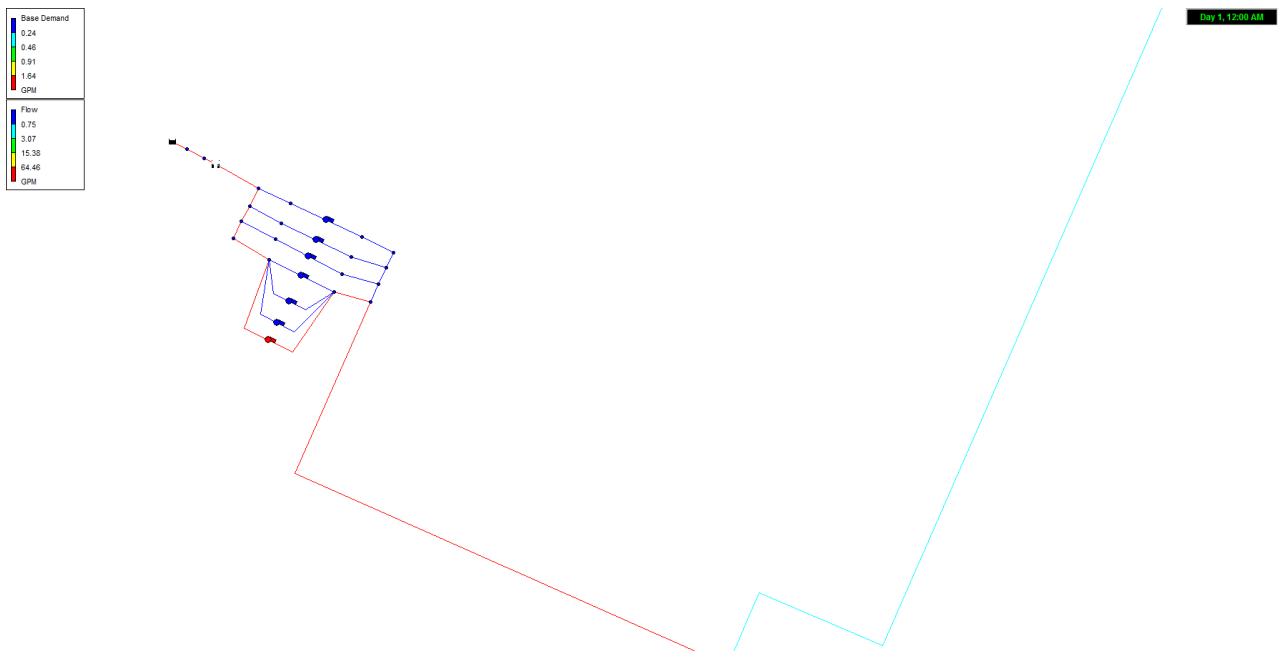


Figure 14. Cleveland Utility Commission Filter Plant (CU FP).

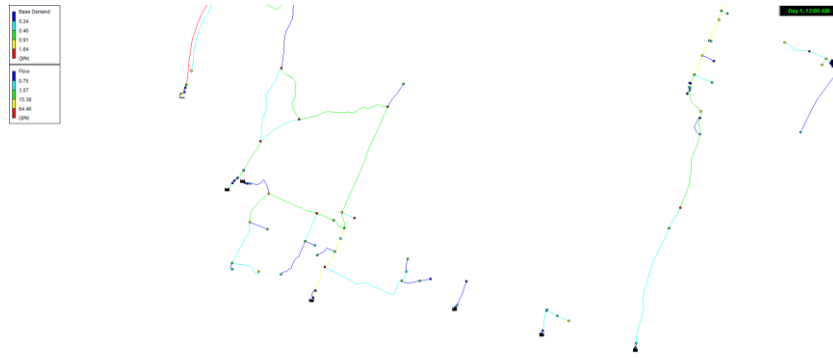


Figure 15. Eastside Utility District Meter Connections (Reservoirs in the Model).

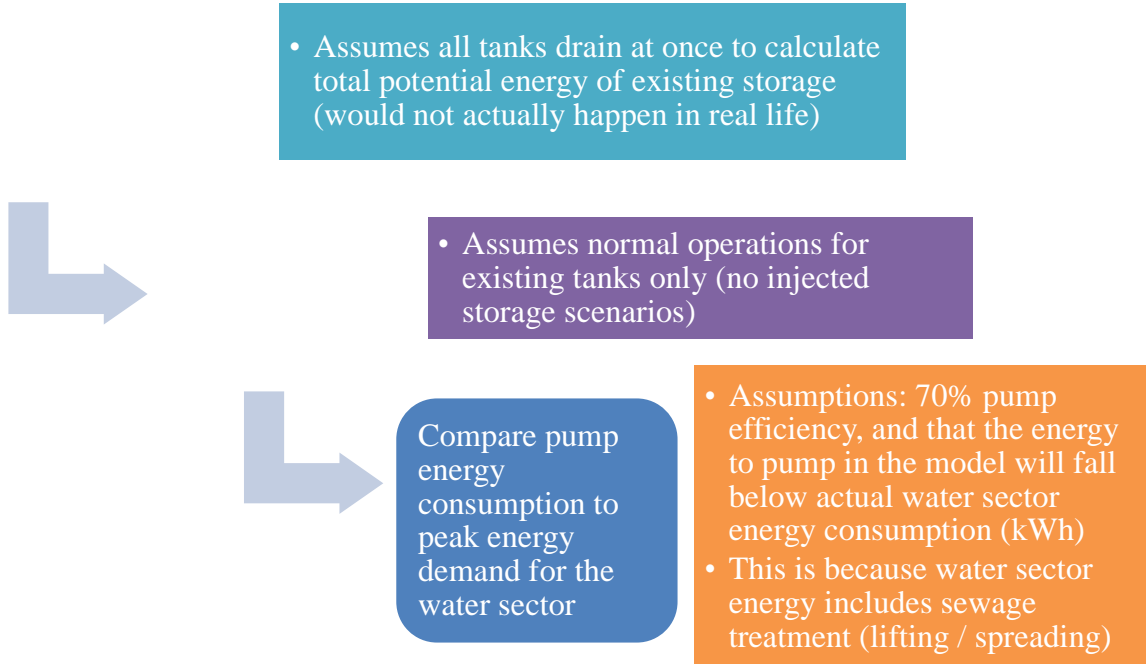


Figure 16. Comparing Energy Demand to Water Storage Methodology.

Table 8. Potential Energy Calculations by Tank, and kWh Required to Fill Them.

Tank Name	Elevation	Depth	Diameter	Volume	Gal to kg	Ft to M	Joules	kJ	KWh	KWh to Pump
Blythe Ferry	1,104	32	50	500,000	1,895,000	10	181,318,936	181,318.93	50	72
Bryant Drive	1,120	77	47	1,000,000	3,790,000	23	872,597,381	872,597.38	242	346
Candies Creek	1,022	30	75	1,000,000	3,790,000	9	343,712,708	343,712.71	95	136
Crown Colony	1,090	32	50	500,000	1,895,000	10	181,318,936	181,318.93	50	71
Eldridge	1,006	37	125	3,500,000	13,265,000	11	1,447,718,382	1,447,718.38	402	574
Johnson	1,051	64	36	500,000	1,895,000	19	359,804,764	359,804.76	99	142
McDonald	1,012	30	53	500,000	1,895,000	9	169,986,502	169,986.50	47	67
Sunset	1,000	43	115	3,300,000	12,507,000	13	1,589,373,801	1,589,373.80	441	630
Waterville	1,016	50	70	1,500,000	5,685,000	15	849,932,514	849,932.51	236	337
Weeks	1,011	32	127	3,000,000	11,370,000	10	1,070,914,967	1,070,914.97	297	424
CFP	820	14	159*	2,000,000	7,580,000	4	305,975,705	305,975.71	85	121
HUC	808	16	200*	3,750,000	14,212,500	5	679,946,011	679,946.01	189	269
Totals				21,050,000					2,237	3,190

**Equivalent diameter*

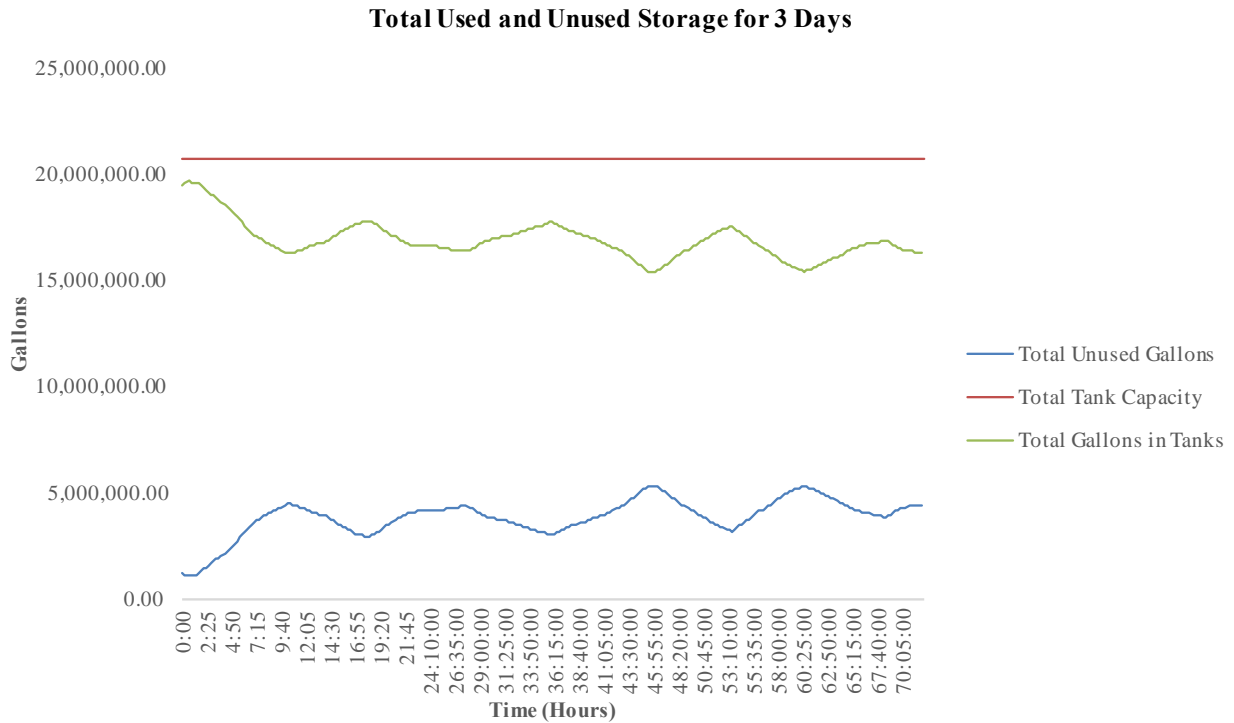


Figure 17. Comparing Energy Demand to Water Storage: Finding Unused Storage Gallons.

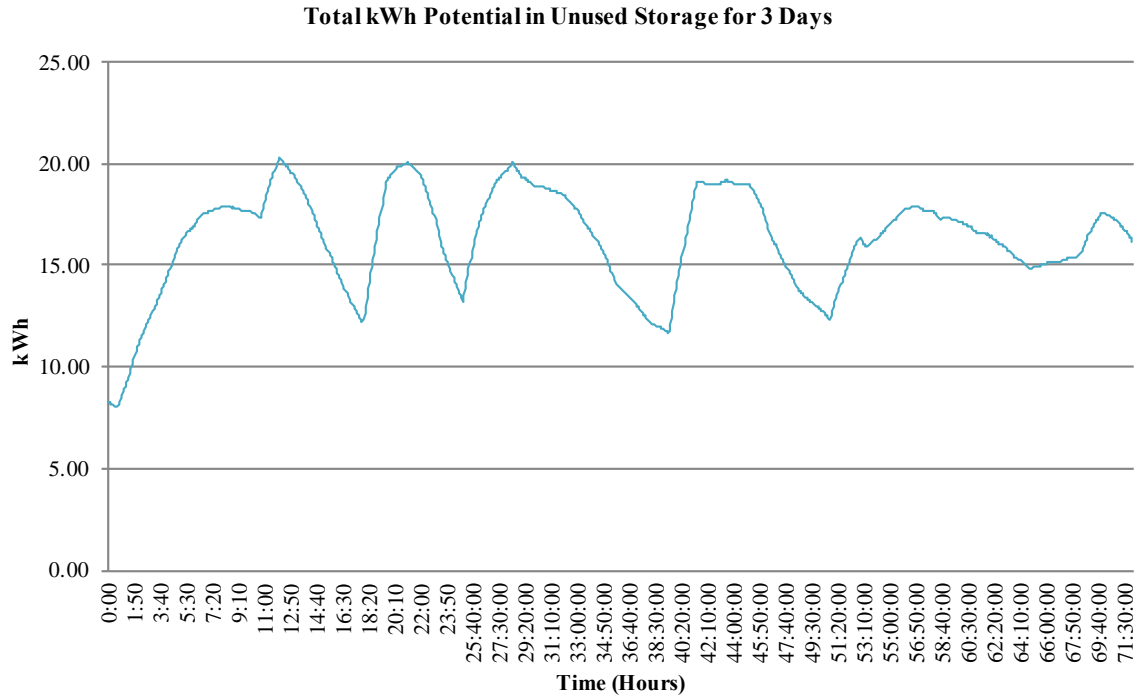


Figure 18. Comparing Energy Demand to Water Storage: Finding Unused Storage kWh.

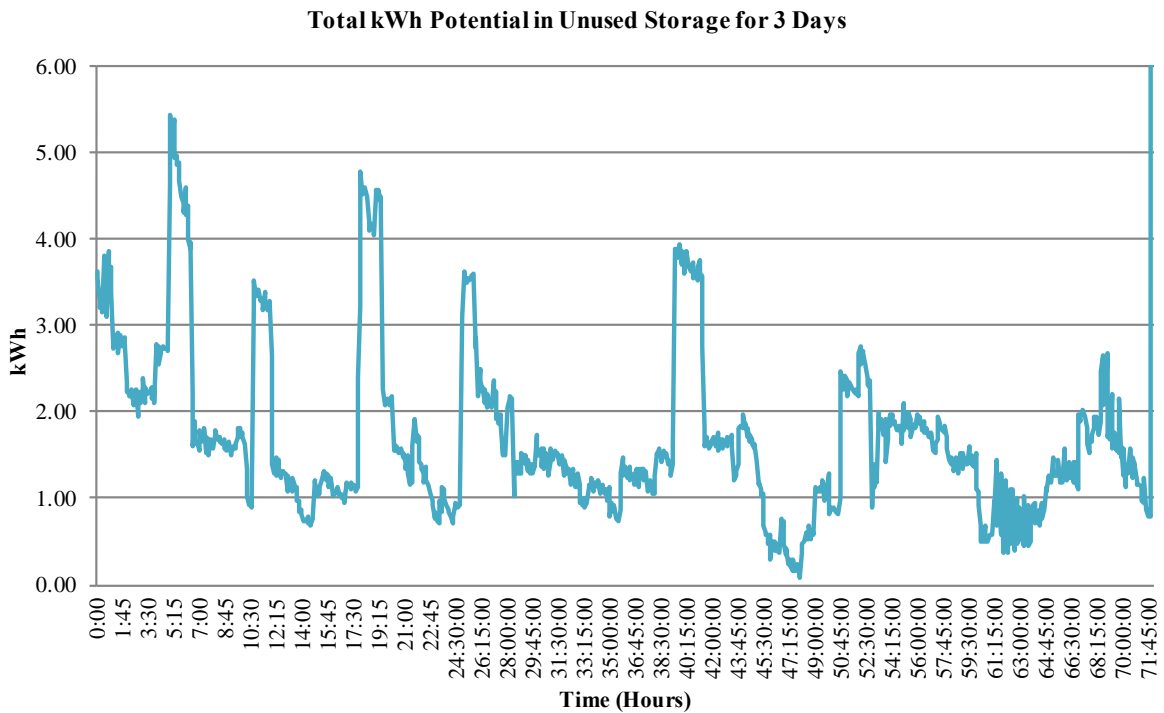


Figure 19. Finding Energy Potential in Normal Drain Patterns.

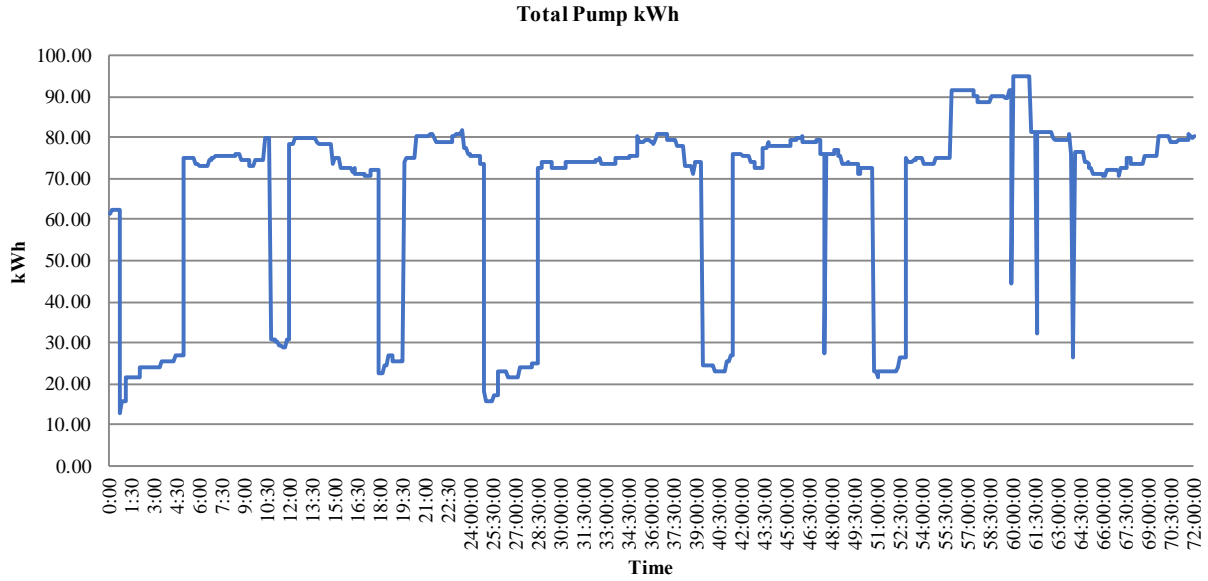


Figure 20. Finding Energy Consumption of CU pumps.

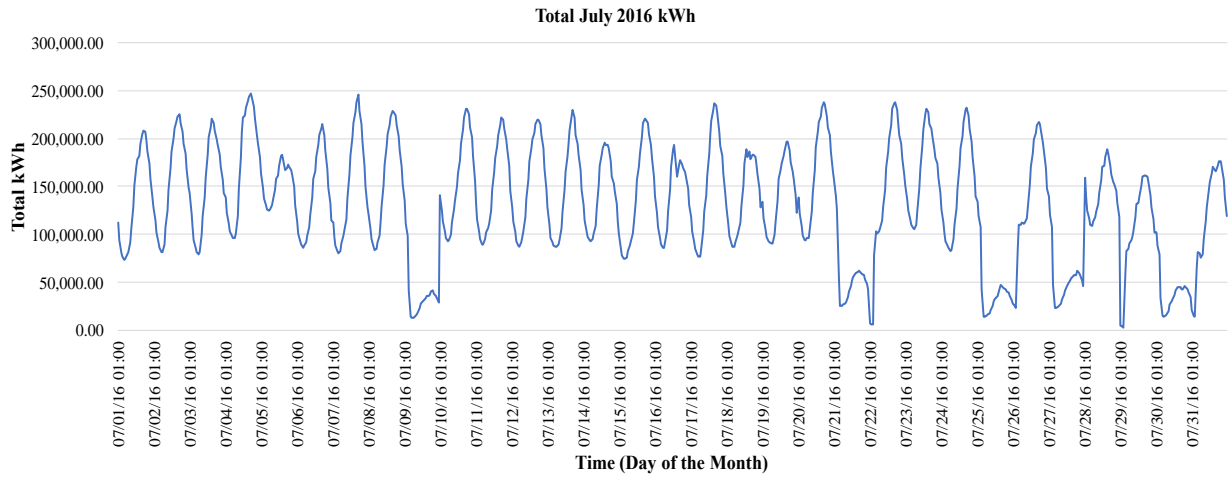


Figure 21. July CU Electricity Consumption, All Sectors.

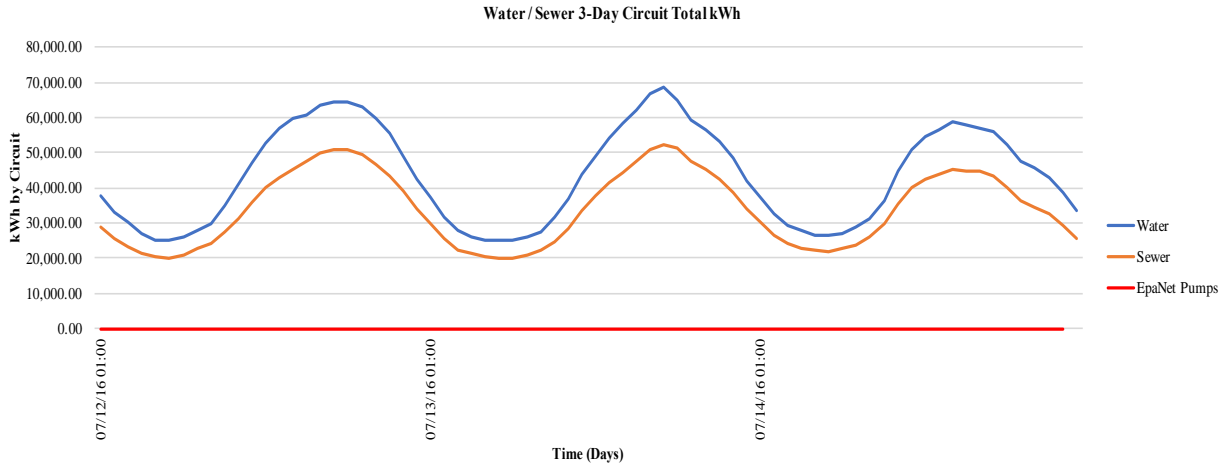


Figure 22. CU Water and Sewer Sectors and Pump Electricity Consumption Comparison.

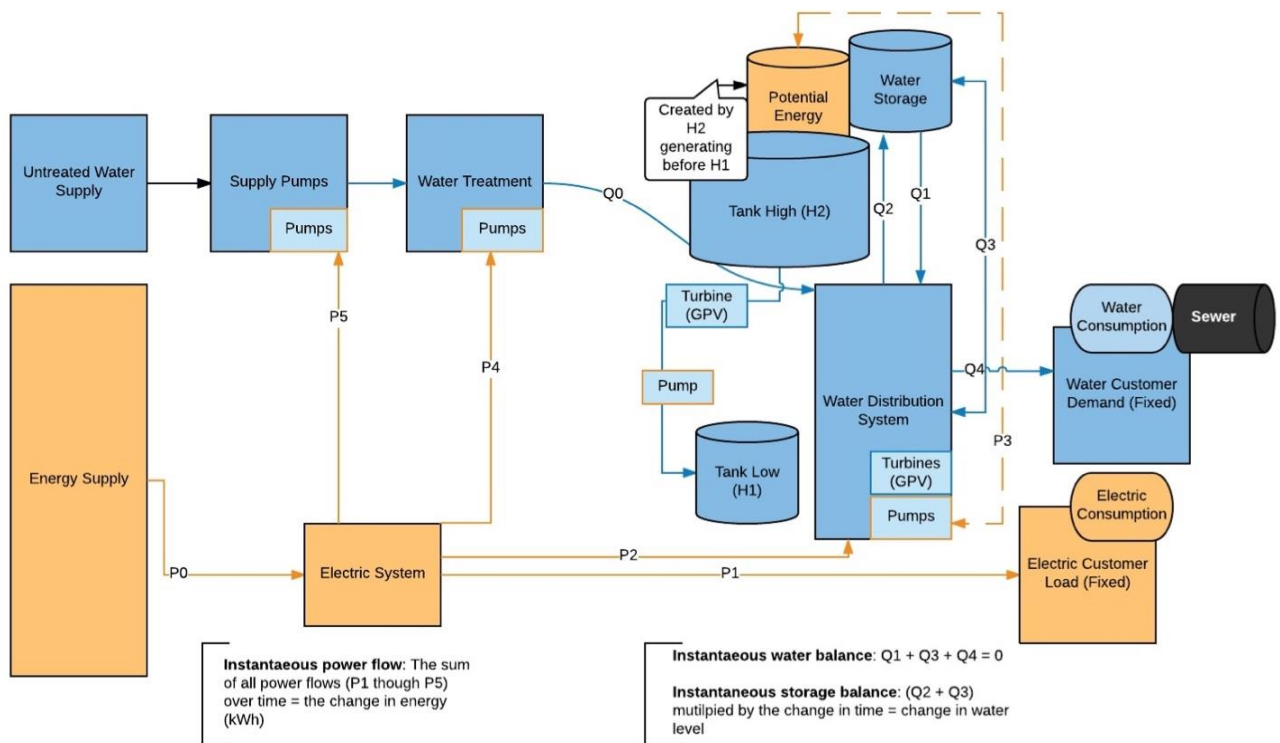


Figure 23. Water and Power Flows in an Urban Water System.

Table 9. Energy Required to Level and Shave CU Peak Electrical Demand over 3 Days.

Peak Hour	Day		
	July 12	July 13	July 14
13:00	175,968	164,485	182,811
14:00	189,683	181,602	189,798
15:00	198,620	194,512	195,916
16:00	205,827	208,591	193,759
17:00	215,578	223,465	193,008
18:00	219,913	230,375	189,690
19:00	220,148	222,078	176,216
20:00	214,878	204,110	160,560
21:00	203,775	194,076	153,549
Total Ave. kWh by Day	260,680	342,927	253,367
Total kWh to level 3 days of peak energy use	856,974	Total kWh to shave peak by 10%	85,697

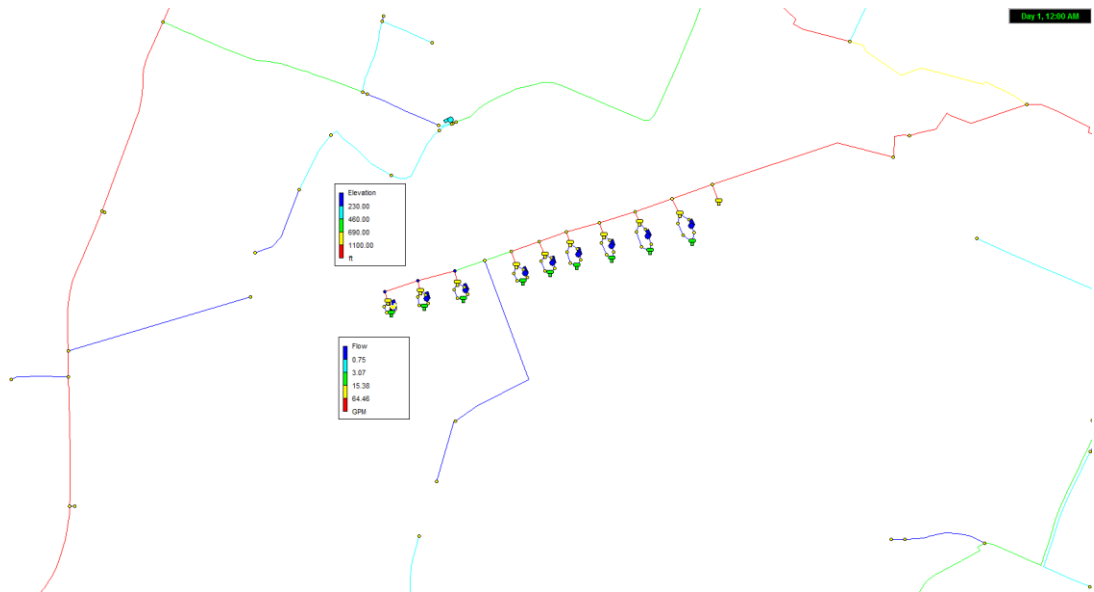


Figure 24. Scenario A1, Concentrated Storage in a Tank Farm, South Cleveland.

Table 10. Scenario A1 Concentrated Storage GPV and Pump Controls.

CU Model Scenario A1 – Concentrated Storage GPV and Pump Controls		
Tank Generating Loop Component	Setting	Model Run Time
LINK TANKFARM1_GPV	Open	At Time 13.00
LINK TANKFARM1_GPV	Closed	At Time 21.00
LINK TANKFARM1_GPV	Open	At Time 37.00
LINK TANKFARM1_GPV	Closed	At Time 45.00
LINK TANKFARM1_GPV	Open	At Time 61.00
LINK TANKFARM1_GPV	Closed	At Time 69.00
LINK TANKFARM1_PUMP	Open	At Time 21.00
LINK TANKFARM1_PUMP	Closed	At Time 37.00
LINK TANKFARM1_PUMP	Open	At Time 45.00
LINK TANKFARM1_PUMP	Closed	At Time 61.00

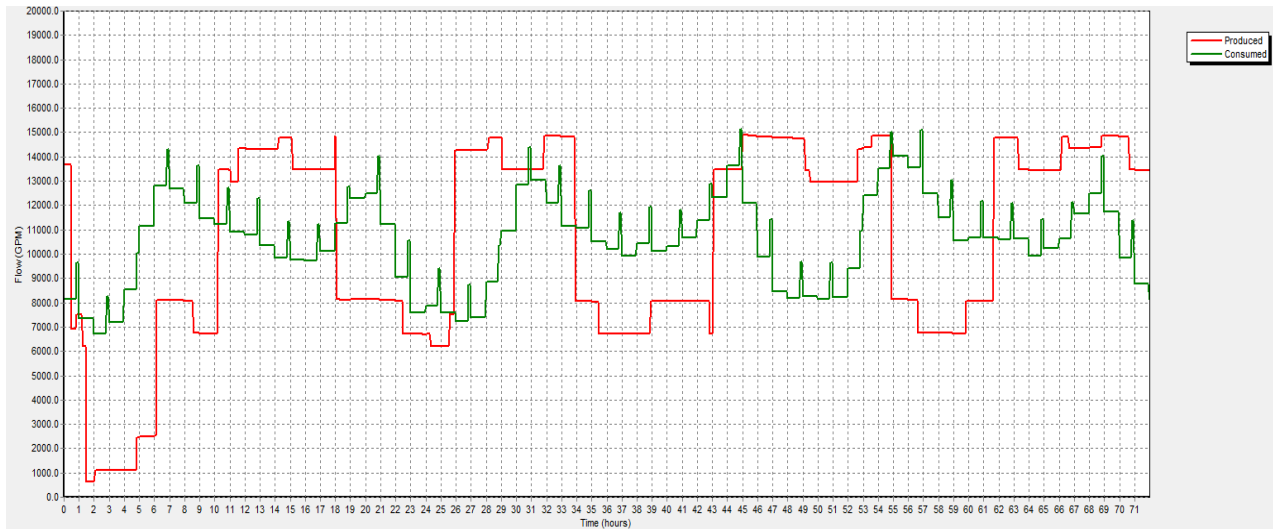


Figure 25. Scenario A1 Water System Balance with Fire Flow.

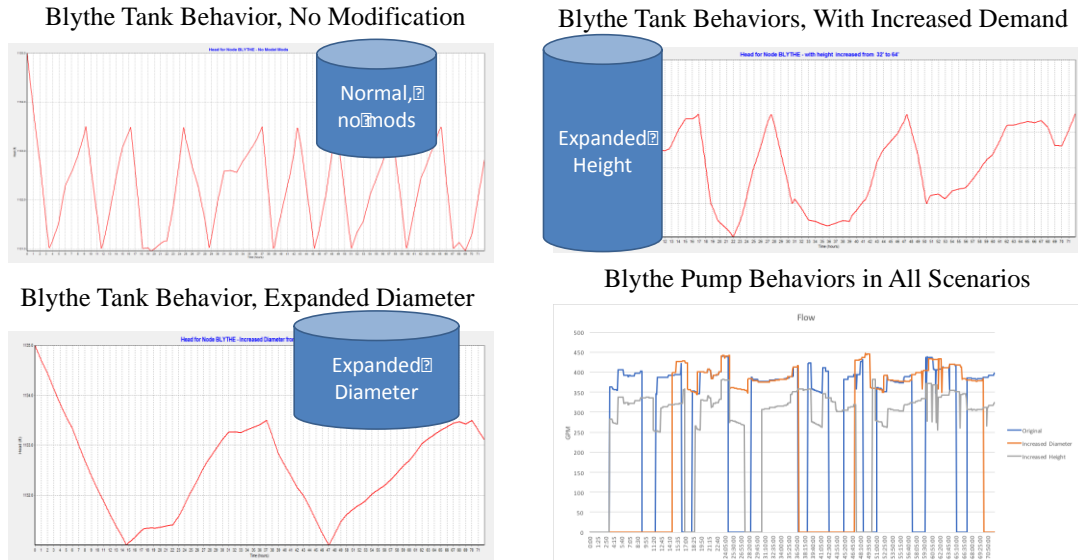


Figure 26. Blythe Water Tank and Pump Behavior Comparison: Normal and Expansions.

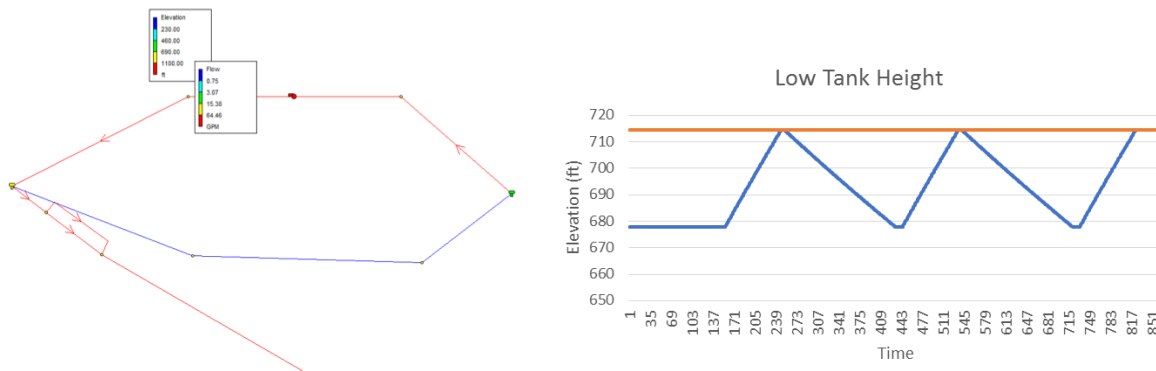


Figure 27. Scenario B1, Distributed Storage, Generating Loop and Lower Tank Behavior.

Table 11. Scenario B1 Distributed Storage GPV and Pump Controls.

CU Model Scenario A1 – Concentrated Storage GPV and Pump Controls		
Tank Generating Loop Component	Setting	Model Run Time
LINK BLYTHE_GPV	Open	At Time 13.00
LINK BLYTHE_GPV	Closed	At Time 21.00
LINK BLYTHE_GPV	Open	At Time 37.00
LINK BLYTHE_GPV	Closed	At Time 45.00
LINK BLYTHE_GPV	Open	At Time 61.00
LINK BLYTHE_GPV	Closed	At Time 69.00
LINK BLYTHE_LOWER_PUMP	Open	At Time 21.00
LINK BLYTHE_LOWER_PUMP	Closed	At Time 37.00
LINK BLYTHE_LOWER_PUMP	Open	At Time 45.00
LINK BLYTHE_LOWER_PUMP	Closed	At Time 61.00

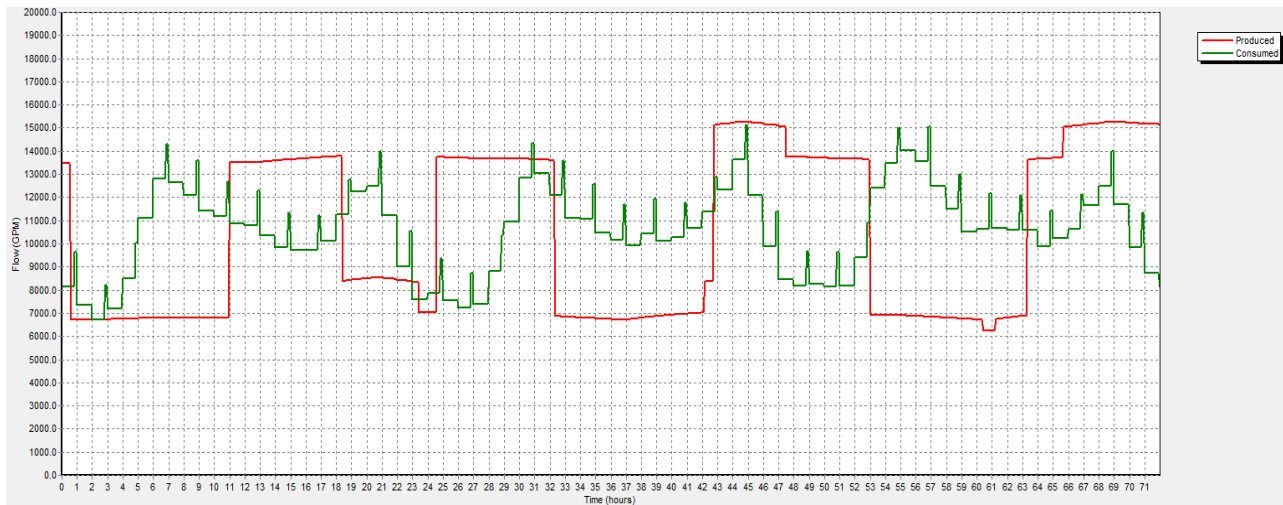
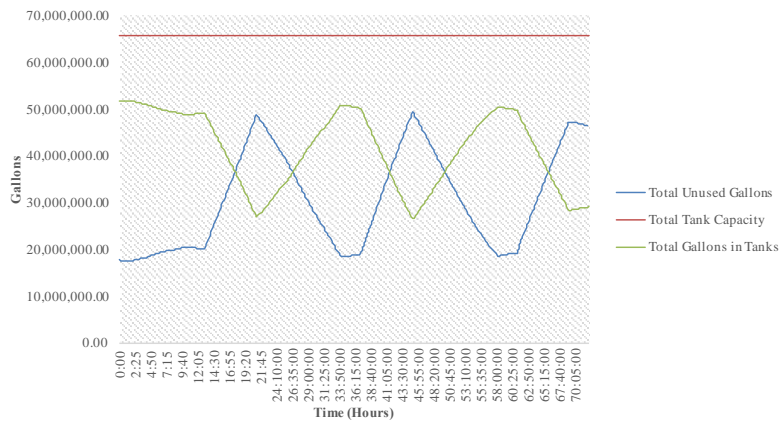


Figure 28. Scenario B1 Water System Balance with Fire Flow.

A1 - Total Used and Unused Storage for 3 Days



B1 - Total Used and Unused Storage for 3 Days

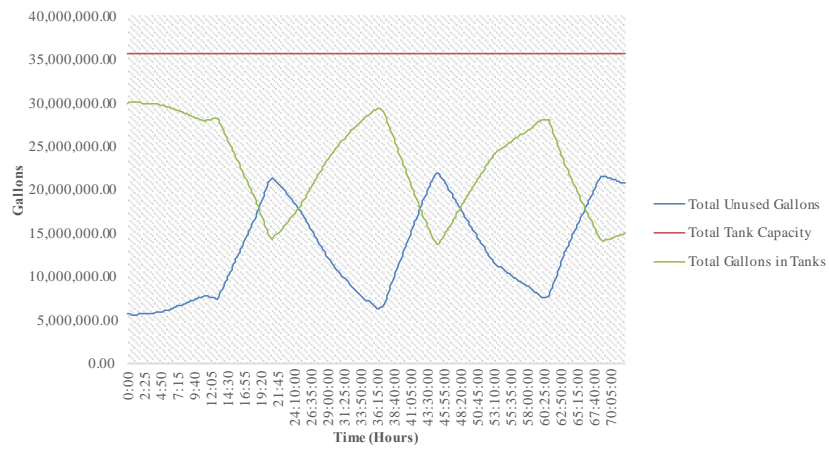


Figure 29. Scenario A1 and B1 Used and Unused Storage over 3 Days.

Table 12. Scenario A1 Energy Generation Comparison by Tank Name and kWh Sum.

Tank Name	Nom. Volume (gal.)	kWh
Tank Farm 1	3,500,000	9,988
Tank Farm 2	3,500,000	9,976
Tank Farm 3	3,500,000	9,932
Tank Farm 4	3,500,000	9,882
Tank Farm 5	3,500,000	9,898
Tank Farm 6	3,500,000	9,885
Tank Farm 7	3,500,000	9,875
Tank Farm 8	3,500,000	9,863
Tank Farm 9	3,500,000	9,876
Total kWh*		89,175

**10% of peak only, not 10% of whole system electrical load = 85,697 kWh*

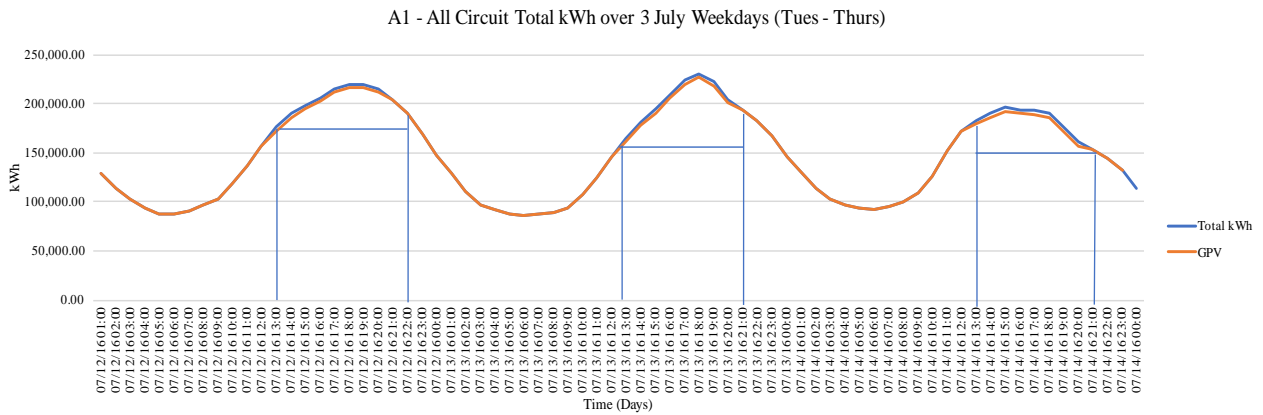


Figure 30. Scenario A1 GPV Peak Shaving Over 3 July Days.

Storage was not doubled at the HUC and CFP plants due to it already being a combined storage total in the model.

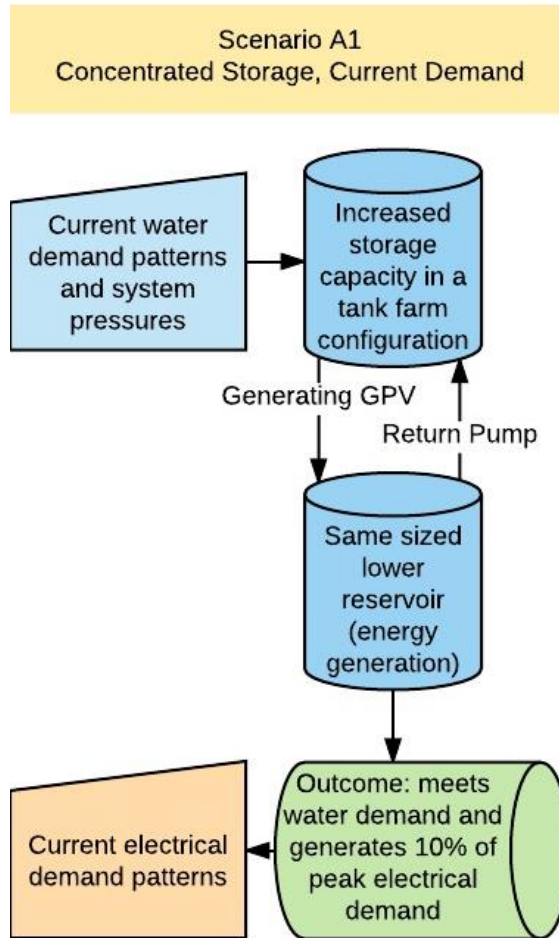


Figure 31. Scenario A1 Outcome Visualization.

Table 13. Scenario B1 Energy Generation Comparison by Tank Name and kWh Sum.

Tank Name	Nom. Volume (gal.)	kWh
Blythe Ferry	1,000,000	1,395
Crown Colony	1,000,000	1,402
Waterville	3,000,000	4,290
Eldridge	7,000,000	9,959
Bryant Drive	2,000,000	2,981
Johnson	1,000,000	1,442
Sunset	6,600,000	9,879
Weeks	6,000,000	8,892
McDonald	1,000,000	1,472
Candies Creek	2,000,000	2,992
Total kWh		44,704

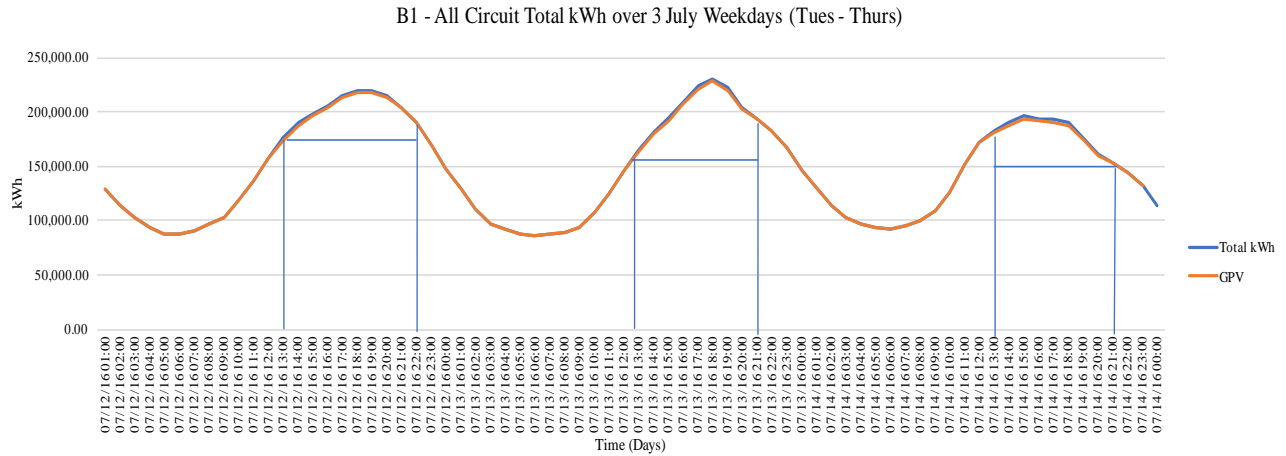


Figure 32. Scenario B1 GPV Peak Shaving Over 3 July Days.

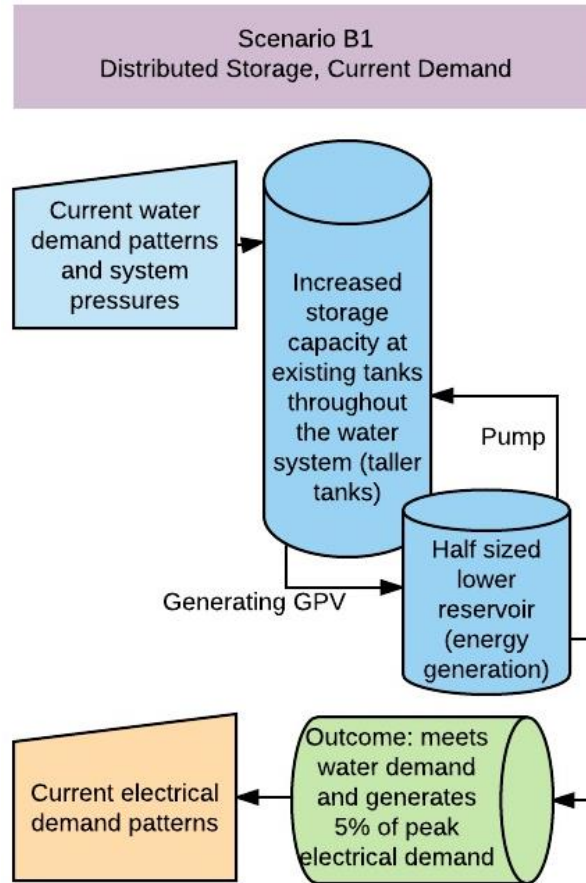


Figure 33. Scenario B1 Outcome Visualization.

CHAPTER 2
RESILIENCE IMPLICATIONS OF STORAGE IN URBAN WATER SYSTEMS

Abstract

This study explores urban water system resiliency within a community that has additional water storage added for energy generation, but which is faced with a doubling population. The tested hypothesis assumes that increased water storage capacity can also increase water system flexibility to meet new demand from the chronic stressor of persistent population growth. Additional water storage is modeled in concentrated and distributed configurations in a water distribution system model of Cleveland, Tennessee. New demand is added to test potential population growth patterns and ultimately, to double the water demand throughout the system. The ability of both scenarios to meet system requirements with double the water demand is examined, both with and without energy generating capabilities. Model outcomes show that the distributed water storage configuration makes a water system more resilient to population growth, and can meet demands from a doubled population. The concentrated storage configuration cannot meet doubled demands, due to the inability of the design to manage pressure and water demands across the space-and-time continuum. Both scenarios sacrifice energy generation potential, as the additional water storage is being used to meet demands and maintain pressures instead. This research concludes that the examination of an urban water system for resiliency, as well as for potential energy generation, should be done at the microgrid scale. The orders of magnitude between the amount of community-wide water storage that can be realistically added and the significantly larger community electrical demand, which would also double with twice the population, are too disparate to use as a viable local approach to water and energy system integration.

2.1 An Introduction to Water and Energy Resiliency in an Urban Context

Communities across the United States (U.S.) face a growing number of social, economic, and environmental challenges as populations expand. Variables to consider include aging infrastructure, increasing climate variability, economic volatility, and increasing economic disparity between community groups. Many communities lack the resources to prepare and respond effectively to these threats (Chaskin, 2008). Research surrounding sustainable and resilient urban infrastructure identifies the need to design and manage engineering systems considering environmental, societal, and economic conditions (Ouyang et al., 2012). A key engineering challenge is to develop tools that can measure and enhance the sustainability of urban infrastructure over time (Sahely et al., 2005).

In recent years, many framework and indicator sets have been developed (Cutter et al., 2008). These tools attempt to resolve complex issues, with many variables, into viable ways to assess the sustainability and resilience of urban infrastructure systems (Dasgupta & Tam, 2005). Frameworks focus on interactions

and feedback loops between aging infrastructure and surrounding environmental, economic, and social-system conditions (Baird, 2010). Ultimately, frameworks resolve into sets of sustainability criteria and indicators for the built environment (Francis & Bekera, 2014). While cities are systems of systems (Rinaldi et al., 2001), energy and water systems are of particular interest, because social and economic structures are so critically dependent upon them (Younos et al., 2009). Additionally, the interactions of these two systems with other urban structures, like transportation, allow communities to function and thrive with uninterrupted delivery of services (Lee et al., 2007).

Integrating water and energy systems can work to support community resilience. Strategic integration can strengthen both systems, so that each can deliver more reliable and affordable services for local governments, businesses, and households (Wilkinson, 2007). City administrations are seeking ways to meet increasing demands for water and energy from growing populations, while grappling with acute and chronic variables: flooding from extreme rainfall, drought, and rising sea levels in coastal communities, for instance (*Water Resilience for Cities*, 2015). Systems integration is becoming increasingly attractive, in the form of microgrids and other distributed infrastructure that can insulate a city from extreme resource disruption (Wang & Wang, 2015).

Before narrowing focus to how increased water storage in an urban water system can potentially strengthen the resiliency of a city's water and energy systems, it is important to discuss the term "resiliency" in terms of infrastructure (O'Rourke, 2007). This is because it is an emerging field of practice, and thus the term still has a variety of meanings in various contexts (Masten, 2001; Comfort, et al., 2010). This research explores resiliency as it relates to water and electrical systems in an "emerging" city (Smith et al., 2011), a term that is also discussed in the following sections.

Defining Resilience

The National Infrastructure Advisory Council's report on Critical Infrastructure (2009) states: "Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event." According to this definition, infrastructure resilience is about delivering services regardless of disruptive events. This understanding of resilience is common in the water and energy sectors. However, these systems are more than their engineered parts, involving complex interactions between human, technological, and environmental components (Knoeri & Russell, 2014).

Resilience is often discussed in terms of acute risk and reliability, and resiliency to chronic stressors is still emerging from concept into operation in urban water systems (Haimes, 2009). Water managers consider it practically as the ability to bounce back from a stressor, or how quickly system recovery can be achieved after a disruption. Some address resilience through the acute lens of manmade or natural disasters: terrorism, fire, wind, and water storms, or isolated geological events, for instance. Others view resiliency only in terms of the magnitude of risk and the probability of reliability. The older fields of risk management and emergency management focus on the ability to prevent acute failures from acute natural disasters and to maintain or stabilize an ideal system state. In contrast, resilience is emerging as a method, focusing on planning for uncontrollable chronic factors, and identifying ways to manage system adaptation to change over the long-term (Blackmore & Plant, 2008).

For researchers who study the behavior of these systems, the idea of resilience has very broad implications. According to the 2014 U.S. Department of Energy (DOE) report *Ensuring the Resiliency of Our Future Water and Energy Systems* (U.S. DOE, 2014), urban resilience is “the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience.” For the purposes of this research, this definition best defines resilience at the local level. Improved water and energy system resilience means that a community is prepared to respond to and minimize chronic disruptions, like fluctuation in population or climate variability. It does not tend to focus on disasters or attempt to neutralize all acute risk to infrastructure (Novotny et al., 2010). Local resilience focuses on vulnerability and capacity to cope in the face of chronic and significant disruptors, because those are the elements of risk a community can best control (Magis, 2010).

Resilient Water and Energy Systems

Energy and water systems are typically discussed in terms of reliability (Bao & Mays, 1990; Rausand & Arnljot, 2004). The target through that lens is usually uninterrupted and/or perfect operation. Resiliency is the newer lens through which the ability of local water and energy infrastructure systems to recover over time from certain types of failure is examined. The goal is not perfect operation, but instead, maintaining functionality from the customer’s perspective (Handmer et al., 1999). Operations may in fact be somewhat compromised, but the customer is unaware, and delivered services minimize inconveniences (Fiksel, 2006). Because resilience can mean a variety of things to practitioners from different fields, Table 14 distills this literature. All figures and tables referenced in this Introduction are placed in in Appendix 2, in the order they are mentioned in this text

Resilient Water Systems. Urban water systems require the measureable capacity to respond to and recover from significant threats and multiple changes, with minimum damage to public safety and health, the economy, and the environment (Milman & Short, 2008). The urban water system faces challenges arising from densely populated areas, such as high use demands and pollution from point and nonpoint sources (Falkenmark & Widstrand, 1992). Increasingly, they need to be designed not only for safe provision of services during emergencies, but also for resilience to threats that emerge over time (such as from population growth, climate changes, or lack of system preventative maintenance), which can lead to system lapses or failure if not proactively addressed (Cunningham et al., 2001).

Resilience can be built into existing water systems by implementing a range of strategies, like embedding redundancy and flexibility in the designs, or rehabilitation to increase the ability to maintain service levels during times of chronic system stress (Tidball & Krasny, 2007). *Water Resilience for Cities*, a 2015 policy white paper from Arup Consulting, recommends that city administrations consider a combination of increasing raw water storage capacity, combating salination (in coastal areas), implementing demand management, and improving river basin management. The report asserts that cities will increasingly face the challenge of how to store water during times of plenty, so that sufficient water resources are available in times of need. This additional storage capacity could be used for energy generation when the stored water isn't required for basic needs.

To design for resiliency, urban water system managers need to know how much water is needed now, how much will be needed in the future, and how to obtain and manage it when considering these demands (Rijke et al., 2013). They also need to understand water system influencing parameters, like source availability, available storage, the rate of demand growth, and water system pressure needs to be able to deliver water to all users (Vogel & Bolognese, 1995). Progressive water system planning models are often used to accommodate specific demands at system nodes to test growth demand over time and water system response capacity (Qi & Chang, 2011).

Resilience planning is very different from traditional water system planning and is not yet a standardized practice. It (1) examines projections, rather than historical trends, taking an integrated approach, rather than fragmented silos; (2) requires new types of institutional collaboration (watershed/basin players; multiple urban systems; multiple levels of government); and (3) requires stakeholders to agree on the desired level of physical resiliency. A resilience lens impacts every aspect of water management, putting

a premium on efficiency and demand management. Many water utilities do not have the capacity, in the form of awareness, expertise, capital, and adequate planning tools, to become resilient (Rijke et al., 2013).

Planning for resiliency challenges water utilities' current financial condition. It can increase operational and capital, financing, and insuring costs and require rate increases and new revenue sources. New utility business models are emerging because of these factors. However, some resiliency investments can avoid costs through reducing demand or by reducing the need for infrastructure. Resiliency is often linked to community sustainability efforts, such as reduced energy use and increased water and energy system integration (Tidball & Krasny, 2007). The following list summarizes the anticipated outcomes of increasing resiliency and adaptive water management (Milman & Short, 2008):

- Competing demands should result in stricter management of water supply
- Maintaining / improving water quality and habitat should result in better storage capabilities
- Understanding the impact of habitat destruction on species should result in better water quality
- Institutional constraints should be removed, resulting in less difficulty with jurisdictions
- Lack of data or access to data results in scientific and economic uncertainties
- Inadequate information makes it difficult to plan for practical applications
- Poor stakeholder communication results in rising rates, without the need for these cost increases being widely understood

This research does not consider modeling of, and potential implementation of, energy storage in urban water systems to be a “silver bullet” for either resiliency or energy generation. It is considered one tool in Energy storage within an urban water system is one tool in a portfolio of water system resiliency planning options. Portfolio planning consists of developing parallel strategies and assessing each option in terms of life-cycle costs, including energy footprint, and regulatory and environmental hurdles. Examples of measures that can be ramped up or down as they prove feasible and cost-effective include: (1) building more water storage; (2) conjunctive use of surface water and ground water, with ground water recharge; (3) desalination (if the community is coastal); (4) rainwater harvesting/stormwater harvesting; (5) use of recycled water including industrial process water and treated wastewater; (6) keeping water supply and management public or privatizing portions of it; (7) acquisition of water rights from agriculture; and (8) better matching of water use to water quality. Model results across studies and geographies can be inconsistent, but provide better planning information than nothing at all. The goal is to assess possible

future conditions that go beyond understanding current trends. These may be surprising but plausible conditions (Chang & Shinozuka, 2004).

Model scenarios are treated as equally likely to occur, rather than having assigned probabilities, such as what is done within the bounds of classic decision analysis. In resiliency modeling, implications and future needs of each scenario are identified and adaptation strategies are developed to meet the needs of each scenario. Ideal adaptation strategies have near-term actions that are common to all or most scenarios. “Signposts” can be established within resiliency decision frameworks, to monitor the development of the scenarios and determine when adaptation measures are no longer common to all or most scenarios (Chorn, 2010).

Resilient Energy Systems. Like urban water systems, the electric system in the U.S faces the challenge of changing conditions and projected needs (Skea et al., 2012). This includes addressing chronic stress challenges by integrating more energy from renewable sources, and enhancing efficiency from non-renewable and distributed energy processes (Manfren et al., 2011). Any advances to the electric grid must maintain a robust and resilient electricity delivery system (Carrasco et al., 2006).

For the energy system, resilience means providing affordable energy services, minimizing disruption or volatility of those services, and providing them without adversely impacting other systems (Molyneaux et al., 2012). While the first two pieces of this definition have long been the focus of efforts related to energy assurance, the final piece has not (Giampietro et al., 2006). Factors like climate variability and population growth indicate that the old understanding of energy assurance is no longer enough. A resilient energy system needs to go beyond infrastructure to reduce internal vulnerability, and to begin to include measures that increase community educational capacity to cope with external stresses (Afgan et al., 1998).

A changing climate, urbanization, and the reliance of economic systems on energy production and delivery pose unprecedented risks for urban energy systems. Investments should be made and policies should be implemented to further advance technologies that can improve resilience and sustainability. Enhancing resilience through better intelligence includes developing information technology tools to harnesses big data. This data should be used to advance system analytics, and result in better monitoring and, ultimately, automation. Physical and operational changes to systems are imperative for energy system redundancies, coupling, and decoupling capacity. Local government planning entities are

necessary to develop resilient solutions, and should pursue policies that incentivize investment, research, and innovation (Donovan & Work, 2015).

Energy storage can play a significant role in meeting these challenges by: (1) improving the operating capabilities of the grid; (2) lowering cost and ensuring high reliability; and (3) deferring or reducing infrastructure investments (Castillo & Gayme, 2014). While energy storage focuses on leveling the differences between demand and production, it can also be instrumental for emergency preparedness because of its ability to provide backup power, as well as grid stabilization services (Grid Energy Storage, 2013).

2.2 Understanding Water and Energy System Infrastructure Modeling and Growth

Literature that presents attempts to model water and energy systems together has been examined. Finding studies that do this in a comprehensive manner is difficult, in part because the dynamics and scales of water and energy systems are so vastly different. It is hard enough to model one system, without adding another system on top of it to search for viable interplays. The following discusses the state of the resiliency modeling field from the perspective of both systems. Examples of integrated modeling continue to be few, and are far more specialized (system optimization, for instance) than resiliency modeling currently is. It also discusses physical water and energy system growth over time in an urban setting.

Examples of Using Models to Understand Water and Energy System Resiliency

By modifying water and energy use projections, models can aid in answering questions around how using water system storage tanks for pumped hydropower could play a role in urban water system resiliency. Modifying consumption patterns can account for variables like population growth. This is because the state of a water system is often defined by how much water is available for storage and use, according to specified demands (Mitchell et al., 2001).

Water System Resiliency Models. Water distribution systems are modeled as a representation of networks of multiple nodes (such as reservoirs, storage tanks, and hydraulic junctions) interconnected by physical links (pipes or pumps, for instance). The connectivity patterns of this network affect its reliability, efficiency and robustness to failures (Yazdani et al., 2011).

Pressure zones within the water distribution system directly impact the transfer of water from one area to another. Water system states are primarily physical-component based. Urban water systems obey laws of

accumulation, conservation, and depletion: inflows increase the stock and outflows decrease it (Barnes et al., 2012). Non-physical, or perceived states can be included as well, especially at the local level. Safety and reliability of the water supply are examples of perceived states (Howe et al., 1994).

Urban water systems are increasingly modeled for resilience (Yazdani et al., 2011). One study uses a quantitative approach for assessing how resilient water supply systems can be when faced with disruptions. It examines recovery robustness and timeframes in relationship to disruption frequency, and simulates resilience in water system performance (supply level, and water travel by pipe or vehicle) and in supply scheduling to ascertain loss by scenario (Liu et al., 2013).

Another study focuses strictly on resilience to drought and flood scenarios (Barnes et al., 2012). Still another study investigates the performance of water distribution and urban drainage during simulated pipe failures. This study's results indicate that flexibility in system design ensures continued service during pipe-failure scenarios and degraded functionality. Results also indicate that a design strategy that incorporates upstream-distributed storage tanks minimizes the volume of flood waters and the mean duration of flooding events. The study concludes that considering potential failure costs, resilient design strategies prove to be a sound investment strategy (Mugume et al., 2015).

Models that can examine urban water system resilience require inputs and produce outputs with varying degrees of detail (Yazdani et al., 2011). They can aggregate data on many different scales, from citywide to neighborhood, and can be correlated with specific physical assets and parameters. At some point in the model, demand can be assumed, at the 6-inch line level, for instance. Most models do not calculate demand on a house-by-house basis (Loucks et al., 2005).

Energy System Resiliency Models. Likewise, energy systems are also increasingly being modeled for resilience. These models generate insights on the supply and demand of energy in the face of chronic and acute stressors. Models like these are increasingly relevant in the face of growing energy security concerns, the contemplation of climate policy, economic development pressures, and the challenges faced by evolving energy systems.

One study groups energy models into 4 categories: energy systems simulation, energy systems optimization, power systems and electricity markets, and qualitative or mixed-methods scenarios (Pfenninger et al., 2014). This study examines the challenges of these 4 analytic methods, and the efforts

being taken to address them: (1) understanding spatial changes over time; (2) balancing uncertainty; (3) addressing multiple energy system complexities; and (4) integrating social risks and opportunities in the form of market signals and human behaviors. The focus is ultimately on energy system models as useful information sources for policy design.

Developing viable methods to achieve energy sustainability is accomplished through incremental adoption of available and new technologies, and through development and testing of good practices. Testing technology and energy policies should work towards decreasing the energy sector's environmental impact, while still providing an adequate economic and social standard of energy service delivery. Technology and policy options should be evaluated for trade-offs. For a complex system of systems like a city, advanced multidisciplinary approaches are needed to accurately model real phenomena, while maintaining computational consistency, reliability, and efficiency (Bazmi & Zahedi, 2011).

Methodologies that integrate different computational models and techniques are necessary to enable collaborative energy-system research and integration of energy systems with other urban delivery systems. One study analyzes available models for distributed generation planning and design from the perspective of gathering their capabilities into an optimization framework. This framework is designed to support change analysis in urban energy systems. It builds on the main concept of a local energy management system, and adopts multiple criteria for providing energy services through distributed generation (Manfren et al., 2011).

How Water and Energy Infrastructure System Growth Occurs in Cities

Water and energy utilities make investments in water and energy system capacities to match over time, to keep pace and perhaps even stay ahead of increasing demands (Bettencourt et al., 2007). This means that as a city fills in its growth boundaries with new population, then water lines, pumps, and storage tanks are added to create new water-system pressure zones that will meet new water demand. The existing local power grid is also added to as growth occurs, and more electricity is either created or purchased and transmitted to meet additional energy demands. Cleveland is no exception to this development style, and is in fact progressive in this regard, focusing on current infrastructure improvements to accommodate future growth.

For water managers, infrastructure upgrades can insure access to more supply (Wong & Brown, 2008). For example, increasing pipe sizes from source to water treatment facilities allows a water utility to be able to treat and distribute more water. Additionally, strengthening connections between neighboring water systems becomes an important investment, to allow more water to be purchased or sold as water demand shifts over time. Water utility managers throughout the world bear increasing stresses around sourcing and supplying quality water to communities. In the face of water scarcity or concentrated water influx, there is a growing recognition of the importance of factors other than the costs of providing services. This recognition is forcing a reexamination of business-as-usual (BAU) operations (Hering et al., 2013).

For energy managers, electrical demand management and energy efficiency measures are a first line of defense to manage increasing demands (Gellings, 2009). The ability to access a variety of energy sources in addition to the existing and primary energy supply (either through purchase or generation of demand-side applications such as solar power) is also a valuable tool in the face of increasing electricity demands. Each of these become methods that can help avoid the need to budget for, permit, and construct new power plants (Asmus, 2010).

Realistically, both routine and innovative infrastructure upgrades within U.S. local governments are subject to economic signals, such as the pace of population growth, market pricing, and demand. They are also subject to the time constraints imposed by a democratic process. For a government, there is a public interface to be managed, in addition to project permitting and procuring contractors to do the work through a public bid processes. These things must happen over time before construction can occur. In short, the adjustment of physical infrastructure systems take capital in the form of time (approvals and permitting) and money (capital budgeting and contracting). Therefore, infrastructure upgrades, adjustments, and additions are not undertaken lightly. In certain political climates, there can be a reluctance to change BAU due to a fear of risking tax-payer dollars, potential failure, and perhaps, public criticism of local leadership and utility management.

Within models that can virtually manipulate infrastructure, changes can be designed and made within weeks or months, bypassing the realities of implementation, so that potential outcomes can be observed without significant investments of time and capital. Infrastructure system growth is fast-forwarded to test theories about future needs and possible system responses to stressors that also naturally occur at a much

slower pace. It can be an attractive place to advise from, away from the complexities of real life and the headaches of change-making on the ground (Brown, 1982).

However, both roles are necessary. To achieve more resilience within systems, research and models are needed to understand what is possible. To achieve flexible infrastructure systems, a practical approach must be taken that keeps the possible in mind, but does not sacrifice the celebration of incremental progress as it slowly manifests itself.

Research Motivation

Questions answered by this feasibility research include an exploration of how increased energy storage capacity can aid in water system resiliency to chronic stressors. The tested hypothesis assumes that the addition of storage capacity in urban water systems can make water systems more flexible and resilient when faced with chronic and uncontrollable external variables in modeled scenarios. To answer the motivating research questions and test the hypothesis, a city's water system is modeled with additional water storage in place, and its ability to meet system requirements with double the demand is examined, both with and without energy generating capabilities.

2.3 Cleveland as an Emerging City Case Study

Emerging cities face the same challenges and grow in much the same ways as other urban systems. The key driver of urban water systems dynamics in emerging cities is adaptation to rapid population growth (Bouwer, 2000). There is an ever-present balance to be struck between the rate of infrastructure growth and the rate of population growth (Guy, 1996).

Examining energy and water system integration in an emerging city makes sense, because expansion and evolution are constants in these urban environments. Emerging cities can often act more quickly than established cities. Decision making at the operational scale is usually in real time. Planners can often influence city evolution in shorter time frames than they can in larger cities. Because there is more flexibility for growth, there is also room for innovation in decision-making, in types of infrastructure is used, in management structures, and in ultimate system goals (Gandy, 2004).

Defining Emerging Cities

Now that the context of resiliency has been explored in terms of urban energy and water systems, it is important to understand what an emerging city is. This research focuses on urban water and energy

system resilience through increased water storage in the context of an emerging city. The term “emerging cities” has appeared in various urban planning publications for over 50 years (Greer, 1962), but it still does not have a strong public-facing definition. It can refer generically to various stages of capitalism in urban areas (Scott, 2011). It can refer to cities that are being planned and built even before occupants arrive (Wu, 2007). It can refer to cities that are struggling to move from third to first world (Elshehtawy, 2008). These are just a few examples.

For the purposes of this research, the term describes small but rapidly growing U.S. urban areas. Often, these emerging urban centers were once considered rural small towns, but are now part of a “megalopolis” – a word of Greek origin coined by Jean Gottman to describe the density and coalescence of cities along the U.S. eastern seaboard (Gottman, 1961). Simply described, an emerging city is one that is currently relatively low in population (under 100,000) but rapidly increasing in size and infrastructure (Bednarek et al., 2010).

Emerging cities are generally in the process of reinventing their futures. For instance, a city that has been small and historically industrial may be growing and transitioning into commercial and residential sectors, as manufacturing moves elsewhere and larger neighboring cities encroach (Bednarek et al., 2010). They can be facing the challenge of retaining identity as opposed to being defined as a “bedroom community”, housing residents who commute daily to work in a closely neighboring city (Salamon, 2003).

While larger cities are often early adopters of new infrastructure and technology, they can also be more constrained than emerging cities are by growth restrictions or regulations, existing rights of way, and aging, still-indebted infrastructure. Emerging cities may have skipped several iterations of infrastructure updates due to a previously waning tax base and subsequent lack of funds, so they are ripe for reinvestment as their population grows, and are able to evolve more nimbly by comparison.

Development History of Cleveland

Cleveland, TN has an industrial history, and is home to 13 Fortune 500 manufacturers (Fortune 500 Companies, 2016). It is an emerging city, currently relatively low in population, but rapidly increasing in size and infrastructure (Bednarek et al., 2010). Part of a “megalopolis” (the growing greater Atlanta, GA; Chattanooga, TN; and Knoxville, TN areas), Cleveland is ripe for reinvention. Examining how to use storage in urban water systems to generate energy can be of use to a city like Cleveland, which faces a

great deal of potential growth and associated changes in the coming decades – and will need an arsenal of smart urban growth tactics to continue to address these changes progressively over time.

Cleveland's Growth Projections and Planning Processes

By 2040, the State of Tennessee (TN) is projected to grow by 2 million people, becoming the 15th most inhabited state in the U.S. (Tennessee State Data Center, 2016). Unsurprisingly, this growth is bringing economic, social, and environmental opportunities and challenges. Accommodating future demand on water and electrical resources is being planned now in many TN communities. Bradley County, where Cleveland is located, is no exception.

Cleveland's 2010 census data notes a population of 41,285 (Gates, 2011). Cleveland's urban area is shown in Figure 34, a map created by the Cleveland Metropolitan Planning Organization (Cleveland Urban Area MPO Area Map, 2013). This region is expected to grow by 32,000 people by 2035, almost doubling over a 20-year period (City of Cleveland Comprehensive Plan, 2013). The MPO area has grown steadily over 60 years, and that growth is expected to continue. From a regional perspective, Bradley County has experienced higher than average growth rates.

Land Use Planning. There are many plans to govern Cleveland's development. Cleveland's *Central City Area Plan* is an area plan developed for the Central City Area (CCA). The CCA is in the southeastern portion of the City of Cleveland, including some adjacent portions of unincorporated Bradley County. This plan was drafted in conjunction with two other area plans: The *Northern Corridor Area Plan* and the *Southern Corridor Area Plan*; and three comprehensive plans: the *Bradley County Comprehensive Plan*, the *City of Cleveland Comprehensive Plan*, and the *City of Charleston Comprehensive Plan*. Known collectively as the *Joint Comprehensive Plans*, this group of documents adopted in 2011 outlines anticipated growth in Bradley County and coordinates among various jurisdictions.

Cleveland completed a long-range comprehensive planning process in 2013. The comprehensive planning is not on a regular update schedule, though the local MPO long range transportation plan is updated every 5 years. The most recent update began in 2016. Cleveland is currently working on many of the implementation activities outlined in their 2013 comprehensive plan, within the boundaries shown on the right-hand side of Figure 34. The left-hand side shows areas of projected growth.

Located in the center of Bradley County, the City of Cleveland is on a plateau. The City of Cleveland is less than 30 square miles in size and its urbanized area is roughly 50 square miles. This is about 1/6 of the total Bradley County land area. Bradley County designates almost half of its land for agricultural use (43%). Twenty-one percent of its land devoted to residential use. Three percent is allocated for commercial and industrial use (Table 15).

To support the steady increase of population in Bradley County, historically agricultural lands have been converted to higher density residential areas. Bradley County has retained a greater percentage of its farmland over the past century than surrounding counties, but the percentage has declined by more than 50% (Bradley County Metropolitan Planning Organization, 2013).

Cleveland's urbanized area contains a central business district (CBD), surrounded by professional office areas, a large private university (Lee), an older industrial area, and downtown neighborhoods. Urban development has traditionally occurred in dense concentric circles around the original downtown, with a more recent, spoke pattern of development occurring along valleys and ridge lines. Commercial development has occurred west of the downtown. Industrial development has been concentrated in south Cleveland. A substantial amount of infill development of two-to-four-unit residential structures has occurred in older neighborhoods. Single-family subdivision development has occurred more recently in west Cleveland, in in-fill areas of northeast Cleveland, and in Bradley County near Cleveland.

The location and intensity of growth in Cleveland is influenced by availability of land, utilities, the real estate market, and the proximity to major roads. The introduction of a Volkswagen plant in 2011 created demand for development along the southern Interstate 75 corridor. Based on MPO growth forecasts, the county population is expected to grow from an estimated 98,520 residents in 2010 to 131,212 by 2035, or a total increase of over 32,000 residents in 25 years. This is approximately the size of Cleveland's current population. In Bradley County, population growth is expected to be concentrated along the outer areas of the urbanized area, where water and sewer hookups are available (City of Cleveland, 2013).

Electric Utility Planning. The electrical load can be expected to grow with population increases, forcing the electrical system to also grow. With few exceptions, Cleveland Utilities (CU) provides electrical power services to most users within municipal boundaries of the City of Cleveland. Volunteer Energy Cooperative (VEC) provides electrical power service to most other parts of Bradley County, with the VEC service territory encompassing CU's service territory. Under current policy, whenever the City of

Cleveland proceeds with an annexation, CU negotiates with VEC to acquire and perhaps augment existing facilities required to provide power service to the annexed area. Few recently-annexed subdivisions are currently outside of the CU service area. When considering future urban growth boundaries, CU needs to be aware of plans for city annexations and areas slated for development.

Electrical power for both VEC and CU is generated and transmitted by the Tennessee Valley Authority (TVA). The primary CU system voltage is 7620/13200 volts. Voltage supplied to their customers is generally 120/240V 1-phase, and either 120/208V or 277/480V 3-phase. Customers are responsible for purchasing transformers needed to supply any secondary voltages not normally provided by CU. The CU system receives power via two delivery substations (161 Kilovolts (KV) / 69KV) and provides service to its roughly 31,000 customers via 14 distribution substations (69KV / 13KV), 53.5 miles of 69KV lines and 530 miles of 13KV lines (109 miles of which are underground).

The FY 2013 budget for the electrical division of CU was \$7.6 million. CU has a history of proactive long-range planning, which includes regular updates to a 10-year capital plan. As an on-demand system, CU electrical power distribution facilities can usually be provided whenever new needs arise. Rate and billing structures allow revenues to fund upgrades and expansions of the CU electric system (Bradley County 2035 Strategic Plan, 2013).

Water Utility Planning. Potable water service within Cleveland's urban growth boundary is also provided by CU. As confirmed in the modeling processes, current CU facilities are more than adequate to meet residential, commercial, and industrial demands. The available pressures and flows provide an exceptionally high level of fire protection for the city. CU obtains system water supply from 4 sources: (1) Its own Wastewater Filtration Plant (WWTP), with an average day processing of around 8 million gallons per day (MGD); (2) An average day 9.7 MGD allocation from the Hiwassee Utility Commission (HUC) Water Treatment Plant, which is operated under contract by CU; and (3) A CU-owned-and-operated 1.5 MGD Waterville Springs, and, when needed; (4) Purchased wholesale water via contract from Eastside Utilities (Bradley County 2035 Strategic Plan, 2013).

In considering population growth, the sanitary sewer system seems to be of more concern to CU than does the potable water system. CU provides sanitary sewer service to properties within the city and urban growth boundary. All wastewater collected in the CU system is treated at the 21.6 MGD capacity CU WWTP. CU has 2 main waste water pumping stations: one serving the Candies Creek drainage basin and

one serving the Chatata Creek drainage basin. The force mains from both pump stations are connected to the South Mouse Creek Interceptor. Nearby is a flow equalization facility, used to address peak flows and to improve the effectiveness of the interceptor system. In addition to these components, there are over 350 miles of collector and interceptor lines which serve approximately 19,000 user connections (Bradley County 2035 Strategic Plan, 2013).

A 2010 CU *Wastewater System Capacity Analysis* assesses capacities of both the WWTP and key system interceptor and pump station/force main components, based upon population growth projections made in the *BCC 2035 Joint Strategic Plan*. Projected demand scenario outcomes considered for the WWTP indicate its capacity was adequate for anticipated future growth, though some enhancements may be necessary. Because the sanitary sewer system can often act as a catalyst for development, limiting sanitary sewer services in rural areas can be a planning tool to defer or redirect population growth (Bradley County 2035 Strategic Plan, 2013).

Since CU is owned, operated, and maintained by the City of Cleveland, annexation policies affect both potable and sanitary sewer service. Connection to the sanitary sewer system is not required inside or outside of the city. Inside the city, the full sanitary sewer rate applies, regardless of whether a property is connected or not. If property owners outside of the city decide to connect to the sewer system, billing rates are roughly 150% of the equivalent inside-city rate (Bradley County 2035 Strategic Plan, 2013).

If the projected population growth occurs in South Cleveland, the Candies Creek Pumping Station may need to be upgraded and expanded. The South Mouse Creek Interceptor may also require enhancement to reduce overflow risk. Excessive inflows to the sewer system may present serious current and future capacity challenges. Considering these potential growth impacts on the water system, CU evaluates capacity, management, operations, and maintenance to quantify measures needed to address these concerns. The long-range capital improvement plan budgets for necessary upgrades (Bradley County 2035 Strategic Plan, 2013).

Coordinated land use, transportation, utility service delivery, and capital improvement planning prepares Bradley County for this coming growth. The time is right to examine water and energy system integration. For a small and growing urban area like Cleveland, population and demand growth impact the water system and its capacity to store water. Demand changes over time can be examined in tandem with local planning horizons. Baseline conditions can be considered as the present: now and over the next 5

years, for example. Long-term conditions can be considered as the future: 25 years from now, for example.

2.4 Testing the Impact of Increased Storage Capacity on System Resiliency

Building on the Cleveland, TN water system case study baseline model, this portion of the research defines 2 chronic stress scenarios, and measures resiliency in terms of depth of failure. It examines how the addition of water storage capacity in an urban water distribution system can potentially buffer impacts from chronic population growth. It focuses on translating increased water storage capacity into increased water system resiliency, for an integrated exploration of the possible benefits of additional storage in a water system to both the water and electrical system.

Designing Scenarios to Test System Resiliency Enhancements from Additional Storage

Scenarios are defined by the state of the existing water system, the magnitude and variability of water demand (manifested through population changes), and the magnitude and variability of energy demand. Baseline scenarios (A1 and B1) are designed around the current or near-term (5-year) water system actual and planned configurations, and current or near-term water demand projections. Stressed scenarios (A2 and B2) explore a future state in which water and energy demand growth has outstripped water or power system capacity, respectively. Figure 35 shows an overview of a transferable methodology for concentrated and distributed water storage scenarios in the context of current and future water and energy demands.

Some cities grow through new development within their growth boundaries and service territories. Other cities, already constrained by complete development within their growth boundaries and service territories will add demand through in-fill development. Examining population maps for cities to see what subdivisions, commercial zones, or industrial parks have been or are being added and where, and understanding how many structures are represented in these additions and the pace at which they are being added over time can be helpful on a city-by-city basis.

Population representing new demand should be added within a water model in ways that most closely represent development patterns. In any water model scenario of this sort, population growth and infrastructure additions should be based on historical trends and future projections, and assumptions that are made to fill knowledge gaps during planning cycles should be stated. The capacity for growth of Bradley County and Cleveland, TN are analyzed in the Bradley County 2035 Joint Strategic Plan. The current maximum zoning densities area applied to potential development areas. The analysis shows that

Bradley County does have capacity for the forecasted growth, but that the City of Cleveland does not have enough vacant land to accommodate the forecasted growth without redevelopment and infill development within its current boundary. Most of Bradley County's future development capacity is currently represented in unincorporated areas with agricultural uses. For this reason, an infill approach to adding demand is chosen for the A2 and B2 Cleveland scenarios.

When considering community water demand projections within a water model, demand can be added in 2 primary ways. First, if growth patterns are uncertain or sporadic within a community's growth boundaries, demand can be added uniformly across the system. Percent or multiplier increases can be added to demand patterns to test incremental growth scenarios across a utility's service territory. In this case, new water demand patterns can be designed to account for uniform system demand increases. Second, individual demand increases can be added in the areas most likely to grow. In this case, a water model network can be expanded with the addition of links and nodes (assigned specific water demands) in corresponding locations. Growing a water distribution model's network is not innovative, but is instead standard practice for city utility modelers. It simply takes time to manually increase the water model network.

While the water demand shape will be similar in either case (assuming the same amount of demand is added either in a distributed or concentrated manner), specific locations will influence water system variables, such as pumping requirements by elevation. Growth within a water pressure zone can be more easily managed within a model than can uniformly distributed demand increases, which will prompt pump curve, pipe, valve, and storage increases in the form of model run errors. While it also takes time to make these system upgrades within a water model, it does give a sense of what increased demand will require in terms of delivery, without having to design new and fictitious subdivisions, commercial zones, or industrial parks.

To determine if increased energy storage capacity aids in water system resiliency and can work to meet local water system sustainability goals, addition of energy storage capacity within an urban water system is tested with the variable of increased population growth in modeled scenarios. Steps in this research process include: (1) Determining a likely chronic stress scenario that the case study area could face, using population growth as the chronic stressor; (2) Measuring the ability of the water system to meet demand in associated failure scenarios, using the margin of water storage capacity above water demand; and (3) Comparing these scenario outcomes with and without energy generation. How well the model responds to

increases in population, with the addition of either concentrated or distributed increased storage, determines if adding water storage in various configurations enhances water system resiliency.

Scenario A2 Methods: Concentrated Storage, Future Demand

Scenario A2 is designed to examine the benefit of additional concentrated storage in the face of a doubled population's demands upon the water system. The design steps, assumptions, and model modifications used to create the single location model under future demand constraints are as follows:

1. Using the A1 Scenario model as a baseline for the A2 Scenario model, the primary change from scenario A1 to scenario A2 is to double the demand at each node within the model. As a refresher, concentrated storage is located in a tank farm in southeast Cleveland, close to a 69-kV electrical substation and where a future industrial park is proposed. Nine 3,500,000 gallon tanks are added, with General Purpose valves (GPVs), pumps, and same-sized storage tanks below them to allow for energy generation. Figure 36 shows the Cleveland Utilities (CU) electrical circuit map (green line), the electrical substation service zones (multi-colored areas), and the water pressure zones (blue areas). Recall that the baseline A1 Scenario model (normal demand with the tank farm generating electricity) can complete a run and meet stress testing fire flows, while maintaining pressure and meeting demand throughout the system. The additional tanks function as electricity generators, not to meet demand or to stabilize water system pressures. Figure 37 shows the concentrated storage test tank location, with circles and white spaces representing water system components, such as proposed tanks, pumps, and pipe connections.
2. To double the water demand, a new pattern is created by exporting the existing peak demand patterns, adding a multiplier of 2 to each, and importing them back into EPANET to replace the various PD patterns that occur within the model. While there is one large peak demand pattern that applies to most nodes within the water system, smaller PD patterns occur within the model to represent specific pressure zones, such as Crown Colony, Blythe Ferry, Johnson, and Bryant Drive. These are the default model demand patterns the model runs, unless the user specifies otherwise. Figure 38 is a visual of CU's pressure zones, created by CU staff.
3. Double the Flow Control Valve (FCV) at HUC Clearwells, to allow twice as much water to be pulled from the source. Raise the head at the corresponding supply pumps, and increase pipe diameters.
 - a. During the first scenarios, a rule that was not violated is that no additional water can be taken from the water supply sources, to maintain the conservation of energy and mass over time.

- b. During the second two scenarios, additional water is allowed from the source if need be, to meet the doubled demand in case the water tanks cannot supply it. Pipe sizing upgrades to allow for increased water purchase or withdrawal is something that CU contemplates in future retrofits of the water system, so this method reflects steps that would be taken for a doubled population.
- 4. Attempt to resolve the many model warnings caused by negative pressures and loss of ability to meet additional water demand.
 - a. The A2 model fails with both the doubled population and the existing power generating controls added in A1's design. These controls command the additional storage to be drained during peak and filled during off-peak electrical hours.
 - b. With these controls still in effect, the tank farm will serve only a pumped storage capacity for electricity generation, not to meet demand or maintain pressure. The tank farm needs to be allowed to respond to pressure and water demands, and neutralizing the rules accomplishes this.
- 5. Neutralize the electricity generating tank farm rules so that the tanks can respond at any point to meet demand and pressure needs, within a system representing double water demands. Turn off tank farm generating loops so tanks can meet new demand. Neutralize tank drain rules (put in place in A1 for generation).
 - a. In the model, controls do not have to be physically removed. They can be neutralized by use of semi-colons in front of each written line of code.
 - b. Even with the model energy-generating controls neutralized, the model still fails to meet pressure and demands throughout the system. It continues to crash.
- 6. Search for negative pressures at individual nodes throughout the model and resolve through slight elevation changes or pump curve expansion to the nearby pump.
- 7. Change pump curves throughout the system to address errors, to see if this modification can eliminate negative pressures.
- 8. Remove doubled demand pattern, replace it with the original demand patterns, and add demand to several nodes (representing subdivisions) in the southern half of the CU system, to see if concentrated storage can meet double demand if it is within the same water pressure zone.

Scenario B2 Methods: Distributed Storage, Future Demand

- 1. The baseline model for this scenario is the B1 distributed storage scenario model (example tank shown in Figure 39). Recall that scenario B1 can complete a run and meet stress testing fire flows, while

maintaining pressure, meeting demand, and generating 5% of peak community electrical demand. Additional tanks with General Purpose valves (GPVs), pumps, and half-sized storage tanks below them allow for this energy generation. As in scenario A1, the additional storage added in B1 is used for energy generation, not meet demand or stabilize water system pressures.

2. Double the water demand by importing the new demand patterns created for the A2 model.
3. Double the FCV at HUC Clearwells, to allow twice as much water to be pulled from the source.
4. Raise the head at the corresponding supply pumps, and increase pipe diameters as needed (guided by model run warnings).
5. Attempt to resolve the many model warnings caused by negative pressures and loss of ability to meet additional water demand.
6. Increase pump curves throughout the model to meet new demand (meaning that CU would have to upgrade pumps throughout the system).
7. Neutralize the electricity generating existing tank rules written into the B1 model so that the tanks can respond at any point to meet demand and pressure needs, within a system representing double water demands. Turn off the generating loops below each tank, so that the additional storage previously used for energy generation can meet new demand. This effectively shuts down energy generation potential, so as to use extra storage to only meet new demand and pressure needs.
8. Run fires at 2 hour intervals at all nodes throughout the system to stress test demand response.
9. Insure tanks can hold their maximum and minimum elevations during a model run.

2.5 Results

As predicted, concentrated and distributed storage configurations had very different impacts on water resiliency. When population was doubled by doubling demand in scenario models, concentrated storage was unable to meet demand across the system. Distributed storage can meet pressure and water demands, but at the sacrifice of energy generation.

Scenario A2 Results: Concentrated Storage, Future Demand

This model consistently either crashed or had negative pressures beginning at hour 30 that are unresolvable without entirely rebuilding the distributed CU water system model. Within the currently designed system, it requires too many model modifications to maintain a level of certainty that the model is still representing reality. Correcting an obvious elevation error at a node to resolve a pressure warning is an acceptable solution, while changing multiple elevations throughout the model simply to get the

model to resolve the pressure warning strays too far from the point of the model. A model should reflect realistic possibilities in system operations, even after modifications occur.

After hundreds of hours spent learning the details of what normal operation looks like within the CU system, learning how to modify the model to make it smarter without violating the rules of flow within a water distribution system, and learning to carefully make any reasonable yet needed system modification that does not violate modeling rules, it becomes apparent that this scenario will not run with an accurate flow balance or accurately represent system conditions. The initial 9 increased pump curves result in other pump curves needing to be increased. Following through with an increase of all model pump curves did not correct negative pressures. Three times, the model fails at time 0 after working through all the previous pump errors. Other times, the model status report shows hundreds of negative node pressures, crashing the system's water balance at hour 30 within a 3-day model run.

While the concentrated storage design is better at generating electricity, it does not ensure a water system that is resilient to a doubling population. Because the tank farm is in one place (southeast Cleveland), the additional storage it provides to generate electricity will not also be able to meet the water supply needs of a doubled and distributed population, even if that population is concentrated in the immediate vicinity of the tank farm. Water from its tanks is too far away to answer pressure needs throughout the system or to meet additional demands from nodes in other water pressure zones beyond the first day. The tank farm may be able to meet concentrated demands if high growth occurs in South Cleveland, but it would need to be redesigned to space the tanks out in a manner that allows them to create and service their own pressure zone. If the tanks are used to meet demand and to maintain system pressure, any energy generation gained in A1 will be sacrificed to service this new use (Figure 40).

Additional storage is required elsewhere throughout the A2 model for this scenario to satisfy new water demand, due to pressure zones throughout the system. This outcome ultimately makes sense. Supplying demand is only one function of a tank in an urban water system. Tanks must be located close to the demand they are meeting, and to be able to maintain pressures while supplying that demand when required. The best way to do this is to have tanks distributed so that pressure zones are delineated, each with a primary tank controlling the pressures within that zone. Water systems evolve in this manner, creating new pressure zones when additional tanks are added.

Scenario B2 Results: Distributed Storage, Future Demand

While the B1 distributed storage scenario is not as successful as the A1 concentrated storage scenario in meeting energy generation needs, the B2 scenario is far more successful than the A2 scenario at adding water system resiliency when faced with the prospect of a doubling population. Because the distributed model has doubled the height of each tank, doubling the population and using all the additional storage to meet increased demand (as opposed to using it to generate electricity) is possible. If additional storage is used to meet new demands only (and not to generate electricity), the model can run without error and with an acceptable flow balance even when fire is also instigated.

The B1 scenario flow balance shows the system supplying between 6,500 and 15,000 gallons per minute (GPM) over a 3-day model run. Figure 41 shows that the B2 scenario flow balance is producing between 7,000 and 22,000 GPM over a 3-day model run (red line). With increased inflow capabilities, fire response is less dramatic than it is in the other models.

However, pump sizes must be upgraded at each major pump throughout the system, and any energy generation gained in scenario B1 is sacrificed. This is because all additional storage added in B1 is now going to meet the increased demand added in B2, and cannot also then also be used to generate electricity. To meet doubled water demands and to also generate electricity, storage capacity would need to be doubled again, creating 3 times the amount the system began with. This is not realistic from a cost standpoint.

To ensure a B2 scenario model run that accurately reflects possible water system operations, many failed model runs are overcome. For instance, when the doubled demand patterns are first introduced, the model failed comprehensively at time 0. Increasing 10 pump curves throughout the system to handle increased flow and head resulted in more failed runs, with negative pressures being the most common error. It is not until the FCV settings at HUC Clearwells treatment plant, and the corresponding pipe and pump sizes are upgraded, that the model will run without error.

Head graphs of each tank are examined to observe tank behaviors under these new constraints. Figure 42 shows an example of Eldridge, which was doubled in height during the B1 scenario baseline model. All tanks maintain their desired elevations, and operating preferences are also maintained. Therefore, the system can operate under B2 scenario parameters with double water demand, while providing fire flow to the entire system every 2 hours. Figure 43 shows a visualization of outcomes for the B2 scenario.

2.6 Conclusions

The tested hypothesis assumes that the addition of energy storage capacity can make water systems more flexible and resilient when faced with chronic and uncontrollable external variables in modeled scenarios. To test the hypothesis, a city's water system is modeled with additional storage. Its ability to meet system requirements with double the demand is examined, both with and without energy generating capabilities.

Population is doubled in the A2 and B2 models of the CU water distribution system to understand how increased storage can help a community address the chronic stress of growth. It is doubled by increasing the demands at all nodes, to reflect Cleveland's growth projections of primarily infill and redevelopment. Recall that new storage added in the A1 and B1 scenarios is designed for energy generation only (closed loop upper tank to lower tank), so it captures stored water from the upper tanks, generates electricity through the General Purpose Valve, and then collects it in the lower tank). This water is not used to meet demand or maintain pressures, but used instead to refill the upper tank.

Doubling population in the model means that the storage added in scenarios A1 and B1 must be used to meet new demand and pressure requirements, instead of for energy generation. The additional storage added in scenarios A1 and B1 is therefore considered "used" storage in scenarios A2 and B2. Generating electricity requires unused storage. Storage would need to double again to meet this increased demand and to also continue to generate electricity.

Energy generation is sacrificed and pumps are upgraded throughout the system in both scenarios to meet new demand. The stressed scenario A2 (tank farm with increased water demands) will not function to meet new demands of that magnitude. A tank farm scenario cannot meet double demand throughout a full water distribution system due to not being able to meet demand on the other side of the system at the time it is required, or to be able to control pressures throughout the system. To make the A2 concentrated storage scenario work to meet doubled demand, the whole system needs to be rebuilt, even with intake pipes, pumps, and valves preemptively upgraded as a model presupposition.

The stressed scenario B2 (distributed increased storage with increased water demands) will function to meet new water demands of that magnitude. Distributed storage ensures more system resiliency in terms of meeting demand without huge system modifications to pipes and pump sizes and configurations. Recent literature also is documenting that distributed storage water storage supports system resiliency (Butler et al., 2017).

In terms of water system resiliency, distributed storage is better than concentrated storage, as it would be in real life, with the local water system growing at pace with the local population. As a system grows, managing pressure and meeting demand throughout is more easily done over time if the tanks are close to new development as growth occurs. Isolating storage in one place, while better for hydropower generation, makes less sense through the resiliency lens. However, in both population-stressed scenarios, energy generation must be sacrificed to attempt to meet doubled demands.

It is reasonable to assume that with doubled water demand comes a similar increase in electric demand. As neither stressed scenario can meet new water demand, maintain system pressure, and generate electricity all at once, it becomes clear that without significant water system growth (specifically for energy generation), the community electrical load cannot be significantly reduced by energy generation within the urban water system. The scales of magnitude between the systems are too varied, especially when faced with a doubling population. However, if a community adopted a microgrid mentality towards the provision of water and energy services, there could be opportunities for water and energy system integration at a much smaller scale than community-wide.

For instance, a water tank pressurizing a small local area could not only meet demand and maintain water system pressure for that area, but it could also be designed with in-line pipe turbines to capture tank outflows and convert them into enough energy generation to service the tanks' associated pumping station during peak electrical demand. With peak demand energy pricing, pumping costs could be minimized or covered by tank turbines. This research explores water system support of the electrical system from a community-wide lens, but future research should focus on the distributed microgrid scale. Reducing the scope of study will allow for a clearer understanding of how energy generation from pumped storage within an urban water system can work to make that system more resilient, while also producing electricity in small amounts, which can be used to offset water system operating costs.

A Water Online article from World Water-Tech (2017) with San Francisco's Director of Water Services reveals active thinking around scales around resource recovery, including energy at the local level. After noting that they are exploring small scale water systems, Paula Kehoe said "We are most interested in resource recovery technologies to generate drinking water, non-potable water, fertilizer and energy that can be optimized at various scales. With these new types of technologies becoming cost-effective, we can transform the water sector with resource recovery facilities of various sizes and scales not only in San Francisco, but throughout the world."

References

- Afgan, N. H., Al Gobaisi, D., Carvalho, M. G., & Cumo, M. (1998). Sustainable energy development. *Renewable and Sustainable Energy Reviews*, 2(3), 235-286.
- Asmus, P. (2010). Microgrids, virtual power plants and our distributed energy future. *The Electricity Journal*, 23(10), 72-82.
- Bao, Y., & Mays, L. W. (1990). Model for water distribution system reliability. *Journal of Hydraulic Engineering*, 116(9), 1119-1137.
- Baird, G. M. (2010). A game plan for aging water infrastructure. *American Water Works Association Journal*, 102(4), 74.
- Barnes, P., Egodawatta, P., & Goonetilleke, A. (2012). Modeling Resilience in a Water Supply System: Contrasting conditions of drought and flood.
- Bazmi, A. A., & Zahedi, G. (2011). Sustainable energy systems: Role of optimization modeling techniques in power generation and supply—A review. *Renewable and sustainable energy reviews*, 15(8), 3480-3500.
- Bednarek, J. R. D., Dieterich-Ward, A., Goebel, A. D., Hicks, M. J., Lehman, T. E., O'Hara, S. P., ... & Winling, L. (2010). *After the factory: reinventing America's industrial small cities*. J. J. Connolly (Ed.). Lexington Books. Lanham, MD.
- Bettencourt, L. M., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the national academy of sciences*, 104(17), 7301-7306.
- Blackmore, J. M., & Plant, R. A. (2008). Risk and resilience to enhance sustainability with application to urban water systems. *Journal of Water Resources Planning and Management*, 134(3), 224-233.
- Comfort, L. K., Boin, A., & Demchak, C. C. (Eds.). (2010). *Designing resilience: Preparing for extreme events*. University of Pittsburgh Pre.
- Bouwer, H. (2000). Integrated water management: emerging issues and challenges. *Agricultural water management*, 45(3), 217-228.
- Bradley County 2035 Metropolitan Planning Organization (MPO) Joint Strategic Plan. (2013). Area and Region Plan, Chapter 3. Retrieved May 2014 from <http://www.clevelandtn.gov/?nid=153>
- Brown, L. R. (1982). Building a sustainable society. *Society*, 19(2), 75-85.
- Butler, D., Ward, S., Sweetapple, C., Astaraie-Imani, M., Diao, K., Farmani, R., & Fu, G. (2017). Reliable, resilient and sustainable water management: the Safe & Sure approach. *Global Challenges*, 1(1), 63-77.
- Carrasco, J. M., Franquelo, L. G., Bialasiewicz, J. T., Galván, E., PortilloGuisado, R. C., Prats, M. M., & Moreno-Alfonso, N. (2006). Power-electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Transactions on industrial electronics*, 53(4), 1002-1016.
- Castillo, A., & Gayme, D. F. (2014). Grid-scale energy storage applications in renewable energy integration: A survey. *Energy Conversion and Management*, 87, 885-894.

- Chang, S. E., & Shinozuka, M. (2004). Measuring improvements in the disaster resilience of communities. *Earthquake Spectra*, 20(3), 739-755.
- Chaskin, R. J. (2008). Resilience, community, and resilient communities: Conditioning contexts and collective action. *Child Care in Practice*, 14(1), 65-74.
- Chorn, N. (2010). Key signposts on the road to corporate resilience. *Management Today*, 28(3), 11-17.
- City of Cleveland Comprehensive Plan. (2013). Cleveland, TN. Retrieved April 2015 from <http://clevelandtn.gov/index.aspx?NID=267>
- Cleveland Urban Area MPO Area Map (2013). Cleveland, TN Metropolitan Planning Organization. Retrieved August 2014 from <http://www.clevelandtn.gov/?nid=153>
- Cunningham, W. P., Saigo, B. W., & Cunningham, M. A. (2001). *Environmental science: A global concern* (Vol. 412). McGraw-Hill, Boston, MA.
- Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. *Global environmental change*, 18(4), 598-606.
- Dasgupta, S., & Tam, E. K. (2005). Indicators and framework for assessing sustainable infrastructure. *Canadian Journal of Civil Engineering*, 32(1), 30-44.
- Donovan, B., & Work, D. B. (2015). Using coarse GPS data to quantify city-scale transportation system resilience to extreme events. *arXiv preprint arXiv:1507.06011*.
- Elsheshtawy, Y. (2008). The great divide: Struggling and emerging cities in the Arab world. *The evolving Arab city: Tradition, modernity and urban development*, 1-27.
- Falkenmark, M., & Widstrand, C. (1992). Population and water resources: a delicate balance. *Population bulletin*, 47(3), 1-36.
- Fiksel, J. (2006). Sustainability and resilience: toward a systems approach. *Sustainability: Science, Practice, & Policy*, 2(2).
- Fortune 500 Companies - Cleveland - Bradley Chamber of Commerce. (n.d.). Retrieved September 12, 2016, from <http://clevelandchamber.com/economic-development/fortune-500-companies/>
- Francis, R., & Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering & System Safety*, 121, 90-103.
- Gates, G. J., & Cooke, A. M. (2011). Tennessee Census Snapshot: 2010. Retrieved May 2014 from http://williamsinstitute.law.ucla.edu/wp-content/uploads/Census2010Snapshot_Tennessee_v2.pdf
- Gandy, M. (2004). Rethinking urban metabolism: water, space and the modern city. *City*, 8(3), 363-379.
- Gellings, C. W. (2009). *The smart grid: enabling energy efficiency and demand response*. The Fairmont Press, Inc.
- Giampietro, M., Mayumi, K., & Munda, G. (2006). Integrated assessment and energy analysis: Quality assurance in multi-criteria analysis of sustainability. *Energy*, 31(1), 59-86.
- Gottmann, J. (1961). *Megalopolis: the urbanized northeastern seaboard of the United States*. Twentieth Century Fund.
- Greer, S. A. (1962). *The Emerging Cities: Myth and Reality*. Free Press of Glencoe. New York City, NY.

- Grid Energy Storage. (2013). Retrieved August 11, 2015 from http://www.sandia.gov/ess/docs/other/Grid_Energy_Storage_Dec_2013.pdf
- Guy, S. (1996). Managing water stress: the logic of demand side infrastructure planning. *Journal of Environmental Planning and Management*, 39(1), 123-130.
- Haines, Y. Y. (2009). On the definition of resilience in systems. *Risk Analysis*, 29(4), 498-501.
- Handmer, J. W., Dovers, S., & Downing, T. E. (1999). Societal vulnerability to climate change and variability. *Mitigation and adaptation strategies for global change*, 4(3), 267-281.
- Hering, J. G., Waite, T. D., Luthy, R. G., Drewes, J. E., & Sedlak, D. L. (2013). A changing framework for urban water systems.
- Howe, C. W., Smith, M. G., Bennett, L., Brendecke, C. M., Flack, J. E., Hamm, R. M., & Wunderlich, K. (1994). The value of water supply reliability in urban water systems. *Journal of Environmental Economics and Management*, 26(1), 19-30.
- Knoeri, C., & Russell, S. (2014). Sustainable Resilient Infrastructure.
- Lee II, E. E., Mitchell, J. E., & Wallace, W. A. (2007). Restoration of services in interdependent infrastructure systems: A network flows approach. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 37(6), 1303-1317.
- Liu, X., Liu, J., Zhao, S., & Tang, L. C. (2013). Modeling and Simulation on a Resilient Water Supply System Under Disruptions. In *Proceedings of the Institute of Industrial Engineers Asian Conference 2013* (p. 1385-1393). Springer Singapore.
- Loucks, D. P., Van Beek, E., Stedinger, J. R., Dijkman, J. P., & Villars, M. T. (2005). *Water resources systems planning and management: An introduction to methods, models and applications*. Paris: UNESCO.
- Magis, K. (2010). Community resilience: An indicator of social sustainability. *Society and Natural Resources*, 23(5), 401-416.
- Masten, A. S. (2001). Ordinary magic: Resilience processes in development. *American psychologist*, 56(3), 227.
- Manfredi, M., Caputo, P., & Costa, G. (2011). Paradigm shift in urban energy systems through distributed generation: Methods and models. *Applied Energy*, 88(4), 1032-1048.
- Milman, A., & Short, A. (2008). Incorporating resilience into sustainability indicators: An example for the urban water sector. *Global Environmental Change*, 18(4), 758-767.
- Mitchell, V. G., Mein, R. G., & McMahon, T. A. (2001). Modelling the urban water cycle. *Environmental Modelling & Software*, 16(7), 615-629.
- Molyneaux, L., Wagner, L., Froome, C., & Foster, J. (2012). Resilience and electricity systems: A comparative analysis. *Energy Policy*, 47, 188-201.
- Mugume, S. N., Diao, K., Astaraie-Imani, M., Fu, G., Farmani, R., & Butler, D. (2015). Enhancing resilience in urban water systems for future cities. *Water Science and Technology: Water Supply*, 15(6), 1343-1352.
- National Infrastructure Advisory Council (US). (2009). *Critical Infrastructure Resilience: Final Report and Recommendations*. National Infrastructure Advisory Council.

- Novotny, V., Ahern, J., & Brown, P. (2010). *Water centric sustainable communities: planning, retrofitting and building the next urban environment*. John Wiley & Sons. Hoboken, NJ.
- O'Rourke, T. D. (2007). Critical infrastructure, interdependencies, and resilience. *BRIDGE-WASHINGTON-NATIONAL ACADEMY OF ENGINEERING-*, 37(1), 22.
- Ouyang, M., Dueñas-Osorio, L., & Min, X. (2012). A three-stage resilience analysis framework for urban infrastructure systems. *Structural safety*, 36, 23-31.
- Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews*, 33, 74-86.
- Qi, C., & Chang, N. B. (2011). System dynamics modeling for municipal water demand estimation in an urban region under uncertain economic impacts. *Journal of environmental management*, 92(6), 1628-1641.
- Rausand, M., & Arnljot, H. (2004). *System reliability theory: models, statistical methods, and applications* (Vol. 396). John Wiley & Sons.
- Rijke, J., Farrelly, M., Brown, R., & Zevenbergen, C. (2013). Configuring transformative governance to enhance resilient urban water systems. *Environmental Science & Policy*, 25, 62-72.
- Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems*, 21(6), 11-25.
- Sahely, H. R., Kennedy, C. A., & Adams, B. J. (2005). Developing sustainability criteria for urban infrastructure systems. *Canadian Journal of Civil Engineering*, 32(1), 72-85.
- Salamon, S. (2003). From Hometown to Nontown: Rural Community Effects of Suburbanization1. *Rural Sociology*, 68(1), 1-24.
- Scott, A. J. (2011). Emerging cities of the third wave. *City*, 15(3-4), 289-321.
- Skea, J., Chaudry, M., Ekins, P., Ramachandran, K., Shakoor, A., & Wang, X. (2012). A resilient energy system. *Energy 2050: Making the Transition to a Secure Low-Carbon Energy System*, 145.
- Smith, T. F., Daffara, P., O'Toole, K., Matthews, J., Thomsen, D. C., Inayatullah, S., ... & Graymore, M. (2011). A method for building community resilience to climate change in emerging coastal cities. *Futures*, 43(7), 673-679.
- Tennessee State Data Center, Boyd Center for Business & Economic Research, The University of Tennessee, Knoxville. Retrieved August 31, 2016 from <http://tndata.utk.edu>
- Tidball, K. G., & Krasny, M. E. (2007). From risk to resilience: What role for community greening and civic ecology in cities. *Social learning towards a more sustainable world*, 149-164.
- U.S. Department of Energy (2014). Ensuring the Resiliency of Our Future Water and Energy Systems (Energy.gov). Retrieved August 18, 2015 from <http://www.energy.gov/articles/ensuring-resiliency-our-future-water-and-energy-systems>
- Vogel, R. M., & Bolognese, R. A. (1995). Storage-Reliability-Resilience-Yield Relations for Over-Year Water Supply Systems. *Water Resources Research*, 31(3), 645-654.
- Wang, Z., & Wang, J. (2015). Self-healing resilient distribution systems based on sectionalization into microgrids. *IEEE Transactions on Power Systems*, 30(6), 3139-3149.

- Water Resilience for Cities. Arup report Retrieved September 10, 2015, from http://www.arup.com/~media/Files/PDF/Publications/Research_and_whitepapers/ArupUrbanLife_WaterResilienceForCities.ashx
- Wilkinson, R. C. (2007). Integrating water and energy resource management: progress and opportunities. In *World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat* (p. 1-17).
- Wong, T., & Brown, R. (2008, August). Transitioning to water sensitive cities: ensuring resilience through a new hydro-social contract. In *11th International Conference on Urban Drainage. September. Edinburgh. 10p.*
- World Water-Tech. (2017, July). How the Water Industry Is Building A Resilient Future: An interview with Paula Kehoe, Director of Water Services, SFPUC. Retrieved August 8, 2017 from <https://www.wateronline.com/doc/how-the-water-industry-is-building-a-resilient-future>
- Wu, F. (Ed.). (2007). *China's emerging cities: the making of new urbanism*. Routledge. Abingdon-on-Thames, UK.
- Yazdani, A., Otoo, R. A., & Jeffrey, P. (2011). Resilience enhancing expansion strategies for water distribution systems: A network theory approach. *Environmental Modelling & Software*, 26(12), 1574-1582.
- Younos, T. M., Hill, R., & Poole, H. (2009). Water dependency of energy production and power generation systems.

Appendix 2

Table 14. Resilience in Water and Energy Systems.

	Traditional Definition (dealing with infrastructure/physical states)	Evolving Definition (dealing with community/non-physical states)
Defining Resilience	Reduce the magnitude and/or duration of disruptive events on system performance	The capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience
Resilience Examples by System under the Evolving Definition		
Water	Increased system flexibility to: hold flood waters / decrease overflows / store water for droughts, generate energy if needed, resist failure from overload, etc.	
Energy	Increased system flexibility to: have more than one primary energy generation fuel or source, host microgrids that can service dense populations in times of overall system outages, reduce dependency on supplies (like water) that are needed for life support, etc.	

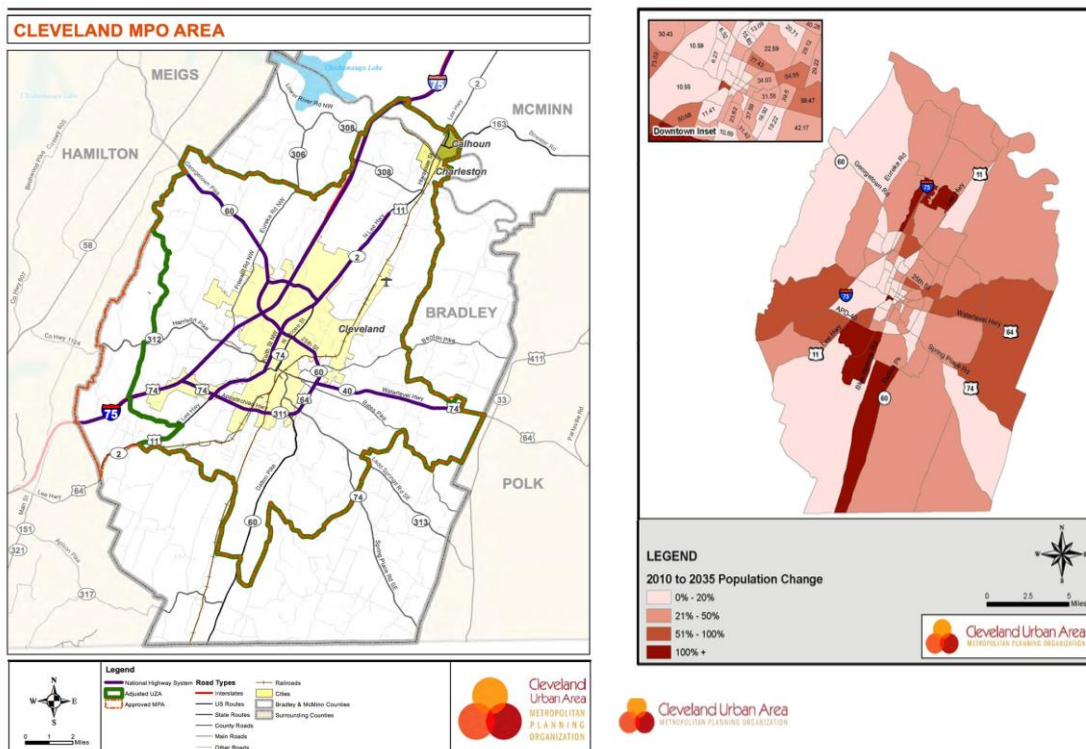


Figure 34. MPO Map of Cleveland's Urban Area and Projected Growth Locations.

Table 15. Bradley County, TN Land Use Types by Total Acreage and Percent.

Existing Land Use Type	Total Acreage	% of County
Agricultural	91,462	43%
Commercial	1,591	1%
Forest/Undeveloped	54,437	26%
Industrial	4,467	2%
Infrastructure	8,875	4%
Institutional	2,533	1%
Office/Professional	376	0%
Parks and Recreation	1,218	1%
Residential	45,208	21%
Water	2,299	1%
Totals	212,466	100%

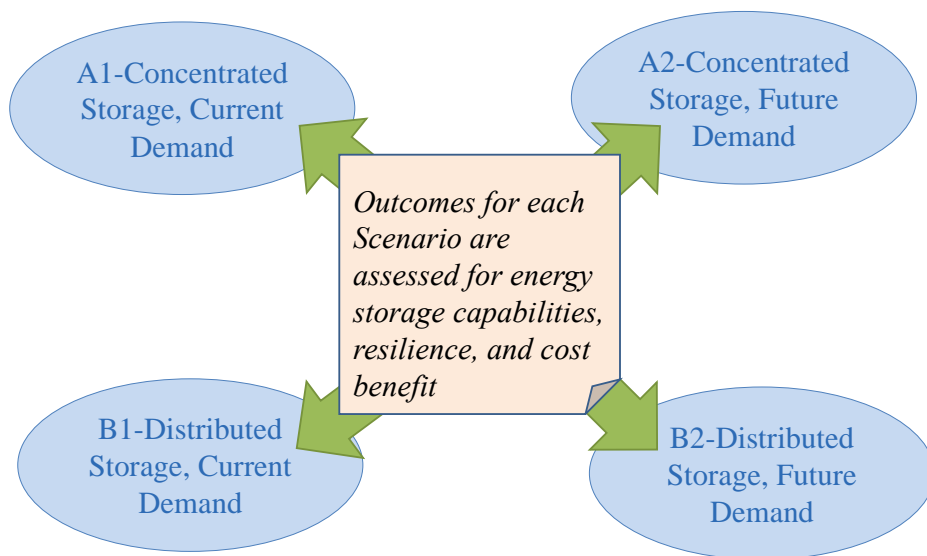


Figure 35. Transferrable Method for Analysis of Storage Implementation Strategies.

- **Insert nine 3,500,000 gallon tanks**
Use the extra space originally designed for storage only (not system pressure or demand) to try and meet doubled water demand
 - Near the South Cleveland 69kV circuit line (also where new industry will be located)
- **Adjust the model so pressure is not too high in the system**
- **See if the extra gallons can meet new demands** (resilience implications)



Figure 36. Concentrated Storage Scenario Development to Examine Resiliency Implications.

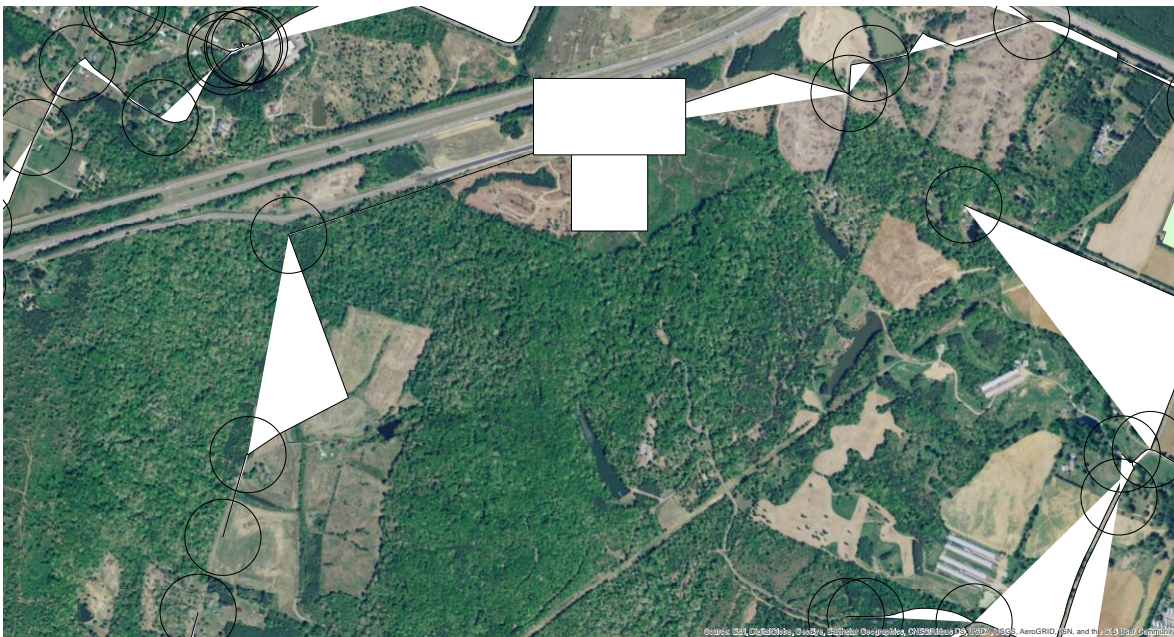


Figure 37. Concentrated Storage Testing Location in South Cleveland, TN.

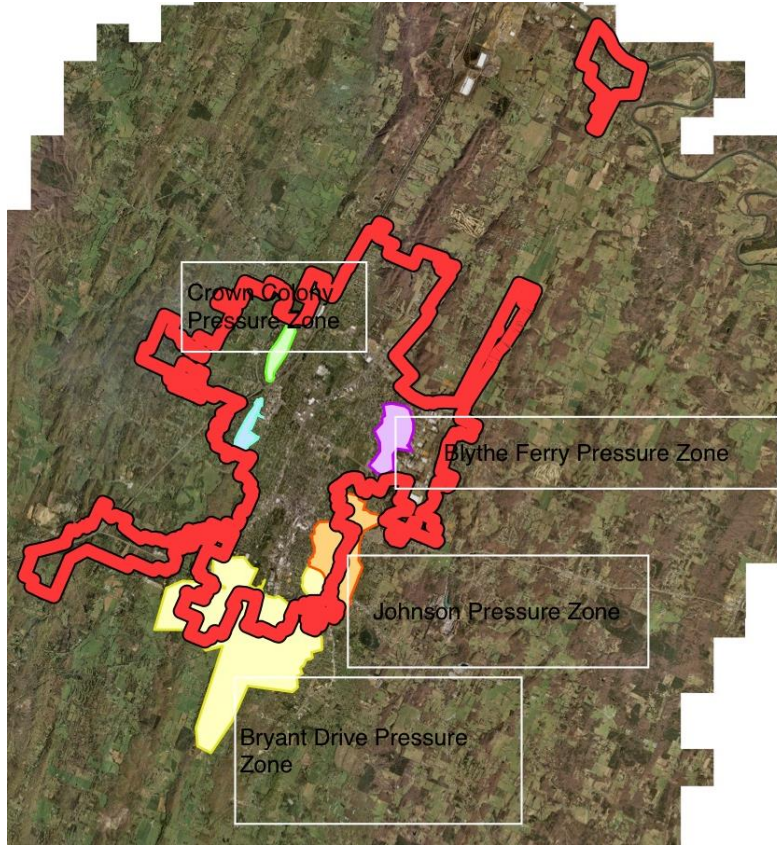


Figure 38. CU's Map of their Water Pressure Zones.



Figure 39. Example of Distributed Storage Testing Location in Cleveland, TN.

Scenario A2
Concentrated Storage, Future Demand

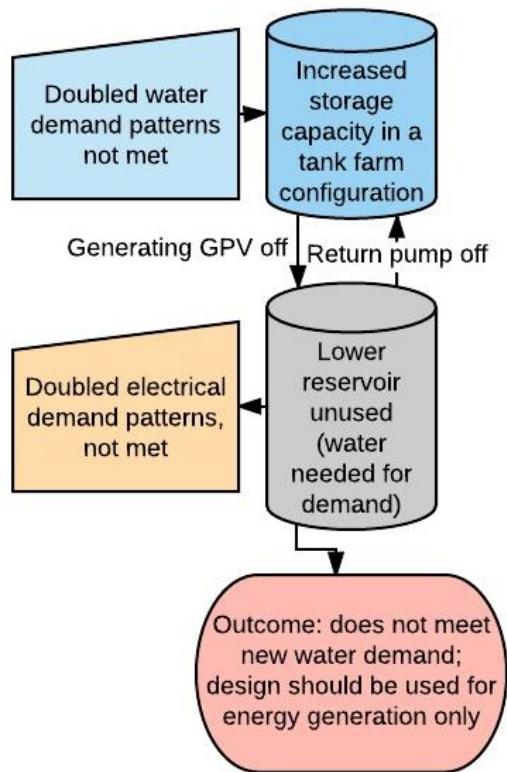


Figure 40. Scenario A2 Outcome Visualization.

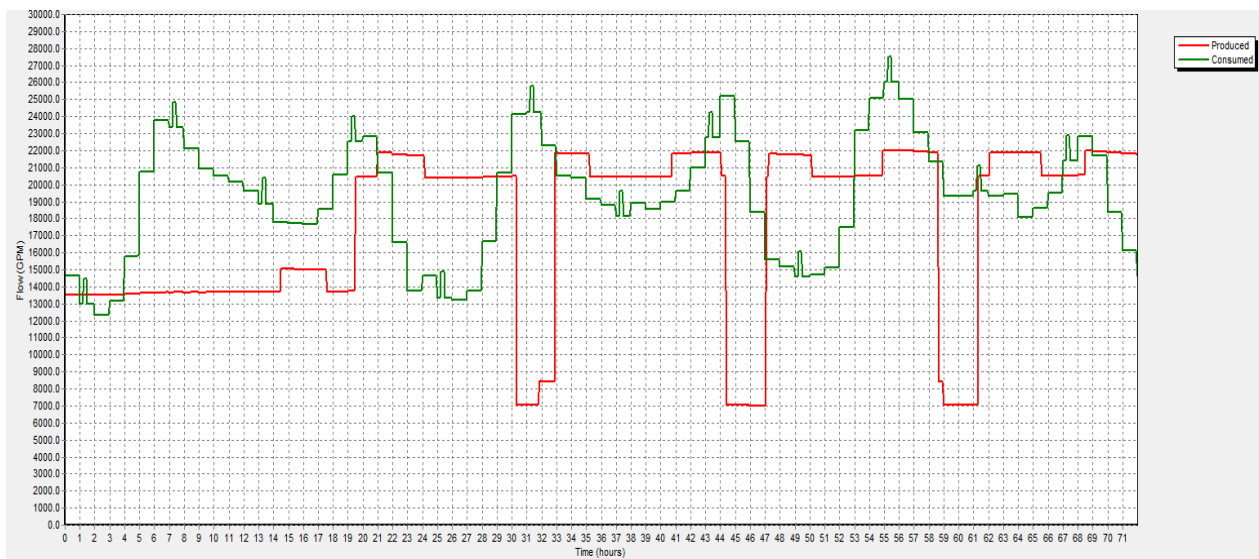


Figure 41. Example of Distributed Storage Testing Location in Cleveland, TN.

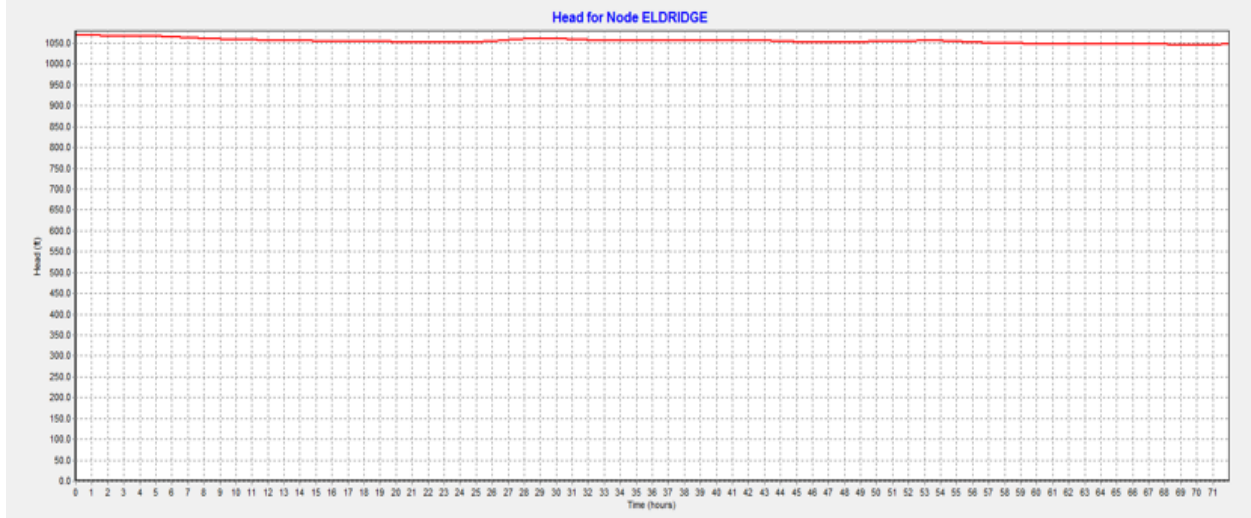


Figure 42. Example of Distributed Storage Tank Holding Increased Height Elevation.

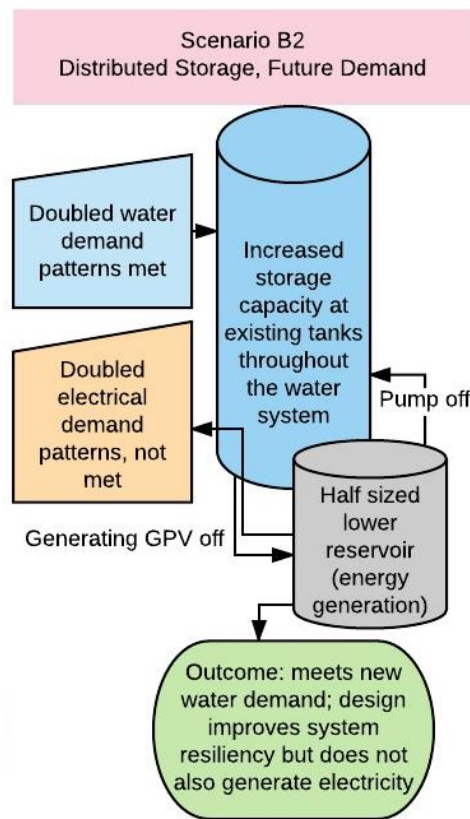


Figure 43. Scenario B2 Outcome Visualization.

CHAPTER 3
ECONOMIC FEASIBILITY OF ENERGY STORAGE IN URBAN WATER SYSTEMS

Abstract

This research examines the initial direct and indirect capital costs, as well as the annual operating and maintenance costs, of increasing energy storage in urban water systems to offset peak community energy demand in concentrated and distributed configurations. It compares these costs to energy generation potential using peak demand pricing, to assess the attractiveness of increasing water storage for energy generation in urban water systems. The tested hypothesis assumes that energy storage enhancements in urban water systems have financial variables that include localized energy and water costs, and that these costs can be analyzed to determine the fiscal attractiveness of various storage configurations. Concentrated and distributed storage scenarios from a case study water system model are analyzed in an Excel-based scenarios calculator against: (1) energy rate structures; (2) energy consumption to charge storage; (3) energy production potential from additional storage; and (3) the initial capital investment and annual operating costs of installing additional storage. The study finds that neither scenario has a payback period that fits within local utility planning or financing horizons, and that there is a negative return on investment for both concentrated and distributed storage under near and far-term demand conditions, when water storage for energy generation is designed on a community-wide scale. Future studies should concentrate on hydro-generation at the microgrid level for small offsets to specific and localized energy consumption sources.

3.1 Economics of Energy Storage in Urban Water Systems

Like other businesses, water and energy utility managers balance priorities and trade-offs to best use time and capital (Keeney & Raiffa, 1993). The choices presented by trade-offs depend on the specific situation (Makropoulos & Butler, 2010). System owners and operators, developers, regulators, and legislators make choices that shape communities, impacting response to external pressures. For the long-term sustainability of both water and electric systems, decision makers must work together and consider a myriad of variables, including: higher peak electricity demand; greater variability in the hydrologic system; the impact of climate variability on system reliability; ongoing pressures to cut carbon emissions through reduction in energy consumption; and the economic impacts of these decisions (Hussey & Pittock, 2012).

One business-as-usual scenario shows that, without any form of intervention, utility emissions would stay within 5% of current levels, and water withdrawals would not drop significantly until after 2030 (Rogers et al., 2013). One viewpoint is that there is no immediate need for utilities to reduce their emissions (Gollop & Roberts, 1983), or that current water constraints are a result of use patterns (Zetland, 2008).

The opposing viewpoint is that utility emissions reductions are critically needed (Magill, 2014), and that water should be conserved now, instead of waiting until water availability is a common crisis (Oki & Kanae, 2006).

Regardless of viewpoints on market motivators, such as carbon regulations and water conservation, it is evident that not being proactive with water system improvements leaves components of the energy sector (such as nuclear and hydro-generation) vulnerable to water shortages, including increasing competition with other water uses (Savulescu et al., 2005). Likewise, not being proactive in diversifying energy sources to reduce pollution, or in implementation of system efficiencies, leaves the energy sector vulnerable to increasing climate and regulatory volatility. Both vulnerabilities compromise the ability to correctly forecast the need for infrastructure upgrades and facility development planning within an acceptable degree of certainty (Dong et al., 2012). To minimize forecasting challenges caused by unknown externalities, variables, and vulnerabilities, and to forecast using the best available information, it is important to understand how both sectors' resources are valued (Perrone et al., 2011). This is explored in the following sections.

A Comparison of Water and Energy Markets

Water-system sustainability is much more than a function of its energy efficiency or energy supply. Water systems have finite resource limits, a fact that has growing visibility in water-stressed areas like the western U.S. (Green, 2007). Unlike energy, there isn't a growing portfolio of sources or options. Instead, there are usually 1 or 2 primary water supplies in each community. Even so, there is no national discussion about a comprehensive water policy that matches the national debate on the development of a U.S. energy policy. Energy and water systems are complex, but there are stark differences in how they are dealt with in U.S. markets. A 2013 American Water Works Association article reports that 80% of water utilities (potable water, wastewater, and combined systems) say they do not recover the full cost for providing service (Westerling, 2013). Table 16 is created to contrast the two commodities. All figures and tables referenced in this Introduction are placed in Appendix 3, in the order they are mentioned in this text.

Source and delivery reliability is a shared concern of both water and energy systems, and an important dimension of urban water supply. While out-of-pocket losses appear small, water customers still place a high value on reliability (Agudelo, 2001). This demand for reliability can be measured through consumer

surveys and other qualitative methods, while the costs of providing various levels of reliability can be estimated through quantitative hydrologic simulation (Hashimoto et al., 1982).

Water Valuation Techniques

One study develops a framework for optimizing water system reliability from a contingent valuation survey in three Colorado towns (Lundin & Morrison, 2002). Contingent valuation is a survey technique that places value on nonmarket resources, like the impact of contamination in an environment. Despite the low financial value placed on water, it is an economic good (Rogers et al., 2002). As such, after basic needs are met, water is often allocated to the highest value uses (Levi, 1969). Water value informs decisions about: (1) equitable and efficient allocation of water among competing existing and future users; (2) equitable and efficient infrastructure investment in the water sector, including amount, timing, and location; (3) efficient degree of treatment of wastewater; and (4) design of economic instruments, such as water pricing, property rights, tradable water-rights markets, and taxes on water depletion and pollution (Armstrong & Willis, 1977). The price charged by water suppliers does not reflect the actual value of water, or even the full costs of water supply (Dinar, 2000).

Competitive markets are not in charge of water supply because water is necessary for human survival, land ownership can create water monopolies, and property rights are not always well defined for multiple or sequential uses (Dinar & Saleth, 2005). Water is also considered a bulk commodity, and high transport costs, relative to low market values, can inhibit trade (Bruns & Meinzen-Dick, 2000). There are situations where private companies sell unused water allocations on the open market, moving water from Alaska to California, for instance, but monthly withdrawals cannot exceed what the company has been allocated for general use (Kariuki & Schwartz, 2005).

Water valuation techniques can be preference or market-based, and are developed more for cost benefit analysis (CBA), or a return on investment (ROI) analysis of specific initiatives, than for national scales (Birol et al., 2006). Water CBAs often try to measure economic welfare, or total economic value, as opposed to just market price (Pruss-Ustun & World Health Organization, 2008). Programming models measure values in optimized economies, which can differ from actual economies (Draper et al., 2003).

Water values are highly site-specific, dependent on local uses, seasons, water quality, and reliability (Lange, 2007). Situational values are not transferable across geographies. CBAs can be augmented with localized preference techniques, which track willingness to pay by region, from user surveys. Market-

based techniques used to value water are shown in the following Table 17. Methods are summarized from content in *Using economic valuation techniques to inform water resources management: A survey and critical appraisal of available techniques and an application* (Birol et al., 2006). Examples are added to clarify applicable uses.

The most common techniques used to value single uses, such as water required for hydroelectric power generation, include residual value and opportunity costs. The residual value method works best in unregulated electricity markets, because the price charged for electricity consumption better reflects the actual localized market value of the electricity (Berbel et al., 2011). The opportunity cost method is based on differences in production costs, so it is a good technique to estimate the value of water, even if electricity price is regulated (Laughland et al., 1993). Water asset valuation data requirements are considerable: water asset volume and flows over time, and the annual values of all uses of water over time must be measured (Tseng & Barz, 2002). Further, many variables will remain unknown, like multiple combinations and economic values of use demands (Birol et al., 2006).

Optimization models are used to value multiple uses of water. One study found that optimization is an attractive alternative to other models (algorithms, in this case) for the best design of water distribution systems (Maier et al., 2003). Water-use valuation needs to be consistent with the System of National Accounts (SNA), indicating value types and robustness (Diewert & Gordon, 1996). To gain accuracy and manage uncertainty, it is best to start with major uses that are easiest to value. Aggregation of values is simplest at the local level. Asset value begins with a few uses that can be easily assigned a dollar (or metered) amount. Linear programming, Computable General Equilibrium (CGE), and Econometric modeling are used for evaluating changes in water allocation among users, rather than values within current allocation (Haab & McConnell, 2002).

When it comes to assessing the costs of various water systems modifications (assets) from an energy standpoint, it is important to understand what components of the water system use the most electricity. Energy consumed to perform an energy generation function, such as re-charging a tank during off-peak demand hours, must be accounted for by pricing structure, and deducted from energy generation values. This insures a more accurate picture of system adjustment payback over time, and is explored in the following section.

Energy Consumption by Water System Component. The American Council for an Energy-Efficient Economy (ACEEE) evaluated 2005 energy consumption by water use type (Young, 2014). While this white paper focuses primarily on energy and water efficiencies through conservation, it does provide a sense of where water systems use the most energy. Historically, energy and water utilities have had siloed priorities. Energy utilities focus primarily on meeting energy demands over a time-and-space continuum. Likewise, water utilities focus on meeting water demands over a time-and-space continuum.

Because each system has been dealing with its own set of priorities, utilities and policymakers have paid little attention to the potential interactions between energy and water systems. Accurate calculation of energy embedded in water consumption depends on aggregate data collected from a variety of water utilities (Young, 2014). Also, localized variables create a wide range in water system energy consumption (Hussey & Pittock, 2012).

For example, the size of the water and wastewater systems, the need to pump between locations, and raw water characteristics lead to variations in the energy required to get potable water to customers. Since so many variables factor into the energy use of a water utility, having plenty of examples, and an accurate knowledge of the datasets needed for a robust analysis, is crucial for developing accurate savings calculations (Young, 2014). Table 18, adapted from the 2014 ACEEE study, shows aggregate kilowatt hour (kWh) data gathered from a variety of local water and wastewater utilities.

From this table, it becomes evident that energy used to treat source water, thereby making it potable and ready to be distributed for consumption, is the top energy consumer within the water system. Second is the energy used to pump water from the source to the water treatment plant. Finally, wastewater collection and treatment is the third-largest energy user, returning treated water to the source.

Energy Valuation Techniques

Unlike water pricing, energy is an open market commodity: traded, sold, and purchased at price points that increase and decrease in correspondence with real-time energy demands. In addition to purchase price, energy is valued by other components as well, such as security (Månsson et al., 2012), building and/or system efficiency (Kwak et al., 2010), renewable sources (Bergmann et al., 2006), policy development (Komarek et al., 2011), and multiple methods and materials used to implement storage (Dunn et al., 2011; Kienzle et al., 2011; Miller, 2012).

Electricity prices are influenced by many factors. In addition to the cost of a kWh, energy prices include costs to finance, build, operate, and maintain the electric grid, including transmission and distribution power lines, and to build energy-source power plants (Lijesen, 2007). For-profit utilities may also include shareholder financial returns in electricity prices (Eto et al., 2000). A summary of key factors which influence the price of electricity is as follows, adapted from information published online by the U.S. Energy Information Administration (EIA, 2017).

First, the cost of fuel varies by unit. For instance, natural gas is sold by dollar per thousand cubic feet, while coal is sold by dollar per ton. Electricity generators at power plants can have high fuel costs during periods of high demand. Second, there are initial construction investments, as well as ongoing operation and maintenance (O&M) for each power plant in operation. Third, utility or Public Service Commissions may regulate energy prices in some states. Others may have a combination of regulated and unregulated pricing structures. Transmission and distribution may be regulated, for instance, while generators may not be. Fourth, electricity transmission and distribution systems used to deliver electricity have ongoing maintenance costs, including damage repair from storms or other acute stresses. Finally, while weather conditions allow for renewable energy generation (sun for solar, wind for turbines, rain for hydropower), extreme temperatures can increase energy demand. In turn, this can drive pricing structures to meet increased heating and cooling needs (EIA, 2017).

The actual costs to supply electricity changes moment-by-moment (Oren, 2000). Most consumers pay rates based on the seasonal cost of electricity, and electricity prices are usually highest during summer peaks, due to the addition of more expensive generating fuel sources to meet increased cooling demands (Hatami et al., 2011). Price changes not only to reflect variations in energy demand, but also to reflect the availability of primary and/or secondary generation sources, the price of fuel by unit, and the availability of power plants to come online (Sims et al., 2003).

Electric utilities class customers by type, and this classification determines what that customer pays. Residential and commercial consumers usually pay the most, because they require voltages to be stepped down, and distributed at finer scales. Industrial consumers, on the other hand, use more electricity, and can receive it at higher voltages, thereby making the receipt of electricity less expensive and more efficient for the power supplier and utility. Industrial customers can pay close to the cost of wholesale electricity, in some regions (Rothwell & Gomez, 2003).

In 2016, the annual average price of electricity in the United States was \$0.10 per kWh. Annual averages by sector are as follows: commercial customers paid an average of \$0.10 per kWh; industrial customers paid an average of \$0.07 per kWh; residential customers paid an average of \$0.13 per kWh, and the transportation sector paid an average of \$0.10 per kWh. These are presented in averages because, like the cost of water, energy prices vary by local service territory. This is due to the local availability of fuels and fuel costs, the availability of online power plants, local utility pricing structures, and local regulations. For instance, in 2016, the average annual electricity price in Hawaii was 23.87¢ per kWh, but only 7.41¢ per kWh in Louisiana (EIA, 2017).

As with water valuation, there are models commonly used to determine energy pricing. The neural network approach is perhaps most common. One study proposes a neural network analysis to forecast short-term electricity prices (Catalão et al., 2007). With the rise of competitive electricity markets, short-term forecasting is replacing long-term forecasting. Catalão et al. propose a competitive framework to derive energy market bidding strategies. A 3-tiered neural network trained by the Levenberg-Marquardt algorithm is used for forecasting week-ahead electricity prices. The accuracy of the price forecasting attained by the neural network approach is evaluated, using cross-continental data from the electricity markets of Spain and California.

Another study uses a neural network model for short-term electricity price forecasting in deregulated energy markets. The model consists of price forecasting, simulation, and performance analysis. It accounts for variables that impact electricity prices in real-time, such as time, load, reserve, and historical pricing factors. Reserve factors are found to enhance forecasting performance. The model manages price increases more efficiently, because it considers the median as opposed to the average (Yamin et al., 2004).

Valuing Energy Storage

As with valuing water and energy from a market standpoint, valuing energy storage is not a new concept, though examples of valuing it specifically in an urban water system are rare. The Electric Power Research Institute (EPRI) created an energy storage simulation software used to evaluate the potential cost effectiveness of energy storage under customizable assumptions. The Energy Storage Valuation Tool (ESVT) evaluates the cost effectiveness of storage in 3 broad use cases, in 31 separate scenarios. In a California case study, nearly all use cases indicate cost effectiveness. These storage cost saving estimates have not been met however, due to cost structure and regulatory hurdles. The EPRI analysis provides a

break-even cost for each storage scenario, which the utilities can use as a benchmark for cost effectiveness. The storage industry can use outputs as goals (Goldstein & Smith, 2002). Table 19 provides examples of potential cost impacts and benefits of increasing water storage.

Energy storage is an extremely important variable in energy systems planning (Eyer & Corey, 2010). However, due to the case-by-case nature of its implementation, it is also difficult to consistently value. The costs and benefits of an energy storage project are almost always locational (Schoenung et al., 1996). Costs vary because of regulatory, market, and regional differences (resulting in differing policies, costs, and weather patterns), as well as to the wide variability in technology applications (Carmona & Ludkovski, 2010). The range between on-peak and off-peak power prices determines the value (Williamson, 1966). When viewed as an alternative to fossil-fired peaking resources, it is becoming increasingly competitive in some regions (Palensky & Dietrich, 2011).

The benefits of electricity storage are long documented and well established (Copeland et al., 1983). Table 20 provides a summary of these benefits, adapted from a study on the cost per kilowatt hour (kWh) to store electricity (Jewell et al., 2004). However, though electricity storage has evident merit, it is usually considered to be too expensive for deep energy market impact (Ibrahim et al., 2008). The costs of various storage technologies are continually analyzed for implementation possibilities by the private and public sectors. In general, prices are found to be dropping, and the CBA performed on specific case studies show that it is often economically justified (Poonpun & Jewell, 2008).

Because of these variables, caution must be used when contemplating using CBA and ROI analysis for renewable energy sources as transferable benchmarks. For this reason, energy storage CBA and ROI studies are typically conducted by energy technology type: solar photovoltaics (PV), for instance (Kaldellis et al., 2009), or wind (Le & Nguyen, 2008). There are 2 commonly used metrics to evaluate energy storage, however: (1) the ratio of storage to the system size; and (2) a comparison of the total energy output from the storage to the energy consumption of the entire system (Maloney, 2017).

One study compares the feasibility and economics of pumped hydro storage (PHS) when combined with battery storage for a renewable-energy powered island (Ma et al., 2014). It was undertaken to find the most suitable energy storage scheme for local decision-makers. Findings conclude that PHS is cost competitive when combined with battery storage and controlling variables, like increasing energy storage capacity and days of system autonomy. The renewable energy system, coupled with PHS, presents

technically feasible opportunities for continuous power supply in remote areas. Another study examines the ability of PHS to support and optimize a small island's energy system. This study concludes that including pumped storage to allow for larger penetration of renewable energy sources improves both system resiliency and operations (Brown et al., 2008).

Advances in the use of small PHS distributed throughout an urban water system can directly support a community's sustainability goals (Ardizzon et al., 2014). Cities rely on strong economic systems, healthy environments, and human-centered design for a total picture of community health (Haughton & Hunter, 2004). Energy sources directly impact each of these factors (Capello et al., 1999). For a sustainable future, energy should be primarily derived from non-fossil sources, while also being flexible, safe, reliable, affordable, and abundant (Brownsword et al., 2005). Renewable energy generation sources are constrained from adoption in many instances by the intermittency of their outputs (Barton & Infield, 2004). PHS on a small, distributed scale can serve as a viable option for communities as they move into transforming their energy and water systems to include energy storage systems (Dell, & Rand, 2001).

However, most local decision-making officials don't have time or capacity to assess cost-benefit models for water systems, and then learn how to use them. When the element of connecting the water system to the energy system is added, uncertainties and knowledge gaps increase substantially (Lubega & Farid, 2014). In many cases, these officials are appointed for political reasons, rather than for technical skill sets. In these cases, good policy and decision-makers rely on the analysis of system specialists to make sound, timely decisions. Researchers and policy makers interact best when goals, technologies, methodologies, and tools have been digested by the scientific community and are presented to local communities in a way that is easy to understand, with clear decision points and recommendations. Recommendations are strongest when CBA and ROI data is presented with them, so what's technically possible can be clearly translated into real-world constraints and timeframes (Schoenung et al., 1996).

Water System Upgrade Considerations

When cities and counties consider investment options in water infrastructure, they examine water use by potential development pattern (Dandy et al., 1984). They consider the age of the system's components and estimate replacement costs, the cost of doing nothing, and the costs of phasing upgrades (Swyngedouw et al., 2002). A geographic information system (GIS) is a common tool used to overlay these development projections (Maantay et al., 2006). The municipal scenario-based planning process can utilize a wide variety of tools, using baseline data and localized challenges to project economic, social,

and environmental scenarios over specified time horizons (Otterpohl et al., 1997). More and more, communities are turning to the private sector to share the enormous costs of upgrades (Beecher, 1997).

Perhaps the most interesting aspect of the gravity-fed pipe generation pilot project in Portland, OR is the use of a third-party finance model (Electronic Engineering Journal, 2015). The private sector is installing and operating it for 20 years, recouping costs, and then selling the system to the city. This is interesting because it points to the critical role that infrastructure plays in how much storage and potential energy production urban water systems can produce. Most communities in the U.S. host old water distribution systems, and water-piping infrastructure can date back to over 100 years in some instances (Al-Barqawi & Zayed, 2006).

Leaky pipes impact water delivery and transfer, and can inhibit the ability of the system to efficiently host storage and generating equipment (Misiūnas, 2008). Because of the heavy maintenance costs a local utility bears, there is often little room to be proactive (Grigg, 2005). Through tax incentives and credits for renewable energy generation, the private sector can access resources inaccessible to governments (Menanteau et al., 2003). This can in turn buy down the capital costs of planning and implementation. If the private sector can then recoup the costs of the system with an acceptable profit margin, it can sell the system at fair market value to the city or county. That government can continue to realize savings over time, but also faces maintenance of the now-aging infrastructure (Wiser & Pickle, 1998). This finance model manifests itself repeatedly in public-private partnerships centered on renewable energy generation (Lewis & Miller, 1987).

Distributed energy storage (DES) refers to stationary electric energy storage systems located at or near the end use that they serve, such as residential, commercial, or industrial buildings (Zogg et al., 2007). DES systems, in combination with advanced power electronics, will play a significant role in the electrical supply systems of the future. Right now, when energy storage systems are integrated into conventional electric grids, each requires its own unique design. This process has direct budget implications to utilities contemplating implementation of these systems (Carpinelli et al., 2013).

Because of the growing move towards energy system transformation (Jacobsson & Lauber, 2006), more flexibility with distributed generation and storage is needed (Atzeni et al., 2013). Small and medium storage systems are needed in both the supply and demand sides as storage moves from concentrated storage (reservoirs, in the case of traditional PHS) to distributed storage (equipped with intelligent power

electronics conversion systems that control small scale PHS, for instance). As with any newer system technology, models, planning tools, and budget methods that will enable the use of storage devices at the DES level are not yet widely used (Mohd et al., 2008).

Research Motivation

This research examines the financial implications of increasing energy storage in urban water systems. It examines the cost of augmenting an urban water system with additional water storage for energy generation in concentrated and distributed configurations, and compares the attractiveness of increasing storage for energy generation to the initial capital direct and indirect capital costs, together with operating and maintenance (O&M) costs. It examines the benefits and costs associated with various water storage enhancements within an urban water system. It explores key financial factors and levers that impact energy storage decisions within an urban water system. The potential impacts on capital planning budgets are examined.

The tested hypothesis assumes that energy storage enhancements in urban water systems have financial variables that include localized energy and water costs, and that these costs can be analyzed to determine the fiscal attractiveness of various storage configurations. To answer the motivating research questions and test the hypothesis, concentrated and distributed storage scenarios already developed in a case study water system model are analyzed in an Excel-based scenarios calculator against: (1) energy rate structures; (2) energy consumption to charge storage; (3) energy production potential from additional storage; and (3) the initial capital investment and annual operating costs of installing additional storage.

3.2 Cleveland Utilities Budget Summary

Using Cleveland, TN as the case study water system, it is important to understand how this city and municipal utility allocate resources. The city prepares an annual fiscal year (FY) budget. There is also a separate 6-year Capital Improvement Needs Inventory (CINI), which includes all requested capital projects, by department.

Water and Energy System Expenditures

CU prepares a separate document for its water, wastewater, and electric capital improvements. Figure 44, taken from the *City of Cleveland Tennessee Annual Budget, FY 2016-2017* (p. 244) presents a summary of CU's FY 2017 budget highlights. It also presents water division capital expenditures by category.

City and Utility Enterprise Funds. The CU Water and Electric division enterprise funds accounts for all water, wastewater, and electric service provision to occupants within the CU service territory. Enterprise funds are used for the acquisition, operation, and maintenance of city government facilities, as well as for services that are predominantly supported by user charges. The accounting of these enterprise funds show profit or loss. According to the Government Finance Officers Association (2017), enterprise funds differentiate between current and latent assets and liabilities (2017). This distinction allows cities to calculate working capital, which is current asset value minus current liability value. In summary, working capital is a measure of total liquid enterprise fund capital, constituting a margin that can be used to meet other fiscal commitments.

Cleveland has 3 enterprise fund service plans: (1) Stormwater Management, which is used to meet the National Pollutant Discharge Elimination System (NPDES) requirements; (2) Cleveland Utilities (CU) Electric Division, which accounts for all activities required to provide electric service to the residents of the City; and (3) CU Water/Wastewater Division, which accounts for all activities required to provide water and wastewater service to the residents of the City. CU's proprietary enterprise funds depend on utility use, which are impacted by annual variations in weather and market conditions. CU's electric, water, and wastewater divisions are considered major funds of the City.

Proposed and anticipated 2016-2017 revenues are \$102,225,948 for the electric division enterprise fund, and \$28,285,859 for the water/wastewater division fund (p. 32). Proposed and anticipated expenditures for the 2 funds are \$97,307,022 and \$22,976,631, respectively (p. 34). Figure 45, taken from the *City of Cleveland Tennessee Annual Budget, FY 2016-2017* (p. 25), presents a summary of CU's revenue funds.

City and Utility Revenues and Fund Transfers. Although CU's budget is presented within the City of Cleveland's budget, CU is not funded from the City of Cleveland's budget. This is because the utilities operate on their service fees, not from city taxpayer revenue. From the City of Cleveland's FY2016-2017 operating budget, CU's recent local rate increases include: (1) a 5.13% water customer rate increase, which includes a 1.13% Hiwassee Utility Commission (HUC) pass-through; (2) a 4.50% increase for wastewater customers; and (3) a 1.50% rate increase for electric customers, which does not include any potential Tennessee Valley Authority (TVA) rate increase pass-through in FY 2017 (p. 244).

Unlike other utilities in other states, CU does not transfer profit into the city of Cleveland's general fund. They do, however, make transfers in lieu of taxes. These transfers make up 5.2% of Cleveland's total

general fund revenues (p. 79). Payments received by the City of Cleveland as a transfer from CU include \$225,146 in-lieu-of-tax for water services, and \$206,000 in-lieu-of-tax for wastewater services (p. 89). These amounts are based upon the value of water and wastewater division assets, adjusted for depreciation. A transfer of \$1,912,477 from CU's electric division represents the amount of property tax the electric division would pay if they were a private company (p. 244).

Revenues from service charges account for 61% of Cleveland's cash intake, and CU customer bill payments comprise most of this revenue (p. 4). Other city service charges include sanitation, stormwater, school, and recreation fees billed to city residents. CU power purchases account for 36.2% of this revenue use. CU operation expenses are at 10.8% (p. 3).

Principal operating revenues for the City's enterprise funds and internal service fund are charges to customers for sales and services. These include daily operations, administration (including financing and bill collection), maintenance, and depreciation on capital assets. The water division also realizes operating revenue designated to recover new customer connections from its tap fees. Revenues and expenses not meeting the operating-revenue definition are reported as non-operating revenues and expenses (p. 57).

Depreciation and Debt Structures. To allow for depreciation, a composite rate is used. This is a percentage of average depreciable assets. The 2015 rates were 3.7% for the electric division and 2.8% for the water division (p. 59). When property is retired, its remaining costs are combined with removal costs, and charged to the depreciation reserve. Replacements are charged to various utility plant accounts. CU's electric and water divisions charge a portion of equipment use depreciation (vehicles, for instance) to other expense classifications. Depreciation charged to other accounts was \$269,474 for CU's electric, and \$112,385 for CU's water division (p. 59).

For the electric division, structures, including electric transmission and distribution systems, has a depreciation schedule of 33 to 50 years. The water division's depreciation schedule for structures, including the water distribution system, is 25 to 50 years. For both divisions, equipment has a depreciation schedule of 10 to 20 years, and transportation equipment has a depreciation rate of 5 years (p. 59).

To finance CU debt, the city issues general obligation bonds against the taxing authority of the city, as well as against revenues from CU's water/wastewater or electric funds. Cleveland's credit rating is "AA"

with Standard and Poor's Corporation, and "Aa3" with Moody's Investor Service (p. 93). CU's revenue bonds have the same ratings, and they make their own debt service payments from the borrowing division's enterprise fund. CU long-term debt for business activities is 18.2% of the city's total long-term debt, while 31.5% of long-term debt is in CU revenue bonds, comprising almost half of the city's long-term debt (p. 207).

Regarding new debt, CU's Water Division has \$5,000,000 in authorized loans from the State of Tennessee's Revolving Fund. These loans are being draw down over 3 fiscal years, through the end of FY 2017. They are purposed for the completion of Advanced Metering Infrastructure (AMI) meter installation (p. 23). Additionally, CU's electric division budget is projecting \$3,000,000 in new debt. The water division is also projecting \$5,225,000 in new debt, and the sewer division is projecting \$5,652,000. This debt, if incurred, will fund capital projects (p. 32).

Also, in December 2012, Cleveland's City Council approved the issuance of \$6,000,000 for the purchase of property for a new industrial park. Bradley County will fund this park with CU (p. 234). This note is for 15 years and will mature May, 2028. The new debt issuance requires additional revenues to pay the new principal and interest payments. Funds to cover new debt can come from a debt service fund, or from enterprise and internal service funds.

CU pays all the debt service payments on any general obligation bond issued on its behalf (*City of Cleveland Tennessee Annual Budget, FY 2016-2017*). Some proceeds of CU's water division revenue bonds, as well as resources set aside for bond repayment, are restricted assets. This is because they are maintained in separate bank accounts and their use is limited to terms within the bond covenants. When both restricted and unrestricted resources are available for use, restricted resources are used as needed, before unrestricted resources are tapped (p. 58).

The city can choose to finance capital projects through loans from bond proceeds issued by the Public Building Authority of Sevier and Blount Counties, TN (p. 202). These include access to \$16,897,283 for city general projects and \$14,925,752 for CU projects. Figure 46, taken from the *City of Cleveland Tennessee Annual Budget, FY 2016-2017* (p. 38), presents a summary of CU's 2016 schedule of debt payments.

Long-Term Utility Planning

Because providing utility services requires access to significant capital and debt (which requires assurance of timely debt payments), long-term plans are developed to meet financing requirements. CU prepares a budget for the upcoming fiscal year, as well as an estimated budget for 9 years beyond the upcoming budget year (p. 251). The long-range plan included with CU's FY 2017 budget covers FY 2018 to 2026. It accounts for rate adjustments, to avoid unexpected increases and to prevent financial surprises. CU makes assumptions when they prepare long-term budget projections. These include:

- Projected volumes, using historical averages and statistical modeling
- Rate adjustments to match system demands from operating and capital expenditures
- Projected expenses with inflation variables
- Development of capital requirements spanning fiscal years, to account for changing service demands, new regulations, and maintenance and upgrades of existing facilities
- Interest rate and payback period estimates, for new bond issues
- Maintenance of cash balances, to meet payment obligations

Examining customer growth over time is a key part of creating these assumptions. For instance, in 1997, CU had 25,537 electric and 24,053 water customers. In 2015, the numbers grew to 30,808 and 30,928, respectively (p. 252). Examining performance is another key part of creating these assumptions. Figure 47, taken from the *City of Cleveland Tennessee Annual Budget, FY 2016-2017* (p. 255), shows an example of CU's electric division performance measures. Figure 48, taken from the *City of Cleveland Tennessee Annual Budget, FY 2016-2017* (p. 261), shows an example of CU's water division performance measures.

3.3 Tennessee Valley Authority Rate Structures

The Tennessee Valley Authority (TVA) makes the electricity used by 9 million consumers across a 7-state region, including the U.S. states of Tennessee, Kentucky, Alabama, Mississippi, Georgia, North Carolina, and Virginia (TVA, 2017a). TVA sells power to local electric distributors, who then sell power to customers in their service territories. Like other major electric suppliers in the U.S., TVA charges power-purchasing electric utilities a monthly fuel cost.

Roughly 75% of TVA's power supply comes from fuels-based electricity sources, like coal, natural gas, oil, and nuclear fuel rods (TVA, 2015a). TVA's costs change when these fuel prices change, due to

variables such as weather conditions or global supply-chain changes. This results in monthly cost increases or decreases, that are passed on to the customer via the local distributor. In addition to fuel costs, TVA's total monthly fuel costs include fixed costs, such as power plant operations and transmission line maintenance.

For example, the variable portion of the TVA total monthly fuel cost for a residential customer could be around \$10 per 1,000 kilowatt hours (kWh). The fixed portion of the TVA total monthly fuel cost for a residential customer could be around \$20 per 1,000 kWh. The total customer bill in that example will be \$30 per 1,000 kWh. If that household uses 2,000 kWh in a month, they will pay \$60 in total monthly fuel costs. It varies not only by household, but also by sector. Commercial and industrial TVA monthly fuel cost rates will be quite lower than for the residential sector.

Peak Demand Pricing

Weather, fuel type used to create power, and time-of-use influence the cost of each kWh produced. It costs more to generate electricity during peak demand than it does during non-peak periods. TVA has begun to implement peak-demand pricing structures, beginning by season. Once AMI metering is common throughout distributors in the TN valley, peak-demand pricing can be implemented by time of day. Peak demand is somewhat predictable. Summer afternoons and winter mornings are 2 examples of seasonal peak-demand periods.

TVA peak-demand hours occur in the afternoons and evenings of summer (June to September) and early to mid-mornings in winter (December to March). According to TVA's fact sheet, *The Price of Power*, winter peak is from 5:00 AM eastern time (ET), to 11:00 AM ET. Summer peak is from 1:00 PM to 9:00 PM ET (Tennessee Valley Authority, 2015). Summer months are June, July, August and September; Winter months are December, January, February and March; and Transition months are April, May, October and November (TVA, 2015c).

The cost of electricity also increases as commerce and population increase. To meet rising demands, at times more expensive power must be purchased from other companies, or more expensive generation methods must be brought online, such as quick-start natural gas plants (Tennessee Valley Authority, 2015a). Peak demands are growing faster than energy generation infrastructure. Peak-demand pricing structures are not designed to create additional revenue streams for power producers or distributors. Instead, they are intended to incentivize, through a direct market mechanism, reduction of peaks to avoid

having to build new power plants. TVA is using a variety of new infrastructure-avoidance methods, including energy-efficiency incentive programs, peak-demand pricing, and, to a small extent, use of intermittent renewables (TVA, 2017a).

Wholesale Rate Adjustments and Demand Schedules

A rate adjustment is the process by which energy providers increase rates to match revenue needs. According to TVA's final assessment report, *Refining the Wholesale Pricing Structure, Products, Incentives, and Adjustments for Providing Electric Power to TVA Customers* (2015b), recent TVA rate adjustments are of 2 kinds: (1) general electricity pricing structures and rates; and (2) specific adjustments, credits, and products. Within these 2 categories, pricing structures and rates are loosely grouped by size and service mechanism: (1) small-scale wholesale standard service-by-power distributors, which includes residential, commercial, and small industrial customers; and (2) large-scale wholesale service requiring over 5,000 kilowatt (kW) demands, including manufacturing and commercial customers.

This second category includes both individually-metered customers serviced by distributors under non-standard service provisions, as well as customers directly serviced by TVA. Using data from Appendix A of TVA's final assessment report, Table 21 shows the TVA wholesale rate design with time-of-use pricing structure, as well as time-differentiated rates for the TVA General Service Class.

In 2016, TVA distributors adopted TVA's latest customer rate schedules. TVA rate schedules are structured by kWh use, so a type of customer can fall into several different classes if they operate more than 1 property. For instance, a city in the TVA service territory can be in the GSA-2 class for larger buildings (like city hall), a GSA-1 class for smaller buildings (like fire stations), and an LS class for lighting (streetlights, for instance).

Electric distributors bear the burden of explaining TVA rate schedules to customers. Table 22 shows the most recent TVA rate schedule by kWh use, with data adapted from a distributor's website designed to help customers understand their bill structure (Nashville Electric Service, 2017). CU now operates under this rate schedule.

3.4 Financial Analysis Methodology

There are 2 primary costs to consider for an electricity storage system: energy cost/rating and power cost/rating (Ibrahim et al., 2008). Energy cost for storage is the purchase price of the rechargeable

equipment and infrastructure (batteries or pumped hydro reservoirs, for instance) that store energy. The energy rating of a storage system is the total energy the system can store. The energy rating of a storage unit can be calculated using capacity in units. For instance, reservoir gallon capacity can be converted into kW or kWh, and batteries have ampere-hour (Ahr) ratings that can be converted into watt-hours (Wh), kWh, or Ahr (Zakeri & Syri, 2015). In this research, energy cost is expressed in unit-cost of stored energy, or in U.S. dollars (USD) per kWh.

While also expressed as the cost-per-unit of power (USD/kWh), power costs measure the purchase price of 1 unit of electricity (to run the pumps that fill a hydro-power reservoir, for instance). The power rating of a storage unit measures the unit's instantaneous capacity, or how quickly the storage system can be re-charged. Power and energy costs together provide the total initial capital cost of a storage unit (Hrafinkelsson et al., 2016).

Calculating Potential Renewable Energy Generation Credits

TVA Green Power Providers (GPP) is a renewable energy program that structures how TVA accommodates customer-generated small-scale renewable energy. Customers within the TVA region have been requesting access to “net metering”, which is a bi-directional meter that measures electricity current flowing from a system to meet localized energy consumption, or onto the grid, if unused by the system owner. Net metering is commonly used in other utility service areas, and is attached to a billing mechanism that credits renewable energy system owners for any electricity they put onto the grid, after their own energy needs have been met.

In response, TVA created an alternative to net metering they call “dual metering”. More complicated than net metering, dual metering involves the installation of 2 meters at a renewable energy system: 1 to measure power output from the system, and 1 to serve as the billing meter. Rather than allowing customers to harvest generated energy for their own use, TVA instead requires that TVA purchase 100% of the energy generated by GPP participants, while they continue to purchase electricity from their local distributors. TVA will buy the renewable energy output at the retail electricity rate and retain the renewable energy credits (RECs) for the duration of a 20-year agreement. TVA uses this generation to credit their “Green Power Switch” program, which allows other customers to buy renewable energy credits to offset their own fossil-based energy use (TVA, 2017c).

While the GPP program is designed for residential and commercial customers of local TVA distributors, it is being examined now to understand how a power purchase agreement could be constructed in the case of CU and any potential small-scale hydropower generation. Ideally, and if they were in a different utility's service area, CU would be able to use any hydro-generation to offset their own water system's energy consumption. However, unless open to net metering negotiations with a local power distributor, TVA will purchase in full any hydro-power generation (or, "generation credit") from CU under a 20-year GPP agreement.

This is only if CU presents any hydro-generation as a secondary use, the primary purpose of the water system still being to meet water customer demands. According to the 2017 GPP Guidelines, TVA accepts a minimum of 0.50 kW and a maximum of 50 kW per contiguous-property customer. A GPP applicant must provide its projected annual usage (kWh), as well as their proposed nameplate capacity of the qualifying system.

To TVA, the generation credit refers to accrued credits a GPP participant earns by generating renewable energy. It is calculated by applying the energy charge in the applicable retail rate schedule to the kWh energy output the generation meter measures. CU would likely be classed in the GSA-1 retail rate, which is the rate schedule TVA applies to industrial (large) customers.

The generation meter measures alternating current (AC, from a non-inverter-based energy system), and can be interval, non-interval, or both. In addition to submitting a professional estimate of expected generation, the GPP participant must adhere to a TVA annual capacity-factor-by-generation type. "Low-Impact Hydropower" is 50%, for instance. Using the kW per year generated one of the case study energy storage scenarios (89,175 kWh over 3 days from concentrated storage), the CU equation to calculate maximum nameplate capacity for generating tanks as follows:

$$3,303 \text{ kW per year} * 3,285 \text{ discharge hours per year} * 50\% \text{ capacity factor} = 5,424,961 \text{ kWh, where}$$

$$kW = (89,175 \text{ kWh} * 121.67 \text{ 3-day periods in a year}) / 3,285 \text{ generating hours per year}$$

This means that by TVA GPP standards, CU would be generating too much (more than 50 kW) hydro-power to fit into this program. A special distributor program would need to be developed between CU and TVA, ideally one that allows for net metering. It would benefit CU to be able to offset water system

energy costs before returning any power to the grid. TVA, while not being able to capture the renewable energy generation credit in this case, would still benefit from no longer needing to provide for CU's water system energy load, which could become a self-servicing, independent microgrid.

Financial Analysis Inputs and Outputs

The costs of developing a small-scale hydro generating system can be classified as either initial capital costs or annual operating costs. Capital costs include the purchase of design time, materials and equipment, and construction labor. Annual operating costs describe daily operation and maintenance. Table 23, adapted from data presented in a study on the cost per kWh for energy storage (Poonpun & Jewell, 2008), summarizes generic inputs needed to perform these calculations, and the outputs from these calculations.

Municipal decision-makers not only want to understand costs and benefits of infrastructure investments. They also want to understand the lifespan of infrastructure components, which is typically assigned by the manufacturer in a year range in an equipment specification sheet. Additionally, they want to know estimated return on investment, if that infrastructure will be used to generate service fees or profit. Finally, when it comes to the installation of renewable energy systems, payback periods are also important to understand. These calculations provide a sense of when the investment begins to generate profit, once the initial investment has been payed off by system-generation outputs. Table 24 describes the ways in which cost benefit analyses (CBAs), return on investments (ROIs), and payback periods differ.

Pricing Assumptions

Until bids for a professional engineering feasibility study, site analysis, engineering design, and construction, including equipment specification sheets, are in hand, CBAs and/or ROIs are performed using certain market and system operating assumptions.

As with the water system model, which is a tool to simulate performance in conceptualized scenarios, initial financial analyses are also a tool to provide a starting point for exploring budget possibilities. As water system model controls must be stated, so that system operating assumptions are clear, likewise financial analysis must be clear on cost assumptions and areas of pricing flexibility.

Energy Pricing Assumptions. Time-of-use rates provide the basis for determining energy generating and pumping costs by kWh. In the case of the 2 CU water distribution system storage scenarios, concentrated

and distributed, storage tank operation is designed to charge tanks during off-peak electrical use times of day, and to discharge them during peak times of day. Storage tanks discharge during daily peak-electrical periods (1 to 9 PM ET), and recharge each day during off-peak hours (from 9 PM to 12 AM ET). Water tanks are modeled using controls that prompt tank discharge to generate electricity during 1 peak-electrical diurnal curve, for a period of 9 hours in a 24-hour day, 356 days per year.

Since the CU electric generating potential is much greater than what the TVA GPP guidelines (TVA, 2017b) will accommodate, a specially negotiated rate will need to be agreed upon between CU and TVA. This agreement would dictate terms, such as the TVA purchase price of CU on-peak energy generation by kWh, as well as the rate CU would pay for energy to re-charge storage during off-peak hours. However, lacking such an agreement, and for the sake of this fiscal research to understand scenario costs, the TVA rate schedule TGSA-2 is initially used to calculate on-peak and off-peak generation prices.

The TGSA-2 schedule is for customers that fall into the greater than 50 kW and less than or equal to 1,000 kW use range. According to this rate schedule, during the summer season, the customer is charged \$0.09 per kWh used during on-peak hours, and \$0.06 per kWh used during off-peak hours. Depending on scenario, CU can generate between 200 and 400 kW from storage discharge, and requires between 300 and 600 kW to recharge it (assuming a 70% pump efficiency ratio). It is assumed for the purposes of this research that CU could be paid \$0.09/kWh for on-peak generation, and be charged \$0.06/kWh for off-peak energy consumption to re-charge the water storage tanks (TVAc, 2017).

Negotiated energy rates, whether paid for generation or charged for pump energy consumption, would be subject to the following conditions: (1) base energy use charges increase or decrease according to current TVA rate adjustments and power purchase rate changes; (2) the “hydro allocation credit”, or what is paid for energy generated, is also subject to increases or decreases to the applicable wholesale power rate schedule; and (3) any contractual arrangements made between TVA and CU, as the local distributor.

Initial Capital Cost Assumptions. Initial capital costs include the direct costs of equipment, such as reservoirs, generating equipment, pumps, and distribution piping. Direct equipment costs can be found in hydro-electric industry catalogues, and in various hydro cost-estimating calculators. Understanding equipment type, size, material components, and quantity needed is important to get a reasonable estimate. However, equipment costs can vary widely by distributor, region, and desired materials, so initial pricing

estimates are simply a starting point for an initial financial analysis of project costs (Aggidis et al., 2010). Determining direct costs for small-scale hydropower becomes the basis for calculating indirect costs.

Indirect Capital Cost Assumptions. Initial capital costs also include the indirect costs of engineering design, project management, and construction labor. While it is common for professional engineering feasibility studies and site selection analysis to happen prior to commissioning a generation system design, it is expected that the engineering design and project management fees will comprise at least 10% of the total project costs. It is also expected that construction costs will be approximately 40% of total project costs (Bailey & Bass, 2009).

Annual Cost Assumptions. Annual operating costs are comprised of financing charges, such as interest and equipment depreciation rates. It also consists of operations and maintenance fees, such as energy consumption and equipment replacement. While operating costs may vary from year to year depending on various lifespans of equipment components, annual operation costs can also be estimated based on hydropower project costs. Annual operating and maintenance (O&M) costs are typically quoted as a percentage of the investment costs. O&M for small hydropower can range from 1% to 4% (Paish, 2002). This percent typically includes mechanical and electrical equipment refurbishments, such as turbine overhauls, generator rewinding, and upgrades in control and communication systems (Kusakana et al., 2008). For this research, 1% is used as the O&M percentage.

Financing charges are estimated at 2% of the total project costs, based on a 20-year AA municipal bond (Brueckner, 1997). For depreciation, 1% of total project costs is used (Hosseini et al., 2005). For energy consumption, 1 year of storage recharge pumping costs are derived in kWh from recharge pump energy consumption summed from each storage scenario model's off-peak pumping hours. Pumps are assumed to have 70% efficiency, making the energy used to pump greater than the energy created from generation (Williams, 1996).

3.5 Results

Research from the CU case study resulted in the testing of 4 water storage and demand scenarios: (1) concentrated storage with current water and electrical demand conditions (A1); (2) distributed storage with current water and electrical demand conditions (B1); (3) concentrated storage with future water and electrical demand conditions (A2); and (4) distributed storage with future water and electrical demand conditions (B2). The design parameters used to create scenario A1 are the same for scenario A2, as only

demand changes in A2. However, demand changes would result in the doubling of existing storage again, and necessitate at least 10 pump upgrades throughout the water distribution system.

Demand changes would also result in a pipe sizing upgrade from water source to water treatment plant. Likewise, the design parameters used to create scenario B1 are the same for scenario B2, as only demand changes in B2. However, demand changes will result in 10 pump upgrades throughout the system. It would also result in a pipe sizing upgrade from water source to water treatment plant. The following section outlines results by scenario.

Scenario A1 Results: Concentrated Storage, Current Demand

Scenario A1 direct capital cost estimates total \$20,068,839. This includes the cost of upper and lower tanks, turbines, generators, powerhouses, control systems, electrical systems, pumps, and piping loops that connect upper tanks to lower tanks. The concentrated storage scenario calls for 18 total 3.5 million gallon tanks, to supply the upper and lower configurations.

The design assumes an in-line turbine. Each generating loop will require a small associated pumping station that houses the associated generator, electrical, and control systems. The turbine chosen for pricing is the Pelton, designed to be impulse motivated. Invented by Lester Allan Pelton in the 1870s, this turbine generates energy from water movement, unlike other turbine designs that rely on the water weight. It is common for small scale systems to use this kind of turbine, especially if water flow is to be harnessed within the pipe distribution system itself (Islam et al., 2013).

Table 25 is designed by item, detailing unit cost, total units required, total cost, life expectancy, and primary pricing and lifespan sources of information. Due to manufacturer pricing variability, sources are cross-referenced against available pricing structures to ensure that the numbers presented are strong estimates of possible costs by unit. A primary source is listed in Table 25 for reference purposes.

Scenario A1 indirect capital cost estimates total \$10,034,420, and are presented in Table 26. Scenario A1 annual O&M cost estimates total \$1,562,162, and are presented in Table 27.

Scenario A1's annual energy generation potential from peak-hour discharge by tank is 10,849,992 kWh/year. This is calculated by summing tank discharge in 5-minute time steps over a 3-day model run and extrapolating that kWh (89,175) over 1 year. The potential pump energy used to recharge tank storage

is 15,499,889 kWh/year. It is calculated by summing energy consumed by pumps that are refilling the generating tanks during off-peak hours and extrapolating that kWh (127,393) over 1 year.

Fiscal cost analysis calculations are originally performed using TVA's TGSA-2 schedule, which designates \$0.09/kWh used during on-peak hours, and \$0.06/kWh used during off-peak hours. However, when this rate was put into the Excel-based financial cost analysis spreadsheet built to perform these calculations, buying electricity at \$0.06/kWh and selling electricity at \$0.09/kWh produces an annual financial loss of \$585,669. Using this pricing structure, annual operating costs for an initiative like this will not break even until the electricity can be sold for somewhere between \$0.14 and \$0.15/kWh.

For this reason, the TVA TSGA-1 schedule is applied instead. Use of this rate would have to be negotiated as a special term of the power purchase contract, but it would allow CU to be paid \$0.17/kWh for on-peak generation, while purchasing off-peak pumping power at \$0.06/kWh, thus managing a slight annual financial gain, rather than an annual operating loss. Table 28 presents this energy generation and consumption potential by possible rate paid for generation, and charged for consumption.

The results of the scenario A1 fiscal analysis are featured in Table 29. The amortization timeframe used from initial installation is 20 years. This is used to calculate the ROI, to insure the formula is not written to attempt to recuperate the entire investment in one year. CU would have to purchase off-peak electrical energy at \$.06/kWh and sell it at nearly \$3.25/kWh to pay the project off in 1 years' time. The total installation cost estimate concentrated storage configuration is \$30,103,259. When combined with the total annual operating cost and the estimate of total annual value of energy generated, the ROI for the concentrated storage configuration is 112 years. This is not within local planning and financing time frames.

Scenario A2 (concentrated storage, future demands) would incur the same system upgrade costs as exhibited for scenario A1. Additionally, because the tank farm scenario cannot meet doubled water demands throughout the system, it would also require existing storage throughout the rest of the water system to double again before it will deliver adequate pressures and water supply. It would result in at least 10 additional pump upgrades throughout the system, as well as 1 water source intake up-sizing. The payback period for scenario A2, which is already prohibitive, would be at least double the payback period for scenario A1.

Scenario B1 Results: Distributed Storage, Current and Future Demand

While scenario A1 tanks are all the same size, scenario B1's tanks are each different. This is because in scenario B1, existing tank heights are doubled, and the bottom storage tank is half the size as the upper tank, as only the doubled capacity can be used to generate electricity. The rest (original size) must still be used to meet water system demand, maintain system pressures, and keep at least 1 day in fire storage. Table 30 shows each original tank's modifications, as well as the gallon capacity of each new lower tank. Cost estimates are calculated by tank gallon capacities.

Scenario B1 direct capital cost estimates total \$15,718,065. Table 31 is designed by item, detailing unit cost, total units required, total cost, life expectancy, and primary-pricing-and-lifespan sources of information. Due to manufacturer pricing variability, sources are cross-referenced against available pricing structures to ensure that the numbers presented are strong estimates of possible costs by unit. Scenario B1 indirect capital cost estimates total \$5,239,355, and are presented in Table 32. Scenario B1 annual O&M cost estimates total \$796,291, and are presented in Table 33.

Scenario B1's annual energy generation potential from peak-hour discharge by tank is 5,439,133 kWh/year. This is calculated by summing tank discharge in 5-minute time steps over a 3-day model run and extrapolating that kWh (44,704) over 1 year. The potential pump energy used to recharge tank storage is 7,770,190 kWh/year. It is calculated by summing energy consumed by pumps that are refilling the generating tanks during off-peak hours and extrapolating that kWh (68,863) over 1 year.

As with scenario A1's cost analysis, the TVA TSGA-1 schedule is applied, allowing CU to be paid \$0.17/kWh for on-peak generation, while purchasing off-peak pumping power at \$0.06/kWh, to be able to operate with an annual financial gain, rather than a loss. Table 34 presents this energy generation and consumption potential by possible rate paid for generation, and charged for consumption in the B1 scenario. Table 35 shows the results of the scenario B1 fiscal analysis. As with scenarios A1, the amortization timeframe used from initial installation is 20 years.

Scenario B2 (distributed storage, future demands) would incur the same system upgrade costs as exhibited for scenario B1. It would also result in at least 10 additional pump upgrades throughout the system and at least 1 water system intake upgrade, judging from existing pump curve modifications made

in the B2 water model during scenario development. The addition of 10 pump upgrade costs alone (taking pump costs from \$556,940 to \$1,113,880), makes the payback period for the B2 scenario 157 years.

3.6 Conclusions

Energy storage enhancements in urban water systems have financial variables that include localized energy and water pumping costs, and these costs can be analyzed to determine the fiscal feasibility of various storage scenarios. Energy market design and how these markets treat stored energy must also be considered over time. The price paid for energy during peak electrical demand times, as well as the price charged for energy use during off-peak electrical demand times is only one primary component of the economic justification for storage. The cost of implementation of additional storage, including transmission and generation components, must be considered in a complete economic analysis.

Scenarios A1 (concentrated storage) and B1 (distributed storage) implementation and annual operating costs are assessed against energy generation and energy consumption rate structures, to understand if it is fiscally attractive to modify the water distribution system to include increased water storage for energy generation. This research is performed to understand if energy storage in urban water systems can be an economically realistic decision. Using the CU case study, and under the design parameters outlined for the storage scenarios, the answer is no.

An initial assumption of this research effort was that without peak electrical demand pricing, pumped storage in the urban water system is economically unattractive. This is because it requires more kWh to pump and recharge storage units than can be generated during storage unit release. The results of analyzing costs and benefits for the storage scenarios show that, even using the most attractive rate available for peak-demand electricity generation, peak demand pricing at its current rate is not enough to financially justify the addition of the amount of storage needed to shave community peak electrical demand by 5-10%. Even with long-term utility planning and multi-year capital improvement investments, the cost to upgrade the water system with additional storage capacity is much greater than the benefit of the potential energy generation.

Renewable energy rates currently available from most wholesale energy producing utilities are not substantial enough to make the investment needed to significantly enhance an entire community's water distribution system with more water storage. The prices paid for renewable-energy generation during peak-demand times needs to increase. Additionally, the cost of electricity storage system implementation

needs to decrease before energy storage in urban water systems will be useful for widespread load-leveling use (Ardizzon et al., 2014).

Costs to store electricity are highly dependent on the system's design parameters (the number of discharge cycles per day, or number of operating days per year, for instance). Deviations in scenario design, or the need for additional water system upgrades (as seen in scenarios A2 and B2), can greatly increase the payback period. Cost considerations such as these should be factored in on the front end of a small-scale hydropower storage system's design. Doing so can optimize operation costs, and significantly reduce infrastructure costs.

Cost estimates are a product of the most reasonable prices offered from various vendors. Except for adjusting the negotiable TVA rate schedule from the original assumption of TSGA-2 to the new assumption that TSGA-1 could be negotiated instead, pricing structures were not deliberately underestimated to make the scenarios appear fiscally favorable. In scenario A1, which generates the most energy, operating costs are significant (\$1,562,162). Even with the assumption that CU can pump energy at \$0.06/kWh and sell it at \$0.17/kWh, the annual operating profit is insignificant (\$282,325). As the best cost option of the 4 scenarios, it is still not sufficient to recuperate the initial \$30,103,259 investment before the equipment will wear out and need to be replaced. Even with the initial investment amortized, the ROI is negative (-91%), and the payback period unreasonable (112 years) for a local utility to accept.

As with the operational and design parameters, the limits of scalability are important front-end design considerations. Larger cities with significant water storage already in place (Seattle, for instance) could likely implement distributed generation from storage within an urban water system much more cost-effectively than can a city the size of Cleveland, TN. Even in emerging cities, which are more flexible and which have the advantage of being able to see all kinds of implementation strategies from other cities, in storage situations where water tanks must be constructed within an existing water distribution system to generate electricity, the financial analysis will likely demonstrate infeasibility.

However, current research and implementation projects alike are pointing to the attractiveness of microgrid concepts, or small-scale networks servicing electricity users from a localized power supply, especially from a resiliency standpoint. While microgrids cannot operate on a community-wide peak-demand-leveling energy scale, they can function well from a reliability perspective. Microgrid scale pumped storage can also be designed so that the pumps are solar-powered, which, if additional

photovoltaic component infrastructure costs can be overcome, could significantly reduce the pumping costs to recharge storage significantly over time (Ardizzon et al., 2014).

References

- Aggidis, G. A., Luchinskaya, E., Rothschild, R., & Howard, D. C. (2010). The costs of small-scale hydro power production: Impact on the development of existing potential. *Renewable Energy*, 35(12), 2632-2638.
- Agudelo, J. I. (2001). *The economic valuation of water: Principles and methods*. Delft: IHE Delft.
- Al-Barqawi, H., & Zayed, T. (2006). Condition rating model for underground infrastructure sustainable water mains. *Journal of Performance of Constructed Facilities*, 20(2), 126-135.
- Annual Electric Power Industry Report (EIA-861 data file). (2017). Retrieved data from forms EIA-861, schedules 4A & 4D and EIA-861S on September 3, 2017, from <https://www.eia.gov/electricity/data/eia861/>
- Ardizzon, G., Cavazzini, G., & Pavesi, G. (2014). A new generation of small hydro and pumped-hydro power plants: Advances and future challenges. *Renewable and Sustainable Energy Reviews*, 31, 746-761.
- Armstrong, R. D., & Willis, C. E. (1977). Simultaneous investment and allocation decisions applied to water planning. *Management Science*, 23(10), 1080-1088.
- Atzeni, I., Ordóñez, L. G., Scutari, G., Palomar, D. P., & Fonollosa, J. R. (2013). Demand-side management via distributed energy generation and storage optimization. *IEEE Transactions on Smart Grid*, 4(2), 866-876.
- Bailey, T. P., & Bass, R. B. (2009). *Hydroelectric Feasibility Study: An Assessment of the Feasibility of Generating Electric Power Using Urban Storm Water in Oregon City*. Oregon Institute of Technology.
- Barton, J. P., & Infield, D. G. (2004). Energy storage and its use with intermittent renewable energy. *IEEE transactions on energy conversion*, 19(2), 441-448.
- Beecher, J. A. (1997). Water utility privatization and regulation: lessons from the global experiment. *Water International*, 22(1), 54-63.
- Berbel, J., Mesa-Jurado, M. A., & Pistón, J. M. (2011). Value of irrigation water in Guadalquivir Basin (Spain) by residual value method. *Water Resources Management*, 25(6), 1565-1579.
- Bergmann, A., Hanley, N., & Wright, R. (2006). Valuing the attributes of renewable energy investments. *Energy policy*, 34(9), 1004-1014.
- Birol, E., Karousakis, K., & Koundouri, P. (2006). Using economic valuation techniques to inform water resources management: A survey and critical appraisal of available techniques and an application. *Science of the total environment*, 365(1), 105-122.
- Brown, P. D., Lopes, J. P., & Matos, M. A. (2008). Optimization of pumped storage capacity in an isolated power system with large renewable penetration. *IEEE Transactions on Power systems*, 23(2), 523-531.
- Brownsword, R. A., Fleming, P. D., Powell, J. C., & Pearsall, N. (2005). Sustainable cities—modelling urban energy supply and demand. *Applied energy*, 82(2), 167-180.
- Brueckner, J. K. (1997). Infrastructure financing and urban development: The economics of impact fees. *Journal of Public Economics*, 66(3), 383-407.
- Bruns, B. R., & Meinzen-Dick, R. S. (Eds.). (2000). *Negotiating water rights*. London: ITDG Publishing.

- Capello, R., Nijkamp, P., & Pepping, G. (1999). *Sustainable cities and energy policies*. Springer Science & Business Media.
- Carmona, R., & Ludkovski, M. (2010). Valuation of energy storage: An optimal switching approach. *Quantitative finance*, 10(4), 359-374.
- Carpinelli, G., Celli, G., Mocci, S., Mottola, F., Pilo, F., & Proto, D. (2013). Optimal integration of distributed energy storage devices in smart grids. *IEEE Transactions on smart grid*, 4(2), 985-995.
- Catalão, J. P. D. S., Mariano, S. J. P. S., Mendes, V. M. F., & Ferreira, L. A. F. M. (2007). Short-term electricity prices forecasting in a competitive market: A neural network approach. *Electric Power Systems Research*, 77(10), 1297-1304.
- City of Cleveland Tennessee Annual Budget, FY 2016-2017. (2016). Retrieved August 15, 2017, from <http://clevelandtn.gov/DocumentCenter/View/993>
- Copeland, R. J., Kannberg, L. D., O'Connell, L. G., Eisenhaure, D., Hoppie, L. O., Barlow, T. M., ... & Sapowith, A. P. (1983). *Benefits from energy storage technologies* (No. SERI/TP-252-2107; CONF-840201-11). Solar Energy Research Inst., Golden, CO (USA).
- Dandy, G. C., McBean, E. A., & Hutchinson, B. G. (1984). A model for constrained optimum water pricing and capacity expansion. *Water Resources Research*, 20(5), 511-520.
- Dell, R. M., & Rand, D. A. (2001). Energy storage—a key technology for global energy sustainability. *Journal of Power Sources*, 100(1), 2-17.
- Diewert, W. E., & Gordon, R. J. (1996). Price and volume measures in the system of national accounts. In *The New System of National Accounts* (p. 237-297). Springer Netherlands. Rotterdam, Holland.
- Dinar, A., & Saleth, R. M. (2005). Issues in water pricing reforms: from getting correct prices to setting appropriate institutions. *The international yearbook of environmental and resource economics 2005/2006*, 1.
- Dong, C., Huang, G. H., Cai, Y. P., & Liu, Y. (2012). An inexact optimization modeling approach for supporting energy systems planning and air pollution mitigation in Beijing city. *Energy*, 37(1), 673-688.
- Dinar, A. (2000). *The political economy of water pricing reforms*. World Bank.
- Draper, A. J., Jenkins, M. W., Kirby, K. W., Lund, J. R., & Howitt, R. E. (2003). Economic-engineering optimization for California water management. *Journal of water resources planning and management*, 129(3), 155-164.
- Dunn, B., Kamath, H., & Tarascon, J. M. (2011). Electrical energy storage for the grid: a battery of choices. *Science*, 334(6058), 928-935.
- Electronic Engineering Journal. (n.d.). Retrieved August 18, 2015, from <http://www.eejournal.com/archives/fresh-bytes/portland-to-generate-electricity-within-its-own-water-pipes>
- Energy Storage. (n.d.). Retrieved September 10, 2015, from <https://www.solarelectricpower.org/examine-issues/technology/energy-storage/calculating-the-value-of-energy-storage.aspx>
- Eto, J., Kito, S., Shown, L., & Sonnenblich, R. (2000). Where did the money go? The cost and performance of the largest commercial sector DSM programs. *The Energy Journal*, 23-49.

- Eyer, J., & Corey, G. (2010). Energy storage for the electricity grid: Benefits and market potential assessment guide. *Sandia National Laboratories*, 20(10), 5.
- Goldstein, R., & Smith, W. (2002). *Water & sustainability (volume 4): US electricity consumption for water supply & treatment-the next half century*. Electric Power Research Institute.
- Gollop, F. M., & Roberts, M. J. (1983). Environmental regulations and productivity growth: The case of fossil-fueled electric power generation. *Journal of political Economy*, 91(4), 654-674.
- Government Finance Officers Association (2017). Working Capital Targets for Enterprise Funds. Retrieved August 15, 2017, from: <http://www.gfoa.org/working-capital-targets-enterprise-funds>
- Green, D. (2007). *Managing water: avoiding crisis in California*. University of California Press.
- Grigg, N. S. (2005). Assessment and renewal of water distribution systems. *American Water Works Association Journal*, 97(2), 58.
- Haab, T. C., & McConnell, K. E. (2002). *Valuing environmental and natural resources: the econometrics of non-market valuation*. Edward Elgar Publishing. Cheltenham, United Kingdom.
- Hashimoto, T., Stedinger, J. R., & Loucks, D. P. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water resources research*, 18(1), 14-20.
- Hatami, A., Seifi, H., & Sheikh-El-Eslami, M. K. (2011). A stochastic-based decision-making framework for an electricity retailer: time-of-use pricing and electricity portfolio optimization. *IEEE Transactions on Power Systems*, 26(4), 1808-1816.
- Haughton, G., & Hunter, C. (2004). *Sustainable cities*. Routledge. Abingdon, United Kingdom.
- Hosseini, S. M. H., Forouzbakhsh, F., & Rahimpour, M. (2005). Determination of the optimal installation capacity of small hydro-power plants through the use of technical, economic and reliability indices. *Energy Policy*, 33(15), 1948-1956.
- Hrafinkelsson, B., Oddsson, G. V., & Unnthorsson, R. (2016). A Method for Estimating Annual Energy Production Using Monte Carlo Wind Speed Simulation. *Energies*, 9(4), 286.
- Hydropower Automation Systems. (2017). Retrieved August 4, 2017 from www.adnew.com
- Hydropower Electric Systems (2017). Retrieved August 24, 2017 from www.alibaba.com
- Hydropower Pump Pricing (2017). Retrieved August 18, 2017, www.gerenewableenergy.com
- Hussey, K., & Pittock, J. (2012). The energy–water nexus: Managing the links between energy and water for a sustainable future. *Ecology and Society*, 17(1).
- Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—characteristics and comparisons. *Renewable and sustainable energy reviews*, 12(5), 1221-1250.
- Islam, A. K. M. K., Bhuyan, S., & Chowdhury, F. A. (2013). Advanced composite pelton wheel design and study its performance for pico/micro hydro power plant application. *International Journal of Engineering and Innovative Technology (IJEIT)*, 2(11).
- Jacobsson, S., & Lauber, V. (2006). The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. *Energy policy*, 34(3), 256-276.

- Jewell, W., Gomatom, P., Bam, L., & Kharel, R. (2004). Evaluation of distributed electric energy storage and generation. *Final Report for PSERC Project T-21. PSERC Publication*, 04-25.
- Kaldellis, J. K., Zafirakis, D., Kaldelli, E. L., & Kavadias, K. (2009). Cost benefit analysis of a photovoltaic-energy storage electrification solution for remote islands. *Renewable energy*, 34(5), 1299-1311.
- Kariuki, M., & Schwartz, J. (2005). *Small-scale private service providers of water supply and electricity: a review of incidence, structure, pricing, and operating characteristics* (Vol. 3727). World Bank Publications.
- Keeney, R. L., & Raiffa, H. (1993). *Decisions with multiple objectives: preferences and value trade-offs*. Cambridge university press. Cambridge, MA.
- Kienzle, F., Ahcin, P., & Andersson, G. (2011). Valuing investments in multi-energy conversion, storage, and demand-side management systems under uncertainty. *IEEE Transactions on Sustainable Energy*, 2(2), 194-202.
- Komarek, T. M., Lupi, F., & Kaplowitz, M. D. (2011). Valuing energy policy attributes for environmental management: Choice experiment evidence from a research institution. *Energy Policy*, 39(9), 5105-5115.
- Kusakana, K., Munda, J. L., & Jimoh, A. A. (2008). Economic and environmental analysis of micro hydropower system for rural power supply. In *Power and Energy Conference, 2008. PECon 2008. IEEE 2nd International*(p. 441-444). IEEE.
- Kwak, S. Y., Yoo, S. H., & Kwak, S. J. (2010). Valuing energy-saving measures in residential buildings: A choice experiment study. *Energy Policy*, 38(1), 673-677.
- Lange, G. M. (2007). Case studies of water valuation in Namibia's commercial farming areas. *The economics of water management in Southern Africa: an environmental accounting approach*. Cheltenham: Edward Elgar, 237-254.
- Laughland, A. S., Musser, L. M., Musser, W. N., & Shortle, J. S. (1993). The opportunity cost of time and averting expenditures for safe drinking water. *JAWRA Journal of the American Water Resources Association*, 29(2), 291-299.
- Le, H. T., & Nguyen, T. Q. (2008, July). Sizing energy storage systems for wind power firming: An analytical approach and a cost-benefit analysis. In *Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE* (p. 1-8). IEEE.
- Levi, D. R. (1969). Highest and Best Use: An Economic Goal for Water Law. *Mo. L. Rev.*, 34, 165.
- Lewis, M. A., & Miller, T. R. (1987). Public-private partnership in water supply and sanitation in sub-Saharan Africa. *Health Policy and Planning*, 2(1), 70-79.
- Lijesen, M. G. (2007). The real-time price elasticity of electricity. *Energy economics*, 29(2), 249-258.
- Lubega, W. N., & Farid, A. M. (2014). Quantitative engineering systems modeling and analysis of the energy–water nexus. *Applied Energy*, 135, 142-157.
- Lundin, M., & Morrison, G. M. (2002). A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems. *Urban water*, 4(2), 145-152.
- Ma, T., Yang, H., & Lu, L. (2014). Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island. *Energy Conversion and Management*, 79, 387-397.

- Maantay, J., Ziegler, J., & Pickles, J. (2006). *GIS for the Urban Environment*. Esri Press. Redlands, CA.
- Magill, B. (2014). Utilities Disagree on How EPA Should Regulate Emissions. Retrieved August 6, 2017, from <http://www.climatecentral.org/news/utilities-prepping-for-new-emissions-rules-17276>
- Maier, H. R., Simpson, A. R., Zecchin, A. C., Foong, W. K., Phang, K. Y., Seah, H. Y., & Tan, C. L. (2003). Ant colony optimization for design of water distribution systems. *Journal of water resources planning and management*, 129(3), 200-209.
- Makropoulos, C. K., & Butler, D. (2010). Distributed water infrastructure for sustainable communities. *Water Resources Management*, 24(11), 2795-2816.
- Maloney, P. (2017). Valuing storage: A closer look at the Tucson Electric solar-plus-storage PPA. Utility Dive. Retrieved August 8, 2017 from <http://www.utilitydive.com/news/valuing-storage-a-closer-look-at-the-tucson-electric-solar-plus-storage-pp/448370/>
- Månsson, A., Johansson, B., & Nilsson, L. J. (2012, May). Methodologies for characterising and valuing energy security—A short critical review. In *European Energy Market (EEM), 2012 9th International Conference on the*(p. 1-8). IEEE.
- Menanteau, P., Finon, D., & Lamy, M. L. (2003). Prices versus quantities: choosing policies for promoting the development of renewable energy. *Energy policy*, 31(8), 799-812.
- Miller, J. R. (2012). Valuing reversible energy storage. *Science*, 335(6074), 1312-1313.
- Misiūnas, D. (2008). *Failure Monitoring and Asset Condition Assessment in Water Supply Systems*. Vilniaus Gedimino technikos universitetas. Vilnius, Lithuania.
- Mohd, A., Ortjohann, E., Schmelter, A., Hamsic, N., & Morton, D. (2008, June). Challenges in integrating distributed energy storage systems into future smart grid. In *Industrial Electronics, 2008. ISIE 2008. IEEE International Symposium on* (p. 1627-1632). IEEE.
- Nashville Electric Service. (2017). *Understanding Your Bill*. Retrieved August 24, 2017 from <https://nespower.com/index.aspx>
- Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science*, 313(5790), 1068-1072.
- Otterpohl, R., Grottker, M., & Lange, J. (1997). Sustainable water and waste management in urban areas. *Water Science and Technology*, 35(9), 121-133.
- Oren, S. S. (2000). Capacity payments and supply adequacy in competitive electricity markets. *Sepope, May*.
- Palensky, P., & Dietrich, D. (2011). Demand side management: Demand response, intelligent energy systems, and smart loads. *IEEE transactions on industrial informatics*, 7(3), 381-388.
- Paish, O. (2002). Small hydro power: technology and current status. *Renewable and sustainable energy reviews*, 6(6), 537-556.
- Pelton Turbine Price List. (2017). Retrieved August 10, 2017 from www.alibaba.com
- Perrone, D., Murphy, J., & Hornberger, G. M. (2011). Gaining perspective on the water–energy nexus at the community scale.

- Poonpun, P., & Jewell, W. T. (2008). Analysis of the cost per kilowatt hour to store electricity. *IEEE Transactions on energy conversion*, 23(2), 529-534.
- Pruss-Ustun, A., & World Health Organization. (2008). Safer water, better health: costs, benefits and sustainability of interventions to protect and promote health.
- Rogers, J., Averyt, K., Clemmer, S., Davis, M., Flores-Lopez, F., Frumhoff, P., ... & Yates, D. (2013). Water-smart power: Strengthening the US electricity system in a warming world. *Union of Concerned Scientists, Cambridge, MA*.
- Rogers, P., De Silva, R., & Bhatia, R. (2002). Water is an economic good: How to use prices to promote equity, efficiency, and sustainability. *Water policy*, 4(1), 1-17.
- Rothwell, G., & Gomez, T. (2003). Electricity economics. *IEEE series on power engineering*.
- Savulescu, L., Kim, J. K., & Smith, R. (2005). Studies on simultaneous energy and water minimisation—Part II: Systems with maximum re-use of water. *Chemical Engineering Science*, 60(12), 3291-3308.
- Schoenung, S. M., Eyer, J. M., Iannucci, J. J., & Horgan, S. A. (1996). Energy storage for a competitive power market. *Annual review of energy and the environment*, 21(1), 347-370.
- Sims, R. E., Rogner, H. H., & Gregory, K. (2003). Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy policy*, 31(13), 1315-1326.
- Specifying Municipal Water Tanks. (2017). Retrieved August 8, 2017, from <https://www.tankconnection.com/products/liquid-storage-tanks/municipal-water-storage-tank>
- Swyngedouw, E., Kaika, M., & Castro, E. (2002). Urban water: a political-ecology perspective. *Built Environment (1978-)*, 124-137.
- Tseng, C. L., & Barz, G. (2002). Short-term generation asset valuation: a real options approach. *Operations Research*, 50(2), 297-310.
- Tennessee Valley Authority. (2017a). About TVA. Retrieved August 23, 2017, from <https://www.tva.gov/About-TVA>
- Tennessee Valley Authority. (2017b). Green Power Providers. Retrieved August 28, 2017, from <https://www.tva.com/Energy/Valley-Renewable-Energy/Green-Power-Providers/How-the-GPP-Program-Works>
- Tennessee Valley Authority. (2015a). Integrated Resource Plan Final Report.
- Tennessee Valley Authority. (2015b). Refining the Wholesale Pricing Structure, Products, Incentives, and Adjustments for Providing Electric Power to TVA Customers, Final Assessment Report.
- Tennessee Valley Authority. (2017c). Retail Rates for Cleveland, Tennessee. Retrieved August 28, 2017, from <http://www.clevelandutilities.com/rates.htm>
- Tennessee Valley Authority. (2015c). The Price of Power.
- Water Systems PVC Piping Pricing. (2017). Retrieved August 24, 2017, from www.assureautomation.com
- Westerling, K. (2013). The 13 Biggest Challenges Facing the Water Industry. Retrieved August 18, 2015, from <https://www.wateronline.com/doc/the-biggest-challenges-facing-the-water-industry-0001>

- Williams, A. A. (1996). Pumps as turbines for low cost micro hydro power. *Renewable Energy*, 9(1-4), 1227-1234.
- Williamson, O. E. (1966). Peak-load pricing and optimal capacity under indivisibility constraints. *The American Economic Review*, 56(4), 810-827.
- Wiser, R. H., & Pickle, S. J. (1998). Financing investments in renewable energy: the impacts of policy design. *Renewable and Sustainable Energy Reviews*, 2(4), 361-386.
- Yamin, H. Y., Shahidehpour, S. M., & Li, Z. (2004). Adaptive short-term electricity price forecasting using artificial neural networks in the restructured power markets. *International journal of electrical power & energy systems*, 26(8), 571-581.
- Young, R. (2014, November). Watts in a Drop of Water: Savings at the Water-energy Nexus. American Council for an Energy-Efficient Economy.
- U.S. Energy Information Administration. (2017). Factors Affecting Electricity Prices. Retrieved August 14, 2017 from: https://www.eia.gov/energyexplained/index.cfm?page=electricity_factors_affecting_prices
- Zakeri, B., & Syri, S. (2015). Electrical energy storage systems: A comparative life cycle cost analysis. *Renewable and Sustainable Energy Reviews*, 42, 569-596.
- Zetland, D. (2008). The Water Shortage Myth. Forbes. Water Online, retrieved August 6, 2017, from https://www.forbes.com/2008/07/14/california-supply-demand-oped-cx_dz_0715water.html
- Zogg, R., Tyson, L., Ofer, D., & Brodrick, J. (2007). Distributed energy storage. *ASHRAE Journal*, 49(5), 90.

Appendix 3

Table 16. Fundamental Differences between U.S. Markets for Water and Energy Supplies.

Water Supply	Explanation / Example	Energy Supply	Explanation / Example
A Regional and Local Issue	Visible and accessible. In CA, water supply is a quality of life issue. In TN, water supply is plentiful and not significantly conserved or considered.	Centralized, invisible, belonging to inaccessible entities	500 MW power plant, removed from urban areas, operations not commonly understood, the transmission and delivery of power a thing communities do not control.
Little Monetization	Low consumer rates and no accurate value placed upon water, but we would not survive without it.	Highly monetized, with a moment-by-moment trading market	The energy market significantly impacts all other markets. Low energy costs result in increasing market productivity - high values negatively impact the economy.
Regulated from a Conservation Perspective	The Clean Water Act regularly defends itself, and is rarely revised, to not lose hard-won regulatory ground.	Regulated from a profit perspective	The energy market is restricted from monopolizing as much as possible, but is moving toward deregulation to allow for market influences to better stabilize production and sales.

Table 17. Market-Based Techniques to Value Water.

Technique	Technique Description	Example
Residual Value	Marginal contribution of water to output, is measured by subtracting all other costs from revenue.	Existing hydropower infrastructure value estimate
Production Function Approach	Marginal contribution is measured as the change in output from a unit increase in water input in each sector.	Protecting a reservoir from runoff to reduce purification costs
Optimization Models and Programming	Marginal contribution is measured by changes in sectoral outputs from reallocation of water across the whole economy.	Optimal water usage and treatment in a plant
Hedonic Pricing	The price differential that is paid for land with water resources.	Premium paid for proximity to water (homes, industry)
Opportunity cost	The price differential is defined for alternative methods.	Replacing hydroelectric power with coal-fired electricity

Table 18. Energy Use in U.S Water Systems, 2005.

Water Service Energy Use	kWh
Energy in water conveyance from source	18,700,000
Energy in treatment	23,400,000
Energy in distribution	5,600,000
Wastewater Service Energy Use	kWh
Energy in wastewater collection and treatment	11,000,000
Energy in wastewater discharge	1,500,000

**Adapted from an ACEEE study (Young, 2014)*

Table 19. Cost Impacts and Associated Benefits of Increased Water Storage.

Example Cost Impacts	Example Investment Benefits by Cost
Operating costs will increase to charge water storage tanks (pumping) and extract energy during water tank release.	With a favorable peak energy pricing structure, the energy required to charge storage costs less than peak storage release for energy generation. Energy demand pricing structures matter.
Infrastructure costs to the system will increase with the addition of storage.	Increased water storage can be used to generate electricity in times of normal water system use, or can be allocated to meet water system demand and pressure needs.
New generation technology costs can be high, so it is important to understand the value streams of storage in demand times.	Capturing energy from water tanks requires simple technology for generation and grid connections, and it is possible that the equipment needed for generation could pay for itself over time.
New generation plant costs are enormous.	Stored energy can work to defer new generation plants.

Table 20. Example Energy Storage Benefits.

Benefit of Energy Storage	Description of Benefit
Available generating units	Can increase system capacity, when used during peaks
Automatic generation control	Minimizes difference between scheduled and actual generation
Bulk energy management	Allows for delay of power transfers, by storing the energy until it is needed
Deferring new generating plants	Allows for fewer peaking units, when storage is used to reduce peak demand
Deferring new transmission lines	Allows for reduction of peak loading of transmission lines
Energy efficiency	Allows more constant system set points and reduced maintenance intervals
Environmental benefits	Allows for the reduction of fossil fuel use and emissions
Load follows demand variations	Allows for rapid response to load changes, reducing energy generation needs
Load leveling during peak	Allows for cost efficiency, if storage is charged during off-peak times
Power quality and reliability	Allows energy systems to operate through outages
Quick start-up capabilities	Can be used to start an isolated generating unit
Voltage control	Allows for quick reaction to system needs, providing power on demand
Reduced fuel use	Can reduce the need for natural gas use by peaking units
Support of distributed generation	Allows for system resiliency through multiple generation locations
Supports use of renewable energy	Allows for use during peak demand by reducing variations in power outputs
System stability	Allows for the reduction of system load oscillations

		Electric	Water	Sewer	CLEVELAND UTILITIES-WATER CAPITAL EXPENDITURES - 2017	
Volume	KWH's	1,081,412,995				
Volume	Gallons		2,820,336,551	1,834,464,670		
Avg Revenue	KWH	\$ 0.093			ENGINEERING - DISTRIBUTION	\$ 4,396,000
Avg Revenue	1000 Gallons		\$5.06	\$6.48	WATER - DISTRIBUTION	835,000
Rate Adjustments		4.50%	5.13%	4.50%	FACILITIES MAINTENANCE DEPARTMENT	82,000
Revenue (Sales and Other)		102,225,950	15,380,981	12,904,879	WATER TREATMENT FACILITIES	2,236,000
Expenses		99,730,420	14,271,014	10,853,323	ENGINEERING - OFFICE	2,000
Net Income		2,495,530	1,109,967	2,051,556	INFORMATION SYSTEMS (Includes AMI)	143,000
Tax Equivalents		1,912,477	225,146	206,000	OFFICE EQUIPMENT	2,500
Depreciation (Expensed)		4,691,440	2,516,310	3,242,177	TRANSPORTATION	180,000
Cash Generated		7,489,111	3,809,117	5,383,888	BUILDINGS AND GROUNDS	20,000
Additions to Plant		6,914,000	7,896,500	9,732,104	TOTAL	\$ 7,896,500
Beginning Bond Balance		15,869,200	29,082,776	25,555,790		
Additional Bonds		3,000,000	5,225,500	5,652,305		
Bond Payments		1,380,250	1,863,153	2,380,847		
Ending Bond Balance		17,488,950	32,445,123	28,827,247		
Bond Coverage		4.26	1.60	1.90		

Figure 44. CU 2017 Budget Highlights and Water Division Expenditure Summary.

**CLEVELAND UTILITIES
Electric
Performance Measures**

	FY 2015 Actual	FY 2016 Projected	FY 2017 Projected
KWH Purchased	1,124,645,838	1,112,663,580	1,113,137,411
KWH Sold	1,093,701,541	1,081,509,000	1,081,412,995
KWH Unsold (line loss)	30,944,297	31,154,580	31,724,416
% KWH in Line Loss	2.75%	2.80%	2.85%
Average Retail Price of KWH (Based on kwh's Sold)	8.95	9.25	9.31
Number of Customers			
Residential	26,190	26,425	26,557
Commercial	3,809	3,800	3,795
Industrial	624	619	617
Other	185	118	120
Total	30,808	30,962	31,089
Total Revenues	99,416,702	101,552,351	102,225,950
Net Income	345,199	2,629,761	2,495,530
Additional Investment in Plant	4,432,772	3,470,756	6,914,000
Long-term Debt	15,115,834	15,869,200	17,488,950
Number of Customers per Employee	371	373	398

Figure 45. CU Electric Division Performance Measures and Summary Expenses.

**City of Cleveland, Tennessee
Schedule of Debt Payments
For Fiscal Year 2016**

FY2017 Debt Requirement for Cleveland Utilities						
Tax and Revenue Bonds:						
Series 2007B	0	\$ 880,000	Electric	\$ 85,000	\$ 36,579	\$ 121,579
Series 2007B	0	6,560,000	Water/Sewer	115,000	287,367	402,367
Series 2010	0	4,875,000	Electric	325,000	145,296	470,296
Series 2010	0	1,825,000	Water	95,000	55,736	150,736
Total Tax and Revenue Bonds:	\$ -	\$ 14,140,000		\$ 620,000	\$ 524,978	\$ 1,144,978
Tax and Revenue Loan:						
Series 2012 TMBF	0	\$ 3,000,000	Water	\$ 187,500	\$ 60,000	\$ 247,500
Series 2012 TMBF-Spring Branch	0	\$ 1,524,692	Electric	\$ 112,333	\$ 30,494	\$ 142,827
Series 2014 TMBF	0	\$ 3,282,500	Electric	\$ 181,250	\$ 65,250	\$ 246,500
Series 2014 TMBF	0	\$ 2,475,000	Water	\$ 137,500	\$ 49,500	\$ 187,000
Series 2015 TMBF	0	\$ 2,627,000	Electric	\$ 124,000	\$ 30,473	\$ 154,473
Series 2015 TMBF	0	\$ 2,866,000	Water	\$ 136,000	\$ 85,980	\$ 221,980
Loan - 2017 TMBF	3,000,000	0	Electric	0	0	0
Loan - 2017 TMBF	1,500,000	0	Water	0	0	0
Loan - 2017 TMBF	1,000,000	0	Sewer	0	0	0
Total Tax & Revenue Loan:	\$ 5,500,000	\$ 15,755,192		\$ 878,583	\$ 321,697	\$ 1,200,280
State Revolving Fund Loan:						
SRF Loan	0	\$ 522,769	Sewer	\$ 30,944	\$ 10,732	\$ 41,676
ARRA Loan	0	\$ 104,554	Sewer	\$ 6,189	\$ 2,146	\$ 8,335
SRF-CWO 319	\$ 506,906	\$ 806,572	Sewer	\$ 62,208	\$ 15,492	\$ 77,700
SRF-CWP 320	\$ 3,406,457	\$ 4,397,703	Sewer	\$ 369,840	\$ 87,852	\$ 457,692
2014 DG2 14-151	0	\$ 1,949,754	Water	\$ 87,168	\$ 28,644	\$ 115,812
2015 CG4 15-349	0	\$ 2,325,000	Water	\$ 101,652	\$ 31,440	\$ 133,092
Total State Revolving Fund Loan:	\$ 3,913,363	\$ 10,106,352		\$ 658,001	\$ 176,306	\$ 834,307
Total Long-term Debt-Cleveland Utilities	\$ 9,413,363	\$ 69,106,544		\$ 5,611,584	\$ 2,064,612	\$ 7,676,196
Combined Debt Requirement for FY2017						
Loan Type	Loan Name	Authorized and Unissued at 6/30/16	Amount Outstanding at 6/30/16	Principal	Interest	Total Debt Service
Loan Agreements		7,700,000	58,439,838	3,456,137	1,609,832	5,065,969
General Obligation Bonds		0	19,465,000	900,000	781,456	1,681,456
Tax & Revenue Refunding Bonds		0	29,105,000	3,455,000	1,041,631	4,496,631
Tax & Revenue Bonds		0	14,140,000	620,000	524,978	1,144,978
Tax & Revenue Loan		5,500,000	15,755,192	878,583	321,697	1,200,280
State Revolving Fund Loan		3,913,363	10,106,352	658,001	176,306	834,307
Combined Debt Requirement:		\$ 17,113,363	\$ 147,011,382	\$ 9,967,721	\$ 4,455,900	\$14,423,621

Figure 46. CU Fiscal Year 2016 Debt Payment Summary.

CLEVELAND UTILITIES Water and Wastewater Performance Measures			
	FY 2015 Actual	FY 2016 Projected	FY 2017 Projected
MG of Treated Water Pumped	3,657,319,401	3,720,123,134	3,801,584,470
MG of Treated Water Sold	2,733,381,750	2,790,000,000	2,832,180,430
% of Treated Water Loss	25.26%	25.00%	25.50%
MG of Treated Wastewater	3,285,830,000	1,822,100,000	1,829,944,581
% Inflow/Infiltration	44.42%	45.00%	45.50%
Number of Water Customers			
Residential	27,200	27,381	27,518
Commercial	3,164	3,144	3,139
Irrigation	562	532	522
Total	30,926	31,057	31,179
Number of Wastewater Customers			
Residential	15,785	15,899	15,979
Commercial	2,595	2,572	2,564
Industrial	60	61	62
Total	18,440	18,532	18,605
Total Revenues (Combined)	25,841,882	27,079,843	28,285,860
Net Income (Combined)	3,855,664	2,881,090	3,161,523
*Investment in Plant and Equipment	10,797,505	15,463,373	17,628,604
Long-term Debt	46,461,952	55,556,252	61,272,370
# of Customers per W/WW Employee	441	454	426

*Funded from revenue and debt

Figure 47. CU Water Division Performance Measures and Summary Expenses.

City of Cleveland, Tennessee
2015-2017 Summary of Estimated Revenues, Expenses and Changes in Net Assets
Enterprise Funds

	Enterprise Funds					
	Cleveland Utilities Electric Division			Cleveland Utilities Water/Wastewater Division		
	2015 Actual	2016 Budgeted	2017 Proposed	2015 Actual	2016 Budgeted	2017 Proposed
Operating Revenues:						
Charges for services	\$97,856,518	\$101,403,687	\$100,658,516	\$23,709,760	\$24,817,093	\$25,927,533
Other operating revenues	1,517,530	1,570,476	1,530,031	2,092,602	2,226,418	2,318,659
Total Operating Revenues	\$99,374,048	\$102,974,163	\$102,188,547	\$25,802,362	\$27,043,511	\$28,246,192
Operating Expenses:						
General and administrative	\$0	\$0	\$0	\$0	\$0	\$0
Public works	0	0	0	0	0	0
Recreation	0	0	0	0	0	0
Power purchased	81,846,712	83,994,604	81,432,741	0	0	0
Operation expenses	7,435,789	8,122,471	8,112,734	12,988,868	14,170,787	14,900,134
Maintenance expense	2,901,817	2,860,802	3,046,215	2,148,103	2,346,129	2,252,743
Depreciation and amortization	4,385,804	4,574,933	4,715,332	5,441,808	5,649,216	5,823,754
Total Operating Expenses:	\$96,570,122	\$99,552,810	\$97,307,022	\$20,578,779	\$22,166,132	\$22,976,631
Operating Income (Loss)	\$2,803,926	\$3,421,353	\$4,881,525	\$5,223,583	\$4,877,379	\$5,269,561
Nonoperating Revenues (Expenses):						
Interest income	42,654	32,350	37,401	39,520	36,330	39,667
Interest expense	(466,497)	(527,581)	(510,921)	(1,528,453)	(1,614,034)	(1,716,560)
Other income (expense)	0	0	0	0	0	0
Total Nonoperating Revenues (Expenses):	(423,843)	(495,231)	(473,520)	(1,488,933)	(1,577,704)	(1,676,893)
Change in Net Assets Before Contributions and Transfers:	\$2,380,083	\$2,926,122	\$4,408,005	\$3,734,650	\$3,299,675	\$3,592,668
Capital contributions	0	0	0	333,235	0	0
Operating transfers in	0	0	0	0	0	0
Operating transfers out	(2,034,884)	(1,971,655)	(1,912,477)	(212,221)	(418,588)	(431,146)
Change in Net Assets	\$345,199	\$954,467	\$2,495,528	\$3,855,664	\$2,881,087	\$3,161,522
Est. Net Assets, July 1	55,224,104	55,569,303	56,523,770	63,309,553	67,165,217	70,046,304
Est. Net Assets, June 30	\$55,569,303	\$56,523,770	\$59,019,298	\$67,165,217	\$70,046,304	\$73,207,826

Figure 48. CU 2015-2017 Enterprise Funds Summary.

Table 21. Summary of TVA's 2016 Wholesale Rate Design with Time-of-Use Pricing Structure.

TVA Wholesale Rate Design with Time of Use Pricing Structure					
Season	On-Peak Demand/kW	Maximum Demand/kW	On Peak Energy/kWh	Off-Peak Energy/kWh	On-Off Peak Differential/kWh
Summer	\$7.49	\$2.75	\$0.05356	\$0.03156	\$0.02200
Transition	\$6.63	\$2.75	\$0.03429	\$0.03429	\$0.00000
Winter	\$6.63	\$2.75	\$0.04352	\$0.03352	\$0.01000

Table 22. Summary of TVA’s 2016 Rate Structure by Rate Schedule Demand.

General Power Rate	Demand by Rate Schedule
Schedule GSA-1	Greater than 50kW and less than or equal to 1,000 kW
Schedule GSA-2	Less than or equal to 50 kW
Schedule GSA-3	Greater than 1,000 kW and less than or equal to 5,000 kW
Schedule GSB	Greater than 5,000 kW and less than or equal to 15,000 kW
Schedule GSC	Greater than 15,000 kW and less than or equal to 25,000 kW
Schedule GSD	Greater than 25,000 kW
Large Manufacturing	Demand by Rate Schedule
Schedule MSB	Greater than 5,000 kW and less than or equal to 15,000 kW
Schedule MSC	Greater than 15,000 kW and less than or equal to 25,000 kW
Schedule MSD	Greater than 25,000 kW
Time-of-Day Rate	Demand by Rate Schedule and Optional Commercial Schedules
Schedule TGSA-1	Less than or equal to 50 kW
Schedule TGSA-2	Greater than 50 kW and less than or equal to 1,000 kW
Schedule TGSA-3	Greater than 1,000 kW and less than or equal to 5,000 kW
Optional Commercial Rates	<i>Schedule TDGSA, Schedule TDMSA, Schedule SGSB, Schedule SGSC, Schedule SGSD, Schedule SMSB, Schedule SMSC, Schedule SMSD</i>
Outdoor Lighting	Contract Requirements
Schedule LS	Street and park lighting, traffic signals, athletic, outdoor lighting s

Table 23. Inputs and Outputs for Energy Storage Return-on-Investment Calculations.

Calculated Estimate	Inputs	Outputs
Capital cost of storage infrastructure (USD)	Unit costs of pumping stations, turbines, and generators (USD/tank)	Total cost of pumping stations, turbines, and generators (USD/tank)
	Unit cost for power electronics and transmitters (USD/kWh)	Total cost of power electronics and transmitters (USD/kWh)
	Unit cost for storage units (USD/kWh)	Total cost of storage units (USD/kWh)
	Interest Rate (%)	Time Value of Money (%)
Cost of energy for storage re-charge periods (kWh)	Unit cost for pumping and generating units (USD/kWh)	Total cost for pumping and generating units (USD/kWh)
	Energy used to charge storage cycles per day (kWh/day)	Total energy consumed by the pumps (kWh)
	Pump efficiency rating (%)	Efficiency (%)
Energy generation potential (kWh)	Number and length of charge cycles per day (kWh/day)	Energy production from storage discharge (kWh)
Number of lifespan discharge cycles (cycles/years)	Cyclical replacement costs and depreciation rates (USD/year)	Annual operating and maintenance costs (USD/year)
Capital recovery/return on investment	Operating days per year (days/year)	Total payback period (years)

Table 24. Comparison of CBAs, ROIs, and Payback Periods.

Description	Cost Benefit Analysis	Return on Investment	Payback Period
Purpose	Profit	Investment Return	Time required to generate profit
Formula	(Benefits – Costs)	(Benefits – Costs) / Costs	Total Costs / Annual Profit
Unit	Money (USD)	Expressed as a ratio or %	Time in Years

Table 25. Scenario A1 Direct Capital Cost Estimates.

Scenario A1 Direct Capital Cost Estimates						
Item	Description / Assumptions	Estimated Unit Cost	Total Units	Total Cost	Life Expectancy	Primary Pricing / Lifespan Source
Upper and Lower Tanks	63,000,000 gallons total (3,500,000 gallons each), bolted steel	\$1,050,000	18	\$18,900,000	15-20 years	Specifying Municipal Water Tanks, www.tankconnection.com
Turbine / Generator	Pelton design, assuming 328' of head at 7,000 GPM	\$62,611	9	\$563,499	7-10 years	Pelton Turbine Price List, www.alibaba.com
Powerhouse	\$600 - concrete slab; \$2,000 - concrete block enclosure small access door	\$2,600	9	\$23,400	15-20 years	Hydroelectric Feasibility Study, Bailey & Bass, 2009
Control System	\$800 - automatic valves; \$625 - fittings and connectors; \$550 - level sensor; \$129 - programmable logic controller	\$2,104	9	\$18,936	7-10 years	Hydropower Automation Systems, www.adnew.com
Electrical System	\$250 circuit breakers / sub-panel; \$500 conduit, wire, connectors; \$220 -resistance heater; \$1,000 - generator protective relay; \$300 - relay enclosure	\$2,207	9	\$20,430	30-50 years	Hydropower Electric Systems, www.alibaba.com
Tank Recharge Pump	7,000 GPM vertical turbine pump, stainless steel shaft, retainer bearings, 125 HP motor, airline, anchor belts, fittings and connectors	\$55,694	9	\$501,246	7-10 years	Hydropower Pump Pricing, www.gerenewableenergy.com
Distributing Loop	656 feet per loop; each loop is 328' of piping down and 328' of piping back up. Assume \$7 per foot.	\$4,592	9	\$41,328	50-70 years	Water Systems PVC Piping Pricing, www.assureautomation.com
Total Estimated Direct Capital Costs				\$20,068,839		

Table 26. Scenario A1 Indirect Capital Cost Estimates.

Scenario A1 Indirect Capital Cost Estimates			
Item	Description / Assumptions	Estimated Cost	Primary Source*
Engineering Design / Project Management	10% of total project costs	\$2,006,884	Hydroelectric Feasibility Study, Bailey & Bass, 2009
Construction Labor	40% of total project costs	\$8,027,536	
Total Estimated Indirect Cost		\$10,034,420	

**Note: Corroborated with cost estimate percentages found in other sources during research*

Table 27. Scenario A1 Annual O&M Cost Estimates.

Scenario A1 Annual O&M Cost Estimates			
Item	Description / Assumptions	Estimated Cost	Primary Source*
Interest	2% for a 20-year AA bond	\$30,103	Brueckner, 1997; confirmed in CU's annual operating budget
O&M	1% for smaller hydro	\$301,033	Paish, 2002
Depreciation	1% for the water system	\$301,033	Hosseini et al., 2005; confirmed in CU's annual operating budget
Pump Energy Costs	Annual cost, recharge pumps, assuming 70% efficiency	\$929,933	Sum of kWh for pumps recharging energy storage tanks, from the A1 CU water model
Total Estimated O&M Cost		\$1,562,162	

**Note: Corroborated with cost-estimate percentages found in other sources during research*

Table 28. Scenario A1 Energy Generation and Use (kWh).

Scenario A1 Potential Energy Generation Payment and Use Charge		
Energy Component	Result	Assumptions / Data Used
Annual generation potential (kWh)	10,849,992	89,175 kWh is the generation potential over a 3-day period. 121.67 3-day periods in 1 year: (89,175 * 121.67 = 10,849,992)
TVA potential payment per kWh	\$0.17	Assume TVA is purchasing 100% of the generated power, not that CU is using the power to offset the energy costs of the water system. Assume CU negotiates use of TVA Alternative Season Summer On peak TGSA1 Rate (\$0.17)
Annual profit from peak generation	\$1,844,487	(89,175 kWh every 3 days * \$0.17 * 121.67 3-day periods in a year)
Annual pump energy consumption potential (kWh)	15,499,889	Assumes 70% pump efficiency
TVA potential charge per kWh	\$0.06	Assume CU negotiates use of TVA Alternative Season Summer On peak TGSA1 Rate (\$0.06)
Annual recharge pump energy consumption (kWh)	\$929,993	(127,393 kWh every 3 days * \$0.06 * 121.67 3-day periods in a year)

Table 29. Scenario A1 Financial Analysis Summary.

Scenario A1 Summary of Financial Calculations		
Fiscal Component	Calculation	Formula Used
Total Installation Cost Estimate	\$30,103,259	Direct + Indirect costs
Total Annual Operating Cost Estimate	\$1,562,162	Interest rate + O&M + Depreciation + TVA rate charged to pump / refill storage tanks
Total Annual Value of Energy Generated Estimate	\$1,844,487	kWh generated for 1 year * TVA rate paid for energy generation
Annual Operating Profit	\$282,325	Annual value of energy generated - Annual operating cost
CBA in Y1	-\$29,820,933	Annual value of energy generated – (Total installation cost + Total operating cost)
ROI (%)	-90.8%	(Annual operating profit – (total installation cost / Amortization + Annual operating costs) / (Total installation costs / Amortization + Annual operating costs)
Payback Period (years)	112	(Total installation costs + Annual operating costs) / Annual operating profit

Table 30. Scenario B1 Tank Modifications, Sizes, and Cost Estimates.

Scenario B1 Tank Modifications, Sizes, and Cost Estimates						
Upper Tank Name	Doubled Height	Upper Tank Gallons	Upper Tank Cost Estimate	Lower Tank Height	Lower Tank Gallons	Lower Tank Cost Estimate
Blythe Ferry	64	1,000,000	\$150,000	32	500,000	\$150,000
Bryant Drive	154	2,000,000	\$300,000	77	1,000,000	\$300,000
Candies Creek	61	2,000,000	\$300,000	30.5	1,000,000	\$300,000
Crown Colony	64	1,000,000	\$150,000	32	500,000	\$150,000
Eldridge	73	7,000,000	\$1,050,000	36.5	3,500,000	\$1,050,000
Johnson	127	1,000,000	\$150,000	63.5	500,000	\$150,000
McDonald	60	1,000,000	\$150,000	30	500,000	\$150,000
Sunset	85	6,600,000	\$990,000	42.5	3,300,000	\$990,000
Waterville	100	3,000,000	\$450,000	50	1,500,000	\$450,000
Weeks	63	6,000,000	\$900,000	31.5	3,000,000	\$900,000
Total Upper Tank Modifications Cost			\$4,590,000	Total Lower New Tank Cost		\$4,590,000
Total B1 Tank Cost Estimate (Upper and Lower)						\$9,180,000

Table 31. Scenario B1 Direct Capital Cost Estimates.

Scenario B1 Direct Capital Cost Estimates						
Item	Description / Assumptions	Estimated Unit Cost	Total Units	Total Cost	Life Expectancy	Primary Pricing / Lifespan Source*
Upper and Lower Tanks	15,300,000 total gallons, bolted steel	Various, see Table 36	20	\$9,180,000	15-20 years	Specifying Municipal Water Tanks, www.tankconnection.com
Turbine / Generator	Pelton design, assuming 328' of head at 7,000 GPM	\$62,611	10	\$626,110	7-10 years	Pelton Turbine Price List, www.alibaba.com
Powerhouse	\$600 - concrete slab; \$2,000 - concrete block enclosure small access door	\$2,600	10	\$26,000	15-20 years	Hydroelectric Feasibility Study, Bailey & Bass, 2009
Control System	\$800 - automatic valves; \$625 - fittings and connectors; \$550 - level sensor; \$129 - programmable logic controller	\$2,104	10	\$21,040	7-10 years	Hydropower Automation Systems, www.adnew.com
Electrical System	\$250 circuit breakers / sub-panel; \$500 conduit, wire, connectors; \$220 -resistance heater; \$1,000 - generator protective relay; \$300 - relay enclosure	\$2,207	10	\$22,700	30-50 years	Hydropower Electric Systems, www.alibaba.com
Tank Recharge Pump	7,000 GPM vertical turbine pump, stainless steel shaft, retainer bearings, 125 HP motor, airline, anchor belts, fittings and connectors	\$55,694	10	\$556,940	7-10 years	Hydropower Pump Pricing, www.gerenewableenergy.com
Distributing Loop	656 feet per loop; each loop is 328' of piping down and 328' of piping back up. Assume \$7 per foot.	\$4,592	10	\$45,920	50-70 years	Water Systems PVC Piping Pricing, www.assureautomation.com
Total Estimated Direct Capital Costs				\$10,478,710		

*Note: Before assigning a cost estimate, many pricing and catalogue sources were cross-referenced to understand reasonable market rates. A primary source is listed for reference purposes.

Table 32. Scenario B1 Indirect Capital Cost Estimates.

Scenario B1 Indirect Capital Cost Estimates			
Item	Description / Assumptions	Estimated Cost	Primary Source*
Engineering Design / Project Management	10% of total project costs	\$1,047,871	Hydroelectric Feasibility Study, Bailey & Bass, 2009
Construction Labor	40% of total project costs	\$4,191,484	
Total Estimated Indirect Cost		\$5,239,355	

*Note: Corroborated with cost estimate percentages found in other sources during research

Table 33. Scenario B1 Annual O&M Cost Estimates.

Scenario B1 Annual O&M Cost Estimates			
Item	Description / Assumptions	Estimated Cost	Primary Source*
Interest	2% for a 20-year AA bond	\$15,718	Brueckner, 1997; confirmed in CU's annual operating budget
O&M	1% for smaller hydro	\$157,181	Paish, 2002
Depreciation	1% for the water system	\$157,181	Hosseini et al., 2005; confirmed in CU's annual operating budget
Pump Energy Costs	Annual cost, recharge pumps, assuming 70% efficiency	\$466,211	Sum of kWh for pumps recharging energy storage tanks, from the A1 CU water model
Total Estimated O&M Cost		\$796,291	

*Note: Corroborated with cost estimate percentages found in other sources during research

Table 34. Scenario B1 Energy Generation and Use (kWh).

Scenario B1 Potential Energy Generation Payment and Use Charge		
Energy Component	Result	Assumptions / Data Used
Annual generation potential (kWh)	5,439,133	44,704 kWh is the generation potential over a 3-day period. 121.67 3-day periods in 1 year: (44,704 * 121.67 = 5,439,133)
TVA potential payment per kWh	\$0.17	Assume TVA is purchasing 100% of the generated power, not that CU is using the power to offset the energy costs of the water system. Assume CU negotiates use of TVA Alternative Season Summer On peak TGSA1 Rate (\$0.17)
Annual profit from peak generation	\$924,653	(89,175 kWh every 3 days * \$0.17 * 121.67 3-day periods in a year)
Annual pump energy consumption potential (kWh)	7,770,190	Assumes 70% pump efficiency and
TVA potential charge per kWh	\$0.06	Assume CU negotiates use of TVA Alternative Season Summer On peak TGSA1 Rate (\$0.06)
Annual recharge pump energy consumption (kWh)	\$466,211	(68,863 kWh every 3 days * \$0.06 * 121.67 3-day periods in a year)

Table 35. Scenario B1 Financial Analysis Summary.

Scenario B1 Summary of Financial Calculations		
Fiscal Component	Calculation	Formula Used
Total Installation Cost Estimate	\$15,718,065	Direct + Indirect costs
Total Annual Operating Cost Estimate	\$796,291	Interest rate + O&M + Depreciation + TVA rate charged to pump / refill storage tanks
Total Annual Value of Energy Generated Estimate	\$924,653	kWh generated for 1 year * TVA rate paid for energy generation
Annual Operating Profit	\$128,362	Annual value of energy generated - Annual operating cost
CBA in Y1	-\$15,589,703	Annual value of energy generated – (Total installation cost + Total operating cost)
ROI (%)	-91.9%	(Annual operating profit – (total installation cost / Amortization + Annual operating costs) / (Total installation costs / Amortization + Annual operating costs)
Payback Period (years)	129	(Total installation costs + Annual operating costs) / Annual operating profit

CONCLUSION

Research Goals Summary

Urban water and energy system practitioners need tools that can enable evaluation of: (1) water and energy system integration, and (2) water storage measures that can be taken to advance local sustainability goals. A knowledge gap within the existing body of water-energy nexus work is a lack of understanding of the implications of additional storage capacity within urban water systems allocated for energy storage. To fill this knowledge gap, this study explores a community's energy consumption and the impact the urban water system can have in leveling peak energy demands. It also explores the water system's resilience to chronic growth stress with additional storage. Finally, it explores the cost implications of adding storage to the water system in various configurations.

This research tests 3 associated hypotheses:

1. There are untapped opportunities for energy storage within urban water systems due to a lack of water and energy system integration, and integrated modeling can identify these opportunities.
2. The addition of energy storage capacity can make water systems more flexible and resilient when faced with uncontrollable external variables in modeled scenarios.
3. Energy storage enhancements in urban water systems have financial variables that include localized energy and water costs, and these costs can be analyzed to determine fiscal scenarios and feasibly.

Research Methodology Summary

Research steps included the spatial and temporal modeling of an emerging city's water system. Cleveland, TN is used as a case study. Water distribution system model outputs are compared by scenario to historical aggregated hourly electricity demand data, to answer needed storage capacity questions around peak leveling and shaving. Then, the model is modified and augmented to add enough additional storage to shave between 5% (distributed storage) and 10% (concentrated storage) of peak community electrical demand.

Concentrated and distributed water model scenarios are then assessed by how each reacts to Cleveland's projected population change, to understand the resiliency impacts of both energy storage configurations. Each step is verified with actual water and electrical system data outputs, to determine the validity of the methodology. Finally, the cost implications of each scenario are examined in an Excel-based calculator

created for this research, to understand if payback periods can fit within local utility planning and financing horizons.

Research Outcomes Summary

Scenario outcomes by storage configuration (concentrated or distributed) and demand (current or future) are summarized together in Figure 49. A comparison of outcomes are as follows:

Scenario A1 - Concentrated Storage, Current Demand: Outcomes from this scenario show that design water storage within an urban water system to shave peak community electrical demand by 10% is possible, and that this is the ideal configuration to maximize energy generation. A tank farm consisting of nine 3,500,000 gallon tanks, concentrated close to a medium-voltage circuit, can generate up to 89,175 kWh over a 3-day modeled period of the case study's community daily electrical load. Due to direct and indirect installation costs (\$30,103,259) and annual operating and maintenance (\$1,562,162) estimates, (which include time of use pricing and pump energy requirements to recharge storage) the payback period for this scenario is 112 years.

Scenario A2 - Concentrated Storage, Future Demand: Outcomes from this scenario show that, from a resiliency perspective, concentrated storage is incapable of accommodating a doubled population's water demand. This is due to not being positioned in such a way that allows the tank farm to meet demand or maintain pressures across the water distribution system over time. To be successful in this endeavor, existing storage in the model would need to be doubled again, with at least 10 pump upgrades throughout the system, and 1 water source intake upgrade. This would make the financial implications even less attractive, with a payback period at least twice as long.

Scenario B1 - Distributed Storage, Future Demand: Outcomes from this scenario show that design water storage within an urban water system to shave peak community electrical demand by 5% is possible, but that this is not an ideal configuration for significant energy generation. Ten existing tanks are doubled in height to generate up to 44,704 kWh over a 3-day modeled period of the case study's community daily electrical load. Due to direct and indirect installation costs (\$15,718,065) and annual operating and maintenance (\$796,291) estimates (which include time of use pricing and pump energy requirements to recharge storage), the payback period for this scenario is 129 years.

Scenario B1 - Distributed Storage, Future Demand: Outcomes from this scenario show that, from a resiliency perspective, distributed storage can accommodate a doubled population's water demand. This is because storage is located throughout the water system, allowing the tanks to meet demand or maintain pressures across the water distribution system over time. However, at least 10 pump upgrades will need to occur throughout the system, as well as 1 water source intake upgrade. This would make the financial implications even less attractive. Additional pump costs alone will drive the payback period to 157 years.

Implications and Broader Applications of Research Results

At each step throughout this research effort, the lack of practical end-user data, information, and literature studies is notable. Considerably more work is needed to further explore, quantify, and price various schemes that can integrate urban water and energy systems. Without this additional work, the benefits of the water-energy nexus will remain confusing and vague to local utility decision makers.

While costing scenarios provide sobering implementation implications, field-building knowledge has been gained in this research effort. This is summarized by research category as follows:

Measurement of energy storage capacity in urban water systems and comparison to community energy needs. Academic research on the feasibility of using water storage to meet a portion of community energy needs energy storage in urban water systems contributes to the growing water-energy nexus body of work. It further advances clarity around the opportunities and constraints that complicate integration of urban water and energy systems. Ideally, the finding that community wide water system storage and community-wide energy consumption are two vastly different scales can help turn the focus towards the emerging field of microgrid energy on a case-by-case basis, further advancing cities as they progress towards their sustainability goals.

Addition of energy storage capacity to make water systems more flexible and resilient to chronic stress. Resilience is a priority topic at the local level, but addressing it in practical application to urban water and energy systems is still an emerging practice. Modeling external change scenarios can enable visualization of potential benefits to be gained by various configurations of energy storage in urban water systems. Ideally, the finding that additional distributed energy storage strengthens system resiliency can become a key component to advancing the practice of energy storage in urban water systems at the micro-scale.

Financial ramifications of increased energy storage capacity in urban water systems. Understanding the financial impacts of increased energy storage in urban water systems makes it clear that there is need for energy market progress to make time of use energy pricing more attractive to potential renewable energy generator owners. There is also room for improvement to bring down the cost of energy storage system implementation. These two financial elements, combined with a consideration of what is realistic across water striate and energy consumption scales will be the keys to removing barriers in discussions around advancing storage capacity in urban water systems.

Microgrids as a concept are not new, but they are emerging in renewed exploration and implementation. Utilities have traditionally invested in centralized plants, building transmission lines to move power to users. The aging electrical grid, ever-increasing energy demands, and the increasing frequency of severe weather events have all highlighted the need for energy and water system resiliency. If utilities begin to view microgrids as a way to make energy and water systems more resilient, as well as a way to provide energy for smaller community applications (to offset pumping costs, for instance), then can be assumed that seasonal and time-of-use pricing structures and metering requirements will become more attractive. These regulatory and pricing structure changes will spur more microgrid developments over time.

Designing small-scale hydro-generation systems for an appropriate scale of electricity delivery, finding appropriate storage sites, and structuring attractive financing are all critical considerations. Each potential microgrid site comes with its own unique requirements. Utilities, cities, and potential financiers and private partners must explore ways to make small-scale hydro viable. Academic research can support these conversations, if it provides access to more methodologies, water and energy data, system modeling, and cost explorations. The responsibility of providing this type of information has not yet been fully met.

VITA

Susanna H. Sutherland has lived in Knoxville, TN since 1999. She has a B.A. in Environmental Studies with a Forestry minor (2002) from the College of Arts and Sciences, University of Tennessee. She has an M.S. in Biosystems Engineering Technology (2004) from the College of Agricultural Sciences and Natural Resources, University of Tennessee.

In 2004, Susanna started her career with the Tennessee Valley Authority's (TVA) Environmental Policy and Planning division. She focused on permitting and grant writing, capturing \$1,500,000 for watershed restoration. She later joined TVA's River Operations and Environment division, scheduling river flows for the 7-state system.

In 2007, Susanna was recruited by the City of Knoxville to oversee final design of the south waterfront redevelopment plan. She purchased property, managed construction projects, and captured \$1,497,701 in funding from state and federal sources for Brownfield reclamation and design projects. In 2009, Susanna founded the city's first Sustainability Office with federal funds, and in 2012 it became locally funded.

Her projects brought in \$2,480,780 in unmatched grant funds, \$650,800 in new infrastructure, and are averaging annual utility bill savings of \$1,392,176. In addition to building a new city office with a baseline, a strategic plan, and measureable outcomes, Susanna co-founded the Southeast Sustainability Directors Network and contributed to publications with the National Academy of Sciences and the Environmental Law Institute.

In 2013, Susanna resigned from the City to start a consulting business and pursue a doctorate in Energy Science and Engineering. She works with philanthropic organizations and municipal networks to advance city sustainability and deep decarbonization goals. Her career goal is to embed economically efficient, environmentally logical, and socially fair best practices into our global culture, as energy systems are transformed to become more renewable and resilient.