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Water Microgrids: The Future of Water Infrastructure Resilience

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Abstract

Microgrids have recently come into vogue as a potential solution to address the increasing number of power outages caused by extreme weather events that impact our cities and communities. Such events – often precipitated by increasing global temperatures and climate change – have repercussions that expand beyond damages to a city's electric infrastructure. Water infrastructure is similarly vulnerable to extreme weather events, resulting in significant impacts to clean water distribution, wastewater treatment, and stormwater management. Given this similarity, and other value drivers to be outlined, this paper proposes leveraging concepts behind electricity microgrids to develop a unified framework for microgrid application to promote water resilience in the face of our changing climate.

Many parallels can be drawn between the electric grid and water infrastructure considering both are utilities that generate, store, and distribute an essential product that has been identified as a basic human right. Also similar to the electric grid, water infrastructure is aged and costly to redevelop. For both industries, microgrids are a potential solution that addresses aged infrastructure concerns while also being potentially more cost effective. In addition, by leveraging legacy infrastructural components while developing a new system within the system, microgrids provide redundancy, fortify vulnerabilities and secure the resource supply chain. This paper will investigate parallel components of electric and water infrastructure to provide a vision for future resilient water microgrids.

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1. Introduction

Electricity and water are critical resources of which our society depends; delivery reliability is expected and based on a traditional large-scale, centralized model. Despite being such precious resources, both have numerous delivery challenges, some of which are symptoms of the traditional utility model. An approach leveraged by electric utilities to mitigate these challenges is the development of microgrids that support existing infrastructure. Microgrids for the purposes of this paper can be defined as a grid within a grid – where all functions required for the larger network exist in a modified capacity for a smaller service area. Electricity microgrids are increasingly popular considering their relatively low capital and operational costs compared to redesigning the electric grid, their reliable performance and their ability to mitigate environmental impact. There are many benefits to utilizing energy microgrids many of which would also be realized if microgrid concepts were applied to water infrastructure.

1.1. Energy Microgrids as a model for Water Micronets

Envisioning our water supply networks as a grid, we can apply microgrid components to these networks to develop micronets (water micro networks) for water infrastructure. Like microgrids, micronets are small scale water systems built on top of the existing water supply network infrastructure. This is differentiated from the concept of decentralized water systems (such as decentralized wastewater treatment systems) which are completely segmented from existing legacy infrastructure.

In this paper we will investigate the various components of an electric microgrid and indicate the parallel benefits for water micronets, as outlined in below in Figure 1.

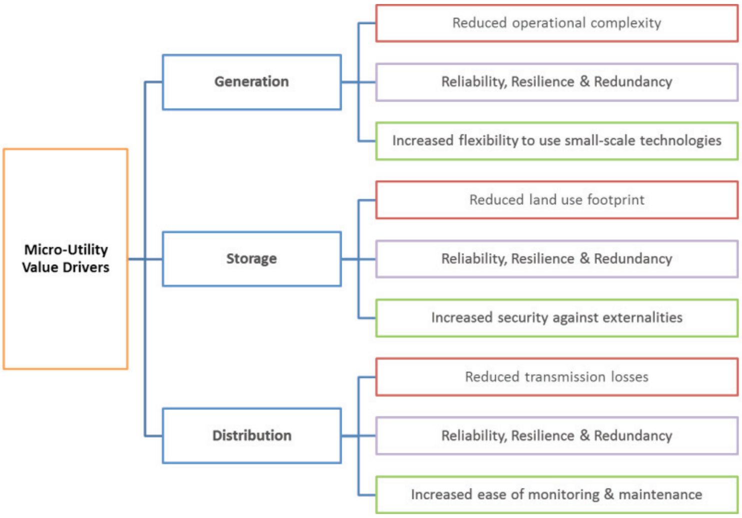

Fig. 1: Conceptual Unified Framework for Micro-Utility Value Drivers

There are three main areas that energy microgrids address: generation, storage and distribution. Each of these can be directly linked to a process that would be required of water micronets. The goal is to illustrate the value drivers of utility micro-infrastructure which prepares us to meet the stresses of future climate effects and increased utilization.

Considering the similarities in structure of water and energy infrastructure, we are proposing a unified framework for utility micro-infrastructure value drivers. By fully exploring these benefits, in the future, business cases can be more easily developed to support such distributed utility systems. The value drivers indicated in Figure 1 will be the focus of the subsequent discussion.

2. Generation

Energy generation is an electromechanical process that cannot be compared with water sourcing; however, both processes are sourcing a resource from locations that are often a significant distance from the point of end use. In this section, the benefits of a microgrid's generation process will be reviewed and applied towards developing a better understanding of the benefit case for micronets.

2.1. Energy Microgrid Features

The primary mode of energy generation is via a centralized process. There are several flaws with this method including: having a single point of generation failure can severely impair the grid in the case of disruption, resources for the generation plant need to be transported long distances to the centralized location and the energy generated from the central plant must be transported for miles to reach the energy's point of use therefore incurring distribution and transmission losses. Many of the faults inherently embodied in the centralized grid model can be avoided by using microgrids and the process of distributed generation. Contrary to generation for the proto-typical grid, distributed generation relies on localized sources for power generation. Rather than having centralized plants at one distinct location whose energy is transmitted over miles of power lines, multiple smaller energy generators are located nearby the point of energy use.

The benefits of distributed generation are manifold and are enabled by the value drivers illustrated in Figure 1. These include: reduced operational complexity, reliability, resilience and redundancy and increased flexibility to use small-scale technologies.

Considering distributed generators are smaller than centralized plants, there are fewer components that can potentially fail. If we compare a combined heat and power (CHP) plant to a coal-fired plant, the scale of generation differs by an order of magnitude. While it is common to see a 10MW CHP plant, the generating capacity of a typical coal-fired plant is 500MWs. The smaller scale of distributed generators also enables easier monitoring and management of emissions.

The dispersed and connected nature of distributed generation enables increased resilience from climate effects. If one generation plant is disabled due to a storm, the microgrid is still supported by the grid which provides a layer of redundancy for an energy service area. This improves the reliability and uptime of energy service for a community. An example of this is when Hurricane Sandy caused a blackout for most of downtown Manhattan and other areas in NYC. Despite this, a microgrid powered by a natural gas-fired CHP plants at New York University (NYU) were able to continue functioning. Had NYU's energy storage for its microgrid not been decentralized, it too would have been impacted by the climate effects and not been capable of providing energy to the 40 buildings it powers[1].

Another benefit of their small size and reduced energy production capacity requirements is the possibility to utilize certain energy generation mechanisms that are cleaner and cannot perform at scale. Certain renewable energy technologies that provide efficient energy production yet are not cost-effective to scale can be used.

While there are many benefits to the small, distributed nature of distributed generation facilities, there are drawbacks as well. Distributed generation plants are capital intensive. Financial concern is compounded as the cost of these plants cannot be spread as widely due to the limited service area. Because of this, it is not always clear who or what entity should be the financier. Also, distributed generation is not appropriate for every region of the grid. Business cases can be most easily made for areas that are subject to high climate risk. Distributed generation is far from a comprehensive solution to aging infrastructure – rather it is a strategic patchwork of repair and fortification.

Each of the benefits and drawbacks of distributed generation also applies to water sourcing and treatment. Benefits will be realized from having reduced operational complexity, reliability, resilience and redundancy and increased flexibility to use small-scale technologies.

2.2. Water Micronet Features

Oftentimes, the water that reaches our taps is sourced from many miles away despite the fact that potential water sources may be closer. In the U.S. alone, there are more than 14,500 surface water reservoirs[2] that are sometimes located as much as 300 miles away from the point of consumption, as seen in Los Angeles, California[3]. Considering the advent of modern technology, low-impact design (LID) techniques, and cost economies from efficient supply chains, our current water supply system is inefficient by some measures and the localized sourcing of water is a component to be further analyzed. Learning from the concepts of distributed generation, we can apply the methods of sourcing water resources locally to the point of use.

The customary potable water system consisting of a massive surface water reservoir, a byzantine system of pipes and pumps, and a centralized and often over-stressed water treatment facility is a system that has many drawbacks. Focusing on the start of the system – the surface water reservoir system – some of the well-known pitfalls are: high evaporation rates, high risk for source water contamination, and large capital and operating expenses, along with significant impacts to local fish populations and the surrounding ecosystem. There are of course many benefits to the dam-approach, but the scientific community and the public (as seen in the award winning documentary, Damnation) often argue that the cons outweigh the pros. Applying the concepts of micro-utilities, where the resource (e.g. water) is sourced in smaller quantities and in closer proximity to the end use, not only eliminates the pitfalls mentioned above but also provides additional benefits.

Firstly, localized water sourcing results in a reduction in operational complexity and operational expenditures. Dam’s are a complex structure that need constant monitoring, improvement, and repair, and with this complex and high-risk structure comes a high operating expense requirement. Localized water sourcing – via localized surface water, groundwater wells, rainwater harvesting, or graywater reuse – provides the opportunity to use more basic engineering structures in a lower-risk environment.

Secondly, the concept of micronets provides increased flexibility to leverage water source technologies and techniques that are often not viable at the large scale needed to support the expansive distribution networks that are status quo. Small-scale graywater reuse, rain water catchment cisterns, air conditioner condensate, and on-site chemical disinfectant systems are all example technologies that have varying financial and non-financial benefits that make them highly attractive in small-scale application. There are examples of locations that have capitalized on the use of these technologies to source water, including rainwater harvesting in New York City, microgrid water purification in Hawaii, and atmospheric water generators in West Virginia.

Lastly, and perhaps most importantly, distributed water supply and treatment would provide for redundancy in case a water supply is adulterated. Climate effects as well as concerns regarding biological and chemical contaminants are increasingly threatening our water supplies. Distributed supply channels for water sources would provide a layer of redundancy that could hedge serious risks to a community in the case of contamination. Such redundancy in water sourcing is rather non-existent today, and puts communities at serious risk, as seen during the January 2014 chemical spill in West Virginia’s Elk River that affected drinking water for 300,000 people and resulted in an estimated $61 million hit to the local economy[4]. If micronets were in use, the contaminated water micronet could be shut down until safe and alternate micronets that were still safe could have filled in for the contaminated supply.

While there are some potential political and financial challenges to develop water micronets, the same principles behind distributed generation in energy microgrids can be transferable to water micronet distributed sourcing and treatment. The benefits realized in energy microgrids apply for water micronets as a result of decreased operational complexity, the use of alternate resource sources and increased redundancy as per Figure 1. Similarly to energy microgrid generation, the purpose of micronet sourcing and treatment is not to replace entire water supply networks; however the goal is to augment the aged infrastructure with micronets for increased water infrastructure resilience.

3. Storage

Resource storage is the key buffer that provides both energy and water utility networks the ability to provide uninterrupted service. Currently though, both energy and water are most often stored in large-scale, centralized locations which is both costly and high-risk; decentralization of storage provides both redundancy and a reduction in the magnitude of impact from failure events. In this section we will explore how microgrid and micronets are used to increase system resilience, among other benefits.

3.1. Energy Microgrid Features

Energy storage is a challenge for the conventional grid as massive mechanisms are required to enable storage. One popular grid storage mechanism includes pumped water hydroelectricity. Here, excess energy produced is used to pump water to high locations where it is stored until energy is needed. At peak demand periods, hydroelectric generation can be initiated at high dispatchability resulting in readily available and quickly generated electricity. Other energy storage features are also reliant on the availability of large natural formations such as salt caverns to store compressed air during off peak periods that could be released to power turbines during peak load thereby offsetting the need for additional generation. Both mass storage apparatuses require a major environmental footprint, are not found in all geographies and considering their limited quantity can cause large-scale disruption if disabled.

Several of the challenges involved with grid storage can be ameliorated through microgrid storage techniques. Considering a microgrid's inherently limited service area, there are often times when the generation of the microgrid exceeds demand. This excess energy can be stored for later use providing reserves for peak load periods. The benefits of microgrid energy storage are manifold and are enabled by the value drivers in Figure 1 including: reduced land use footprint, reliability, resilience and redundancy and increased security against externalities.

Rather than damming rivers for hydropower or commandeering large natural caverns for compressed air storage, microgrid storage options can be small in size therefore reducing the environmental footprint of the mechanism. Also, whereas natural features can be located far from urban centers where energy is consumed, microgrid storage containers such as grid-scale batteries are man-made and can be located in a basement or backyard. An example of this is AES Energy Storage's 32MW lithium ion storage project that supports the nearby 98MW wind farm in West Virginia[5]. Here, storage was placed in the mountains of West Virginia far from typical energy storage features.

Microgrid storage provides redundancy to the grid considering their connection thereby enabling the sale of excess energy from microgrid storage to be sold to the grid. The ability to sell energy to the grid provides increased overall grid resilience as a microgrid can potentially help power other microgrids or level energy loads during peak periods for the greater grid. In this way, microgrids provide increased stability and reliability of energy provision to consumers by helping to prevent brown-outs and power outages. Microgrid storage also helps develop a resilient grid as it enables the use of renewable energy systems to augment the grid even though their generation is variable.

The relatively small size of microgrid storage enables it to be distributed. Distributed storage provides increased security in the case of an attack or climate impact on an energy source. The decentralization of the storage limits the impact on the grid in case one location is affected. The smaller size of the storage also reduces the exposed area to the elements or terrorism as opposed to the impact if something were to happen to a major hydro operation.

While there are several benefits of microgrid storage there is a major limitation which is inherent to the small size of microgrids – the limited capacity of storage compared to the cost of the storage. Grid-scale batteries are extremely expensive and considering they are only intended to store a limited amount of energy for the microgrid, the cost per unit of storage is relatively high. For this reason, the business case is not always clear for how to develop microgrid energy storage. When the cost of risk hedging is considered due to storage's decentralized nature, microgrid energy storage begins to look more attractive, however the costs are still substantial at over $200/kwh compared with that of $5/kWh for natural formation energy storages such as for compressed air salt caverns or hydro[6].

The benefits and drawbacks of microgrid energy storage are very similar to those for micronet water storage. These will be a result of their having similar value drivers of a reduced land use footprint, reliability, resilience and redundancy and their increased security against externalities as noted in the unified value driver framework.

3.2. Water Micronet Features

If you follow a drop of water from source to treatment to distribution you will find many points along the way where water is stored in both open reservoirs and closed tanks. These storage locations either serve as storage of water for use during a later time, or serve as a storage location allowing for chemical processes to take place (e.g.

disinfection and coagulation). As expected, the creation of these large storage reservoirs results in impacts to major natural formations – such as turning an existing valley into a man-made reservoir – which is not unlike the methods used to meet the large storage requirements for energy.

Centralized reservoirs of water storage, both open reservoirs and closed tanks, pose major risks to the water's vulnerability to contaminants and attack. In Portland, Oregon, the Portland Water Bureau was forced to empty, clean and refill 50 million gallons of water due to contamination[7]. The contamination was due to three men urinating into the reservoir. This seemingly menial prank was cause for major waste and inconvenience and such acts are a constant threat to water quality in large storage locations. It is difficult to control what substances end up in reservoirs both intentionally and unintentionally which makes water storage increasingly difficult to manage.

Leveraging principles from energy microgrids' storage, micronets could benefit from similar concepts for water. Using micronets, as per Figure 1, environmental impact can be minimized, magnitude of contamination events can be mitigated, and reliability is increased. Like microgrids, storage locations in micronets would be strategically located in a relatively close proximity to the water's point of use. With this, less storage would be required considering the smaller service network and the reduction in pipe length and corresponding leakages. This in turn can result in a reduction in the land use needs for existing reservoirs and in some cases, the need for intermediary holding tanks. Beyond this, micronet storage would also provide for increased reliability and increased water security due to its decentralized nature. If one micronet reservoir is contaminated, it will impact a discrete volume of water and not spread to other micronet reservoirs, therefore reducing the total water volume impacted by a given contamination event and limiting the potential exposure of a population to water quality issues. Examples of decentralized on-site storage is often found in areas where reliability in quality and quantity is critical, such as large hospital facilities, beverage producers, and rural residential areas.

A challenge with water micronet storage involves the requirement of storage in regions where space might be scarce. While reservoirs might have substantial environmental impacts, the reservoirs are typically in remote areas where real estate is plentiful. If we were to think about installing a micronet in NYC, there could be cause for concern considering the lack of space in the NYC metropolitan area. Also, similarly to a downfall of the energy microgrid, the cost per cubic foot of water storage might not always be cost-effective considering the storage capacity required for micronets in conjunction with the price premium in highly urbanized areas.

These downfalls mentioned are not substantial when considering the potential resilience implications for water networks. Benefits of micronets are numerous and should be considered when determining how to renovate and repair aged water infrastructure. These benefits are enabled via the micro-utility value drivers in Figure 1.

4. Distribution

Perhaps the most complex components of both the energy grid and our water infrastructure are the expansive and complex distribution networks that transport these resources from their source to our sink or outlets. These networks provide opportunities for high transmission losses and opportunities for system failures, both of which are experienced regularly in the traditional utility model. The distribution benefits we appreciate with energy microgrids can be applied to further understand the full value case of water micronets, as will be discussed in this section.

4.1. Energy Microgrid Features

In the United States, the electric grid incurs losses of 6% to transmission and distribution (T&D) of energy[8]. 5-10% of losses are typical for G-20 countries. The cause of loss is in part due to the distance between the source of generation and end use of energy. Not only does the complex network result in losses, but its size and complexity results in increased vulnerability to damage, service downtime and decreased visibility to potential issues throughout the network. These T&D concerns are some of the principal reasons that have driven utilities and governments to call for a fresh look at our electricity grid.

Reducing the service areas of grids helps to ease their T&D requirements – hence one of the reasons for microgrids' increasing popularity. As per Figure 1, there are three core value drivers behind micro-utility T&D including: reduced transmission losses, reliability, resilience and redundancy, and increased ease of monitoring and maintenance.

Considering microgrids' inherently smaller service areas compared to the grid and their use of distributed generation, less miles of cable are required between the generation source and point of use. These shorter distances enable less opportunity for T&D losses to occur. Although it is impossible to eliminate all losses, having electricity generated closer to consumption has been approximated to reduce losses 2-4%[9]. In Burrstone Energy Center's filing for certification of their small power production facility, they estimated losses of only 3%[10].

Reducing T&D infrastructure decreases the risk of impact from climate effects. A primary cause of power outages is downed power lines. Reduced requirements for power lines due to decreased T&D distance can reduce the risk of power outages and improve energy supply reliability to consumers. Also, the ability for microgrids to sell energy to the grid requires a robust connection between microgrid networks and the grid. This connection provides both grid and microgrid T&D redundancy where connected.

The shorter distances required for energy to travel and the associated reduced infrastructure requirements carries less opportunity for points of failure due to corrosion or wiring faults. Because of the reduced complexity in length of microgrid systems, the network is more accessible for maintenance and repairs. Additionally, the microgrid model typically includes robust metering and monitoring capabilities. Microgrids are often built to be "smart grids" which entail the ability for data communication between nodes of operation and a command center thereby providing visibility to consumption, demand and other energy metrics. This visibility enables understanding of real-time requirements for an energy grid. Increased data visibility also provides the opportunity for improved planning and impact assessment for known events that might influence demand requirements. Real-time meter data within a T&D network provides unprecedented control and oversight to the operations and efficiency of the microgrid. Such efficiency was realized by the Siemens-implemented microgrid at the Savona campus of the University of Genoa, Italy. It is estimated that €50,000 annually will be saved due to the smart microgrid infrastructure in place[11].

If a microgrid is owned by the utility, a downfall of the microgrid model is the requirement to maintain two grids. This might not be a problem if the microgrid is owned by a third-party apart from the utility. While not necessarily a major operational challenge, the cost to operate multiple grids could add up over time.

The benefits and drawbacks of microgrid energy distribution will be parallel to water micronets considering similar underlying features. These will be driven by reduced transmission losses, reliability, resilience and redundancy, and their increased ease of monitoring and maintenance.

4.2. Water Micronet Features

Distribution for water today has not changed much over the centuries both in the methodology used to transport water from point A to point B, but also in terms of the pipe materials used. Generally, pressure gradients and gravity are leveraged to transport water from source to storage to end use. When pressure and height gradients are not possible to take advantage of, pumps are used. Water pipes range in material based on when the pipes were laid. Older cities water infrastructure includes pipes made of iron or copper while newer water infrastructure is composed of pipes made from un-plasticized PVC and galvanized steel. A considerable percentage of our water infrastructure in North America is significantly aged[12], therefore; there are many opportunities for water distribution issues.

Considering micronets would be inherently localized, the reduction in piping infrastructure decreases the pipe length where leakage could occur and also provides a small pipe network to maintain. As a result, reduced water loss during distribution is expected. In California, a state-wide water distribution audit found that on average 10% of all water distributed is lost to leaks, a statistic that micronets could perhaps improve[13].

Similarly to microgrids, micronets would connect to existing water infrastructure. This would provide opportunity for micronet redundancy, but also for water supply network redundancy. If water supply for the micronet exceeds demand, the treated water could potentially be sold to the water supply network and vice versa. This could have significant resilience implications for regions facing drought. The water micronet connection to the water supply network could help hedge a micronet and its surrounding region's susceptibility to climate effects. Additionally, considering micronets would be connected to the water supply network, the water supply network would need to be fortified during this process further improving water distribution channels for the region overall.

Additionally, the smaller scale distribution network of a micronet would allow for advanced metering and monitoring equipment. Learning from electricity microgrids, this data-enabled system of micronets could potentially provide the availability to anticipate drought levels in real-time for the micronet and help the region accommodate by sending a signal to other micronets or the water supply network requesting additional water for its service area. In the future, if we used a demand-response-like system for water, data-enabled micronets could be valuable tools to level load and help with peak demand periods – much like electricity microgrids.

Downfalls to water distribution for micronets are the capital costs required to relay piping and fortify existing water infrastructure to connect to the micronets. While developing micronets could be less expensive than repairing all aged water infrastructure, it will still be costly to develop. The jurisdiction of the micronets also may be disputed considering where the water distribution channels flow through.

The distribution opportunities available for water micronets outweigh these downfalls and provide the chance to renew our water infrastructure and benefit from the value drivers in Figure 1. Micronet distribution would realize serious resilience benefits, especially in light of the increased climate effects impacting our water supplies.

5. Conclusion

At a conceptual level, we see a strong overlap in the downfalls of the traditional utility model and the benefits of a micro-utility. Through exploring the overlap of the value driver – as seen in Figure 1 – it is clear that the benefit case of microgrids should be used to further build the business case for micronets. Perhaps the question should be asked, if there's a successful microgrid in a given location, why is there not also a micronet in place – and vice a versa?

Furthermore, given this established overlap, it is also possible that the increased sharing of lessons learned could be beneficial for both microgrid and micronet pursuits. Given the current emphasis in developed countries on replacing aged infrastructure, and the emphasis on new infrastructure in developing countries, now is the time to further explore micronet development in the face of changing resilience requirements for many cities.

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