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Emerging Technologies Review: Water Microgrid

April 2023

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Susan Loper

Prepared for the Air Force Civil Engineer Center
under a Work-For-Others Agreement with the U.S. Department of Energy

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Richland, Washington 99354

Executive Summary

A majority of missions in the Department of the Air Force (DAF) depend on both water and energy. The 2021 Air Force Installation Energy Strategic Plan embraces this dependency and outlines a path to greater mission assurance through the realization of more resilient energy and water systems. The previous energy strategic plan placed equal weight on resilience, cost-effectiveness, and cleaner energy technologies. The new plan emphasizes a focus on resilience and mission-centric efforts, while also highlighting the importance of water: "Resilience has become central to DAF efforts."[1] The 2022 Air Force Climate Action Plan[2] aligns with the Energy Strategic Plan in its third priority, where it calls on the DAF to "Optimize Energy Use and Pursue Alternative Energy Sources." The Air Force Civil Engineer Center has tasked Pacific Northwest National Laboratory with investigating emerging technologies to inform the Air Force's understanding of the technology and to guide key considerations for implementing technologies that are resilient and alternative sources to the traditional methods used in the Air Force today.

This report explores the concept of a water microgrid for deployment at Air Force installations. A water microgrid is a local water system that supplies, treats, and distributes water, with the primary objective to meet critical water demand during a disruption of the primary supply, whether provided by a local utility or an on-site source. A water microgrid can operate independently of an existing primary water system and includes a layer of sensing capability that provides the necessary monitoring and controls to operate the water microgrid. A water microgrid can advance an Air Force installation's water infrastructure and water resilience by being ready to meet critical missions during a primary supply outage.

Water microgrids are composed of a network of components, including water supply, storage, treatment, distribution, power, and controls. Figure ES.1 illustrates the general concept of a water microgrid, which includes the following components:

- **On-site water supply:** Water microgrids have an on-site water supply that is redundant to the primary supply to provide reliable backup water to critical demands in times of disruption.
- **Storage:** Water storage components at different stages in the system (pre- and post-treatment) are critical for reliable water microgrid infrastructure to ensure adequate water supply throughout outage durations to preserve mission function.
- **Treatment:** Water microgrids provide treatment of on-site water to either potable or non-potable levels depending on the demand application requirements.
- **Distribution:** Water is conveyed in a water microgrid through a series of pipelines sized for proper velocity based on flow volume and pressure requirements. The system carries the treated water through the site's trunk mains, distribution mains, and domestic lines controlled through valves and pumps.
- **Reliable power:** To ensure reliability, a water microgrid has sufficient power to ensure the energy requirements of critical components can be met. Water microgrids require energy for a variety of functions, including supply, treatment, pumping/pressurization, distribution, and critical demand isolation.

[1] Air Force Installation Energy Strategic Plan, https://www.af.mil/Portals/1/documents/2021SAF/01_Jan/AF_Installation_Energy_Strategic_Plan_15JAN2021.pdf

[2] Air Force Climate Plan, https://www.safie.hq.af.mil/Programs/Climate/

- **Advanced monitoring and controls:** An overarching controls infrastructure provides real-time monitoring and the capability to enable and disable system components during an outage to meet critical water demands.

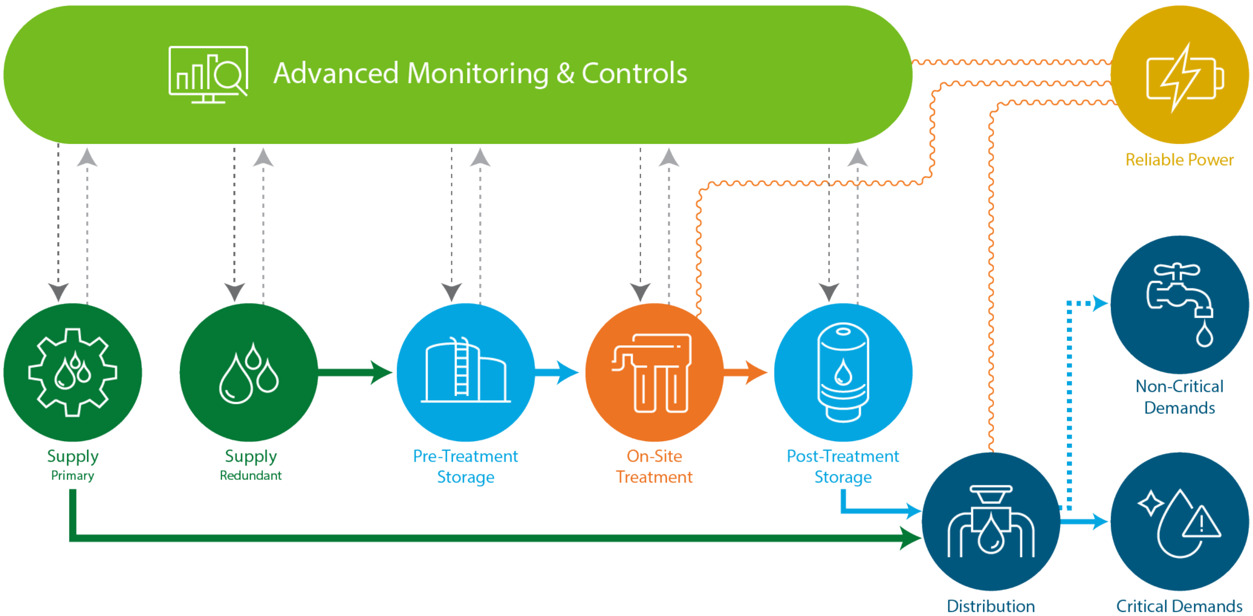

Figure ES.1. Water Microgrid Main Components

For a water microgrid to function properly, it must have these three key characteristics:

- **Self-sufficient**: A water microgrid needs to have the ability to operate in an islandable mode apart from external providers, and this also extends to related aspects such as energy supplies, treatment chemicals, and replacement parts.
- **Reliable**: A water microgrid should be designed and hardened so that all components can withstand whatever disruption interrupted the primary supply (e.g., earthquake) so that no single point of failure can take down the overall system.
- **Automated**: Microgrid controls should be capable of real-time controls that monitor system components and water quality and enable or disable system components during a disruption as necessary to meet critical water demands.

There are many factors to consider when implementing water microgrids, which will be vital in the successful deployment of the system. These include the following:

- **Operation and maintenance**: Water microgrids have a complex set of system components that require proper operation and maintenance by system operators.
- **Current system conditions**: Existing water infrastructure, such as water distribution, storage, and treatment systems, should be evaluated to determine its viability as part of a water microgrid.
- **Regulatory approvals**: Water supplied and treated on-site will likely require regulatory approvals at the local, state, and federal levels.
- **Curtailment plans:** A site considering a water microgrid should have a curtailment plan in place that provides specific procedures on ceasing non-critical water demands and potential

curtailment of critical water demands to meet only the loads that can be met based on microgrid system sizing and status during times of disruption.

- **Emergency planning**: Along with curtailment planning, emergency planning is also an important function at an installation with a water microgrid, providing the installation with the procedures and personnel that are in place to respond to a water emergency.

Moving forward, it is recommended that the Air Force consider deploying a pilot water microgrid to test the feasibility of the technology and assess the performance of specific elements. The Air Force is advised to identify key installations that are good candidates for implementation. Key parameters to consider are installations with existing water infrastructure, high water consumption, high water risk, and primary water supply reliability concerns (i.e., frequent outages). The pilot effort can be at a small scale that includes a single building or a collection of several buildings, which can demonstrate the basic functions of a water microgrid. A second pilot approach could be to implement in-line storage systems and valves to isolate critical water uses and employ controllers to operate them. Both approaches hold measurable resilience gains for the Air Force and should be considered in greater detail in support of the Air Force's overall mission resilience directive.

It is recommended that the Air Force consider the following key criteria when selecting potential water microgrid pilot locations:

- **Mission priority:** Installations that provide critical functions to the Air Force may be good candidates for a water microgrid.
- **Water risk**: By incorporating a redundant water supply, water microgrids can help to mitigate water risks, such as droughts and increased local demand for water, which can significantly impact water availability and affect the Air Force's ability to secure adequate water supplies for critical functions and processes.
- **Existing infrastructure:** Installations with existing on-site water supply, water treatment, and storage provide key infrastructure important for the operation of a water microgrid and may require minimal to modest additions or upgrades.
- **Water consumption:** Installations with relatively high water use may be better suited for a water microgrid because installations with lower water use may be able to meet their water needs using simple solutions such as water buffalos and/or bottled water.
- **Rainwater harvesting potential**: The availability of rainwater to harvest as an alternative water source could provide an additional on-site redundant water source for a water microgrid.
- **Water supply reliability**: Frequent unexpected water outages may indicate an unreliable primary water supply and/or vulnerable infrastructure. Installations with reliability concerns may be good candidates for a water microgrid to help upgrade degrading infrastructure to ensure it can meet critical needs.

Acronyms and Abbreviations

AFCEC	Air Force Civil Engineer Center
CCL	Contaminant Candidate List
DAF	Department of the Air Force
DC	direct current
DoD	Department of Defense
DPR	direct potable reuse
EPA	Environmental Protection Agency
ERCIP	Energy Resilience and Conservation Investment Program
HVAC	heating, ventilation, and air-conditioning
IoT	Internet of Things
IPR	indirect potable reuse
MRDL	maximum residual disinfectant level
NBRC	National Blue Ribbon Commission
O&M	operation and maintenance
PLC	programmable logic controller
PNNL	Pacific Northwest National Laboratory
PV	photovoltaics
SCADA	supervisory control and data acquisition
SDWA	Safe Drinking Water Act

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1.0 Introduction

As the Department of the Air Force (DAF) planners work to enhance the energy and water security of critical sites, identifying proven methods and processes to produce, treat, and distribute water to meet critical mission needs is vital. Climate change and other factors, such as drought risk and increased demand for water, have the potential to significantly impact water availability across the country. These risks can affect the ability of the Air Force to secure adequate water supplies for critical functions and processes.

A water microgrid provides a reliable source of water that serves as a redundant water supply during times of disruption, thereby improving installation readiness and resilience while supporting broader sustainment and environmental objectives. The use of water microgrids supports the requirements outlined in Department of Defense (DoD) Instruction 4170.11 (DoD 2009), which states that DoD components shall “take necessary steps to ensure the security of energy and water resources.” The Air Force Installation Energy Strategic Plan 2021 (Air Force 2021) outlines a path to greater mission assurance through the realization of more resilient energy and water systems. The new plan emphasizes a focus on resilience and mission-centric efforts, while also highlighting the importance of water. The Air Force Civil Engineer Center (AFCEC) has tasked Pacific Northwest National Laboratory (PNNL) with investigating emerging technologies to inform the DAF’s understanding of water microgrids and to guide key considerations for implementing technologies that are resilient and alternative sources to the traditional methods used in the Air Force today.

This report provides a definition of a water microgrid based on the current technology landscape and previous research conducted by PNNL. The focus is on water systems (potable and non-potable) and does not address wastewater systems except as an opportunity to provide an alternative water source where applicable. Section 2.0 describes the components and operational considerations. Section 3.0 provides technical considerations. Section 4.0 provides an overview of regulatory considerations related to potable and non-potable water. Section 5.0 describes social and environmental risks. Section 6.0 provides considerations for funding a water microgrid. Sections 7.0 and 8.0 provide siting recommendations and a path forward.

2.0 Technology Description

A water microgrid is a local water system that supplies, treats, and distributes water, with the primary objective to meet critical water demand during a disruption of the primary supply. The objective of a water microgrid is similar to that of an energy microgrid, which the Department of Energy simply defines as "a local energy grid with control capability, which means it can disconnect from the traditional grid and operate autonomously" (DOE n.d.). A water microgrid may offer a viable solution for a site to address resilience gaps identified through the resilience planning process. For example, a site may not have adequate and redundant water supply to meet critical demands with vulnerabilities in the operating systems. A water microgrid provides the ability to island the water system from the primary water supply to satisfy water demand requirements throughout an outage or disruption.

In contrast to an energy microgrid, water presents resilience aspects that are quite different from energy needs. Water systems support basic human functions in any operating environment for drinking, sanitation, and treatment of generated wastewater. There are also strict regulatory requirements to ensure potable water is safe for human consumption. These unique aspects present opportunities and challenges that need to be considered when examining the potential application of a water microgrid.

A water microgrid secures the ability to respond to primary water supply interruptions, allows for varying demand needs, and ensures that critical water load requirements are sustained in an emergency response scenario.

The terms "water microgrid" and "water micronet" are used interchangeably throughout literature that describes an islandable water system. Adeyeye, et al. (2018) present microgrid and micronet as two systems that operate in synergy, with the micronet functioning as a layer of sensing capability that sits on top of the microgrid (though the delineation between the two is rather loosely defined). Falco and Webb (2015) drop "microgrid" in favor of "micronet," though this seems somewhat arbitrary as they seem to reserve the term "microgrid" for energy and "micronet" for water, without considering the meaning of the words in the context of a water system.

Hereafter in this report, "water microgrid" will refer to a local water system that supplies, treats, and distributes water, with the capability to operate independently of an existing primary water system, and includes a layer of sensing capability that provides the necessary monitoring and controls to operate the water microgrid as shown in Figure 1.

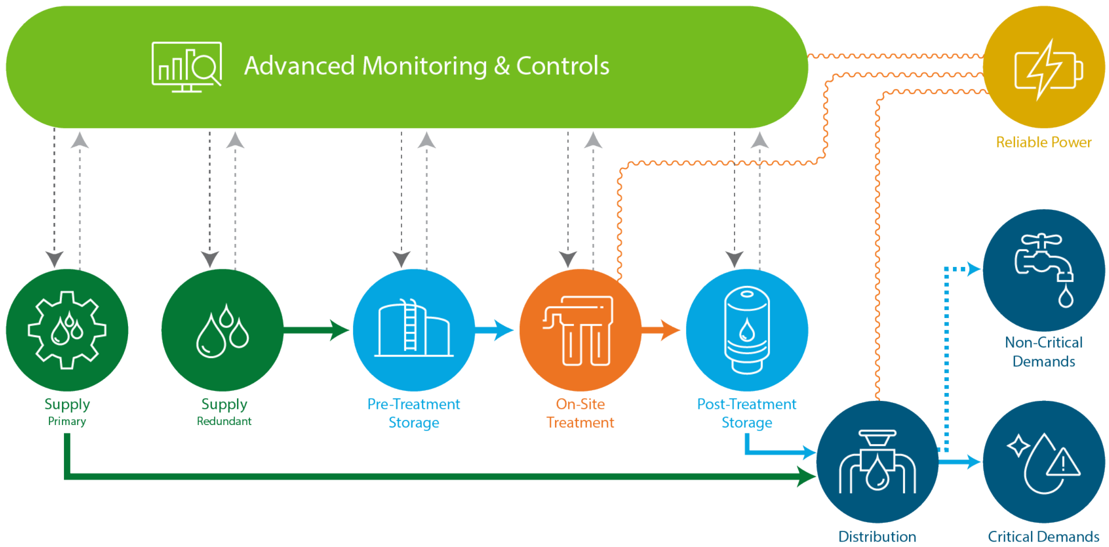

Figure 1. The Relationship Between Water Microgrid Components

2.1 Characteristics

The main function of a water microgrid is to provide redundant on-site water for critical demands during a water disruption. Water is required to enable certain critical functions, operations, and activities. A water microgrid can treat the on-site water supply (primary and/or redundant) to appropriate quality standards and distribute it for consumption. For a water microgrid to function properly, it must have the required characteristics of being self-sufficient, reliable, and automated (Figure 2).

Self-sufficient: A water microgrid needs to have the ability to operate in an islandable mode apart from external providers, but this also extends to related aspects such as energy supplies, treatment chemicals, and replacement parts. Meeting this criterion, water microgrids can treat the on-site water supply to the appropriate quality standards, meeting the regulatory requirements and procuring the appropriate water rights to ensure continual operation.

Reliable: A water microgrid should be designed and hardened to withstand whatever disruption interrupted the primary supply (e.g., freeze event) so that no single point of failure can take down the overall system. A water microgrid is designed to supply critical demands for a specified timeframe and is hardened to withstand disruption under specified conditions, including current and future natural hazards the installation is exposed to as well as more common disruptions such as power outages and pipe failures.

Automated: Water microgrids have an overarching control system providing real-time system monitoring and control. Microgrid controls are capable of protecting system integrity and maintaining safety in response to a disruption. The automated control system also enables or disables system components during a disruption, as necessary, to meet critical water demands. In addition, distributed sensing/control technologies monitor the system with real-time flow meters, pressure gauges, and water quality monitoring equipment deployed throughout the network to gather vital data for the microgrid operation. To do so, valves and sensors dispersed throughout a standard distribution system isolate supply paths in the event of infrastructure failures, per the system design.

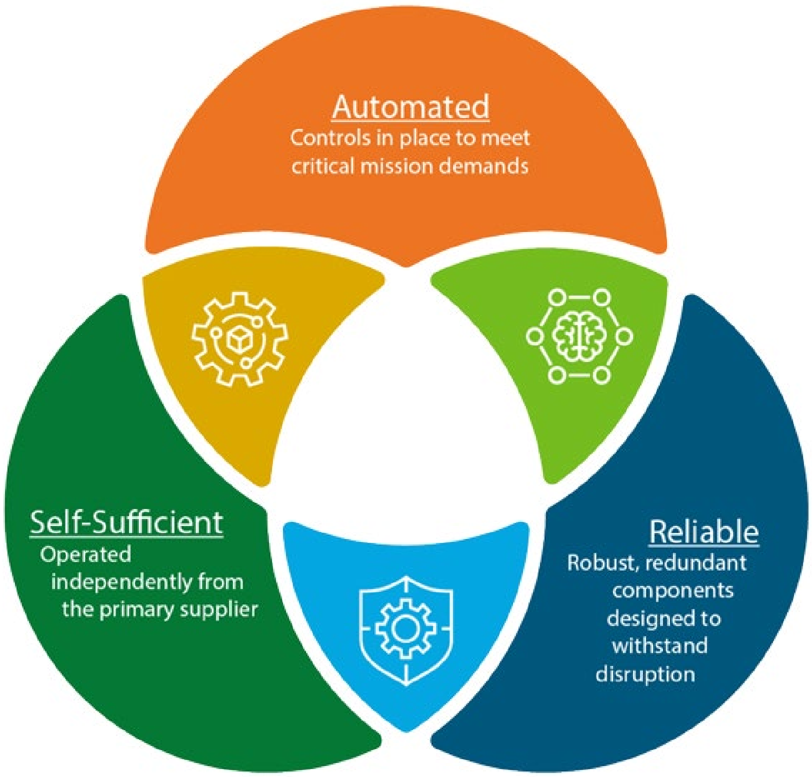

Figure 2. Water Microgrid Characteristics

2.2 Components

A water microgrid is composed of supply, storage, treatment, distribution, reliable power, and automated controls. Water microgrids collect water from appropriate water sources, treat it, distribute it for use in critical demands, and finally discharge to wastewater or return it to the environment. Figure 3 provides an example illustrating how the major components of a water microgrid integrate with the primary system. Dashed lines represent the primary supply (in this case off-site) and non-critical demands shut off during a curtailment event.

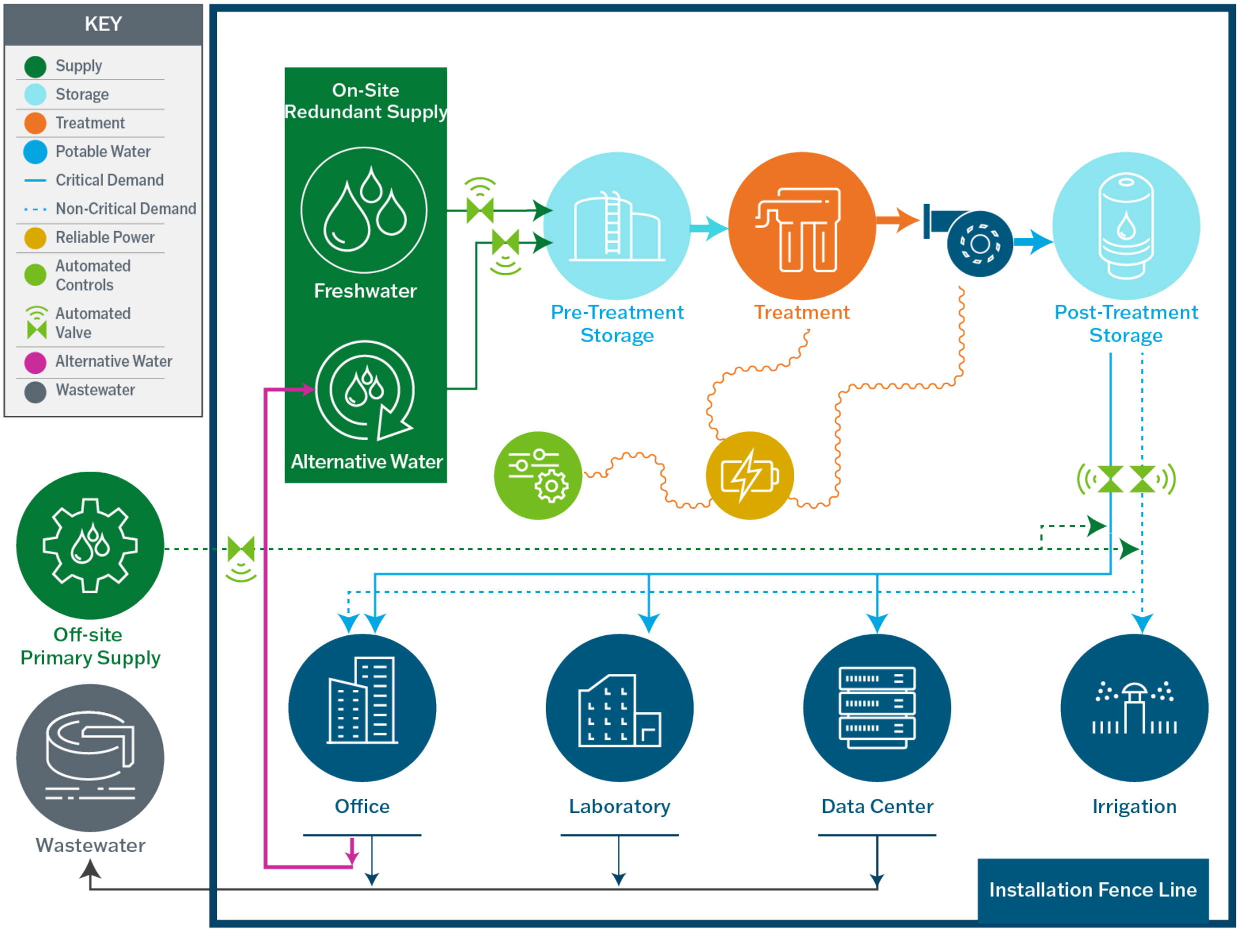

Figure 3. Example Components of a Water Microgrid

2.2.1 Supply

Water microgrids have on-site independent water supply to provide reliable backup water to serve critical demands in times of disruption. As shown in Figure 4, there are two general types of water supply:

- **Freshwater:** Surface water and groundwater found naturally in the environment that has a total dissolved solids concentration of fewer than 1000 milligrams per liter (1000 ppm). Examples include underground aquifers; perennial or ephemeral springs, creeks, and streams; rivers and lakes; and reservoirs.
- **Alternative water:** Water supplied from non-freshwater sources, typically diverted from waste streams or captured, then treated for use. Examples include harvested rainwater from building roofs and other hard surfaces, diverted stormwater, reclaimed wastewater, greywater, captured condensate, atmospheric water generation, water purification concentrate, foundation water, blowdown water, and process reuse. The term "water reuse" is also commonly used and is synonymous with "alternative water."

Figure 4. Basic Water Terms

Both freshwater and water reuse can be treated to either potable or non-potable standards. Potable water is tested, permitted, and approved for human consumption. Non-potable water is not approved for human consumption, even with some degree of treatment to reduce particulates, microorganisms, and impurities. Section 2.2.3 provides more information on treatment as a component in water microgrids.

Water microgrids focused on sustaining critical activities for relatively short and pre-defined outage intervals (as determined by the installation) may be served primarily through storage systems or water reclamation systems and relatively minor treatment and distribution infrastructure. On the other hand, systems that need to be fully self-sufficient for indefinite time periods – a valid goal in the context of seasonal or multi-year droughts or recurring natural disasters – cannot rely on storage and limited treatment alone. Instead, these systems may resemble a small municipal water system that includes multiple production wells or surface water sources, which are interconnected to preclude any single point of failure and are hardened to withstand identified threats and hazards. Lastly, in the case of full self-sufficiency, there is a need to secure water rights to a water source. Even in locations with ready access to an independent freshwater supply, the sourcing of water reuse and its treatment to the water quality standards required by the critical end-uses may result in a more resilient microgrid design. This approach also relieves pressure on local municipal supplies, an important social and political consideration in light of reduced water supplies in many locations in recent years.

Table 1. Water Supply Examples

Water Type	Example Source	Description
Municipal supply	Local water utility from freshwater sources	Piped under pressure directly to the site from the water treatment plant; metered for purchase
On-site freshwater	Groundwater aquifers	Pumped from a drilled, cased well; typically requires no (or minimal) treatment
	Continental surface water bodies	Perennial or ephemeral surface water bodies such as lakes, rivers, streams, and reservoirs
On-site alternative water	Harvested rainwater	Precipitation collected from roofs or other above ground surfaces
	Harvested stormwater	Precipitation collected from ground-level hard surfaces, e.g., parking lots and other hardscape
	Reclaimed wastewater	Treated wastewater to acceptable levels for reuse
	Captured condensate	Condensate flow from heating, ventilation, and air-conditioning (HVAC) systems
	Process reuse	Water captured from processes such as water purification systems and cooling tower blowdown
	Greywater	Lightly contaminated water from showers, sinks, and washing machines
	Atmospheric water	Extracted from ambient air in humid climates

2.2.2 Storage

Water storage systems are critical components of a reliable water microgrid at any scale because they play a significant role in ensuring adequate water supply throughout outage durations (of varying time periods) to preserve mission capability. Water storage plays a role similar to energy storage such as batteries in an energy microgrid, which fills the valleys of intermittent renewable energy production and provides a buffer to extreme and sudden drops (i.e., ramp rates) in energy production. Both elements are relevant to water storage. Like batteries in an electric microgrid, on-site water storage can supplement or replace the primary water supplies when they are partially or completely disrupted. In the case of tiered water supply including backup water systems such as wells or alternative water supplies, storage tanks may help buy time for the redundant water supply to come online.

Depending on the water source, water microgrids may include water storage at the supply (before treatment) as well as post-treatment (before distribution) to ensure quality standards are maintained. There are several options available for water storage. Table 2 provides examples of various storage system types. Storage tanks are generally of atmospheric (including underground) or hydropneumatic design. Atmospheric tanks store water at ambient pressure and rely on booster pumps or elevated towers using gravity's potential energy to provide the water pressure for use. Hydropneumatic tanks pressurize the water with an air chamber, where a bladder or diaphragm compresses the air as water is stored in the tank. This compression provides the delivered water pressure as the water is withdrawn. Underground tanks provide storage below grade and rely on booster pumps to lift and pressurize the water for distribution. Design should prevent direct contact of water with metals to limit corrosive reactions. Operational procedures may include methods to prevent algal growth in pre-treatment tanks and measures to provide a modicum of static pressurization to span minor power outages.

Table 2. Water Storage Examples

Storage Type	Considerations
Atmospheric	• All system scales, both pre- and post-treatment • Water is released at ambient pressure • Needs booster pumps or elevated towers for distribution pressurization • Elevated tanks can maintain system pressure and can span for short durations during power outages
Hydro-pneumatic	• All system scales, typically post-treatment • Pressure vessel with diaphragm or bladder • Pressure is adjustable at installation per system design • Small size (hundreds of gallons), but several can be operated in parallel • Pump re-pressurizes tank at intervals • Can balance water output with input to equalize flow rates • Can protect well and booster pumps from over-cycling
Underground tank	• All system scales, typically pre-treatment storage • Multiple styles and materials, can be single or multiple • Booster pumps lift and pressurize water for distribution • Must be designed to withstand any hydrostatic forces from groundwater and lateral forces from soil conditions and surface traffic

In traditional water systems, storage is commonly sized to meet operational, firefighting, and other emergency needs. Operational storage serves to buffer diurnal variation in system demand. Firefighting storage provides sufficient water to combat a fire of a predefined duration and intensity. Emergency storage is intended to provide backup water in the case of other system disruptions (e.g., a disruption at a local utility water treatment plant or other primary water supply source). While storage criteria vary across regions and municipalities, total storage capacity across all three categories is typically on the order of 1 to 3 times the average daily demand in traditional systems. Storage beyond this capacity is typically deemed impractical due to financial and environmental (e.g., land availability) constraints. In addition, excessive storage capacity in a water system can lead to adverse water quality outcomes due to a lack of mixing and stagnation of water in storage tanks, further limiting the amount of storage that can be practically implemented in a system. Such considerations present unique challenges for the design of storage infrastructure for Air Force water microgrids for which the requirements are defined far more aggressively than in traditional water systems given the criticality of the mission these installations provide.

While some provision of storage beyond that typically accounted for in traditional systems is likely warranted for an Air Force water microgrid, the considerations above will likely limit the amount of storage capacity that can be practically implemented. As such, storage sizing criteria should be customized to the specific conditions of each unique installation, considering the reliability of the primary water supply source, availability of redundant water supply sources, and quality of the stored source water. Storage sizing should be coordinated with these other system features such that the water microgrid can support a water system that has a sufficient volume of water (water quantity) and adequate water quality to meet the water-inclusive requirements of the Air Force Installation Energy Strategic Plan.

2.2.3 Treatment

Water microgrids can treat water supply to either potable or non-potable quality, depending on the application requirements. Potable water is consumed by humans and used for personal hygiene as well as washing applications such as healthcare sanitation, dish cleaning, and laundering. Potable water is required to be tested, permitted, and approved for human consumption directly and thus carries a higher quality burden. The treatment system will be regulated by the local jurisdiction and must meet the requirements of the Safe Drinking Water Act (SDWA) (EPA 2022a); see Section 2.3.1.

Water that is not of sufficient quality for human consumption is considered non-potable. Treatment to non-potable levels can be appropriate for a variety of end-uses, including vehicle washing, toilet flushing, boiler make-up water, cooling towers, and firefighting demands, among other uses. Non-potable water may be supplied through alternative water sources or freshwater. Each type carries unique considerations for the water microgrid design and operation. The level of treatment needed will have to be carefully considered, depending on the requirements of the application. Some alternative water sources such as harvested rainwater may have minimal treatment requirements (with lower energy requirements), while other sources such as reclaimed wastewater require advanced treatment (with energy-intensive water requirements).

A water microgrid should match critical water demand to the most appropriate water supply types, considering the end-use and minimum treatment standards. Table 3 illustrates the minimum required water quality for a variety of end-uses

Table 3. Minimum Water Quality Requirements by End-Use

Water End-Use	Quality Required	Considerations
Drinking fountains, bottle fillers, kitchen faucets for food prep, dishwashers, lavatory faucets for teeth brushing, and eyewash stations	Potable – intended for human consumption	Complex, multi-step treatment to achieve drinking water standards required by the U.S. Environmental Protection Agency (EPA)
Showers, hand-washing, mop sinks	Potable – not intended for human consumption	Moderate treatment; systems with both potable and non-potable sources require parallel supply piping to avoid cross-contamination
HVAC makeup water	Non-potable	
Process	Non-potable	
Toilets, urinals	Non-potable	
Clothes washer	Non-potable	
Irrigation	Non-potable	Moderate to minimal treatment depending on supply type (e.g., rainwater has minimal treatment while process reuse may require moderate treatment; de-chlorination may be required if treated with chlorine or chloramine)
Vehicle wash	Non-potable	Moderate to minimal treatment depending on supply type
Cooling tower	Non-potable	Moderate to minimal treatment depending on supply type

Basic water treatment elements include collection, screening of large particles, settling of sediments, filtration of smaller particles, and disinfection to kill harmful pathogens. A variety of available technologies can serve these functions. These treatment components, both engineered and off-the-shelf, should be carefully designed based on the size of the system and the specific requirements of the application. Table 4 provides a general description of key treatment system components.

Table 4. Treatment System Components

Component	Function	Technology Options
Collection	Storage of pre- and post-treated water	See Section 2.1.1.2, Storage
Screening	Removal of large particles	Gutter screens, vortex filter, screen filter
Settling	Removal of sediments post-screening	Clarifying tanks Biofiltration (gravity or membrane bioreactor) Turbidity filters and monitors
Pre-treatment maintenance	Prevent organic growth	Ozone circulation, chlorine, scheduled flushing
Filtration	Removal of particulates, from medium to microscopic	Small opening screens Bag and cartridge filters Charged membrane filters (4-log)
Disinfection	Kills harmful pathogens	Chemical: chlorine, chloramine Mechanical: ultraviolet, ozone, reverse osmosis
Finishing	Removes odors, taste, or other dissolved solids not filtered out Re-mineralizes[a] excessively soft water (rainwater, condensate or distilled water, reverse osmosis water)	Carbon filters, aeration Trace mineral drops, in-line mineral filter, mineral salts

(a) Kozisek F, 2004. Health Risks from Drinking Demineralised Water. Nutrients in Drinking Water, Chapter 12. World Health Organization, Geneva, Switzerland. https://www.who.int/publications/i/item/9241593989

Water microgrids may require substantially longer storage times than more traditional water systems to ensure sufficient quantity, quality, and accessibility of water. Water quality monitoring is therefore critical to the water storage and treatment components of a water microgrid. Table 5 outlines water quality concerns related to the storage of treated water, which may require treatment.

Table 5. Water Quality Concerns Pertinent to Water Storage

Chemical Issues	Biological Issues	Physical Issues
Disinfectant decay	Microbial regrowth	Corrosion
Chemical contaminants[a]	Nitrification	Temperature/stratification
Disinfection by-product formation[a]	Pathogen contamination	Sediment
Mineralization or lack thereof	Taste and odors	Operation and maintenance

(a) Water quality problem with direct potential health impact

2.2.4 Distribution

The water distribution system is the circulatory system of the water microgrid. Water is conveyed through a series of pipelines, valves, and pumps sized for proper velocity based on flow volume and friction losses based on local codes or acceptable engineering practices. For any building or campus connected to a municipal supply, distribution starts at a water treatment plant, is pressurized, and then routed below ground across great distances in large-diameter water mains. At customer property lines, it passes through a water meter that measures the flow rate (used for billing purposes). The system then carries the pressurized treated water through the site's trunk mains, distribution mains, building branch lines, and finally to individual end-uses. Table 6 provides a general description of the distribution system components. These components should be maintained and tested at regular intervals as recommended by manufacturers to ensure minimal losses. Redundant water supply distribution systems may utilize the same infrastructure as the primary supply, or be completely separate. In either case, designs of distribution infrastructure should optimize energy and water demands to minimize wear and tear on components such as pumps and valves.

Table 6. Distribution System Components

Component	Function	Considerations
Pipes	Convey water from source to end-use	A water microgrid's primary and redundant distribution systems should be well maintained to ensure that the lines have minimal losses. Piping systems are regulated by local plumbing codes and therefore should be reviewed before selecting the appropriate piping material for potable and non-potable supply.
Advanced water meters	Measure and track water use	See Section 2.5.2 for a description.
Pumps	Move water through the system	Pumping applications include constant or variable flow rate requirements, serving single or networked demands, and consist of open loops (nonreturn or liquid delivery) or closed loops (return systems). Designs should be optimized to meet the DAF Water Resource Management Framework requirements of quantity, quality and access. Pumps serving the existing (primary) distribution system should be evaluated to determine if they are appropriate for serving critical demands, especially at sites with significant variations in topography. Pumps serving critical demands should be connected to reliable power systems and advanced monitoring and control systems to remain online during a disruption.
Valves, sensors, & controls	Control flow of water and provide real-time system monitoring	The existing distribution system should be evaluated to determine if it has the appropriate control valves that will allow for isolation of critical buildings and/or demands. Additional valves may need to be installed to provide the appropriate automated and reliable control for the proper function of a water microgrid. These components should be maintained and tested at regular intervals as recommended by manufacturers. No single valve is appropriate for all services, so the proper selection of a valve is important to ensure the most efficient, cost-effective, and long-lasting system. See Section 2.2.6, Advanced Monitoring and Controls, for additional considerations.

2.2.5 Reliable power

A critical component of water microgrids is reliable power. Many of the water microgrid components, including treatment, and pumping, require energy to function and may be energy intensive. For some hazards that may cause a water supply disruption, a reliable primary power supply is sufficient to keep water microgrid infrastructure fully functional. However, a localized independent power source that is fully islandable from the primary power supply allows the water microgrid to be self-sufficient and withstand hazards that threaten water and energy supplies simultaneously. To accommodate these simultaneous outages, on-site reliable power must be provided, and it must be sized to accommodate the water microgrid energy demands. In addition, the design of the reliable power system should be designed to specifically withstand those hazards that may cause an outage of both energy and water supplies.

2.2.6 Advanced Monitoring and Controls

All water systems include control systems used to operate the various components of the primary water supply and distribution, whether they are manual or more sophisticated. In a water microgrid context, the “advanced monitoring and controls” have an overarching infrastructure on top of the existing logic that provides real-time monitoring and the capability to enable and disable system components during an outage to meet critical water demands. This includes hardware, software, and logic protocols to carry out predetermined operation regimes through fully or semi-autonomous operations during islanding from, and subsequent reconnection to, off-site primary water supply networks. Data acquisition and communications elements of water microgrids may also provide early warning of natural disasters to contain or mitigate damage.

All Air Force installations already have extensive water infrastructure, including mains, laterals, interconnections, valves, and other components used to deliver water to end-uses as part of the water distribution system, though they may not include advanced controls or be configured to isolate critical water demands. Individual assessment for a particular site is required to establish what additional infrastructure is needed to provide a complete automated control infrastructure that meets the required characteristics of a water microgrid, especially at smaller distribution pipes or locations. This additional infrastructure may or may not run during normal operations, though it could potentially increase operational efficiency.

Ideally, the advanced monitoring and control functionality is integrated with a hydraulic model that can be used to inform viable operations strategies during a disruption. For example, a hydraulic model could be used to quickly screen several valving strategies to curtail non-critical water uses, identifying those particular solutions that minimize excessive pressure loss from the system and sustain adequate delivery to critical end-uses.

Most sites have critical missions that require water, and sections of the distribution network will need to be enabled and disabled during an outage to meet these critical water demands. In addition, audible and/or visual communications can be incorporated into the control system to notify staff and building occupants to initiate demand curtailment plans. To do so, automated control valves will be dispersed throughout a standard distribution system to isolate supply paths in the event of infrastructure failures, per the design of the distribution lines. With the proper control logic, the master microgrid controller will coordinate through an interface with these valves, and then close off non-critical mains such that critical water demands can be isolated. Thus, a water microgrid is likely to incur additional capital and operational costs for additional valves and sensors. Table 7 provides a summary of the components related to advanced monitoring and controls for critical demand isolation.

Table 7. Advanced Monitoring and Controls for Critical Demand Isolation

Component	Function	Technology Options and Considerations
Pressure sensors	Track changes in pressure that may indicate an outage or system failure.	Pressure sensors are also used to track water losses and identify problems during normal operations. During demand isolation, the system may experience instability in downstream processes.
Automatic Control Valves	Isolate critical demands.	Other criteria-based control actions may operate stormwater conveyance to mitigate flooding risk, for example, or isolate elements of water distribution networks when water quality issues are automatically detected.
Supervisory control and data acquisition (SCADA) systems	SCADA architectures are the physical-digital infrastructure through which water supply, treatment, and distribution are coordinated.	Autonomous or semi-autonomous system control actions will be implemented across communications infrastructure such as fiber, routers, switches, and component controllers, observed through a human-machine interface, and logged for future reference via a historian. Novel Internet of Things (IoT) sensor design and enabling communication advances, such as Low Power Wide Area Network protocols and 5G cellular technology, may be innovative options to support these controllers.[a]
Advanced water meters	Measure water use throughout the microgrid system. Advanced meters can be part of the advanced metering infrastructure, which is an integrated network of advanced meters, communications, and data management systems.	Advanced water meters allow water flow to be monitored across the distribution network to track use, detect potential water loss, and provide notification of demand isolation events. Selecting the appropriate water meter requires identifying and addressing the unique requirements of each application. The primary considerations include: • Meter size and type • Water demand profile (for both critical and non-critical demands) • Accuracy • Acceptable pressure loss • Available installation space • Communication and data management system

(a) 5G cellular technology will bring speeds 10 times faster at 50 times less latency, and bandwidth for 1000 times more connected devices than 4G technology. Data Makes Possible. 2019. 5G vs. 4G – A Side-by-Side Comparison. https://datamakespossible.westerndigital.com/5g-vs-4g-side-by-side-comparison/.

Advanced monitoring and controls could further be used to provide early warning signals of potential impending disruptions, enabling mitigative action to minimize the impacts of those disruptions. For example, distributed pressure sensors could be deployed throughout the system and provide real-time system-wide pressure readings. The advanced monitoring system would persistently screen for abnormalities such as a pressure drop that is unusual for a particular time of day and which might signal a major leak in a portion of the system. The pressure readouts could automatically feed into exploratory hydraulic model simulations to screen the likely location of leaks, further triggering the closure of valves for the potential leak locations. Sensing technology could also be deployed that directly detects potential hazards to the water system, such as distributed seismometers that can be used to estimate seismic damage to critical water distribution system assets and allow for real-time system re-operations that avoid water supply impacts on critical missions during such an outage.

Although not common in traditional water systems, distributed sensing and control technologies are critical to the real-time water quality monitoring of a water microgrid. Most water quality parameters require significant time to perform – including the time needed to send samples out to independent labs for testing – yet the water needs to be continually produced for use. In the event of a disruption of the primary water supply, the timeframe for confirming the required water quality for critical demands is very limited and may be impractical for maintaining critical demands. Also, the need for larger volumes of storage in a water microgrid introduces water quality challenges such as limiting algal growth in pre-treatment storage and maintaining adequate chlorine residual in post-treatment storage.

A water quality monitoring plan must consider possible degradation scenarios at various points in the system due to outages from a natural hazard or physical attacks, especially in treatment, storage, and end-of-line distribution. This includes monitoring and treatment of organics, bacteria, viruses, biological oxygen demand, and residual chlorine.

Recently available off-the-shelf technologies can be implemented to address real-time disinfection optimization. As potable water quality is regulated by the local jurisdiction and must meet the requirements of the SDWA, water quality reporting requirements should be investigated to ensure real-time sensing equipment is allowed to substitute for traditional external laboratory testing for reporting purposes.

A programmable logic controller (PLC) is a ruggedized industrial computer adapted for control of activities that require reliability, easy programming, and fault diagnosis. PLCs have become the standard in complex plumbing, mechanical, and water treatment systems over the last 25 years as the simplified and more durable replacement for printed circuit boards, relays, and timers. PLC features may include digital or analog, connection to SCADA systems (building automation systems), and graphical/schematic representation of programming/controls for non-software engineer operators.

Modern sensors used in water systems can measure flow, pressure, level, temperature, quality, and leaking. Some considerations for sensors include location and orientation, calibration, and material compatibility with the water type. Table 8 provides the common sensor types and their properties. Pre-packaged systems are available that may make installation and use easier, more affordable, and more integrated.

Table 8. Water Sensor Types

Sensor Category	Measure	Type	Applicable to	Notes
Flow switch	Flow	Digital	Supply, Treatment, Distribution	Water flow actuates mounted paddle, which makes or breaks a circuit
Flow meters	Flow	Analog or Digital	Supply, Treatment, Distribution	Options include Disk, Turbine, Compound (combined disk and turbine), Magnetic, Ultrasonic. Refer to FEMP Water Meter Best Practices (Cejudo et al. 2022) for more information, including installation and operational considerations.
Pressure switch	Pressure	Digital	Supply, Storage, Treatment, Distribution	Pressure changes position of a diaphragm/piston held in place with a spring. Select unit that is suitable for the specific pressure range of application.
Pressure transducer	Pressure	Analog	Supply, Storage, Treatment, Distribution	Pressure changes an internal diaphragm's shape. Change in capacitance or resistance to DC power is measured. Pressure range must match. May need "snubber" device to protect.
Differential transducer/ switch	Pressure	Analog	Supply, Storage, Treatment, Distribution	Measures pressure difference between 2 locations with transducers. Units are dynamic / flow dependent.
Float switch	Level	Digital	Storage	Uses weighted ball and rocker switch with spring return. Float will roll on and off the switch. Install with tether to set height and prevent tangling. Ensure unit does not interfere with tank overflow.
Ultrasonic	Level	Analog	Storage	Sends waves from top of tank to liquid level, and speed of bounce back determines level. Ensure unit does not interfere with tank overflow.
Hydrostatic	Level	Analog	Storage	Height of water in tank causes pressure on a diaphragm (compression causes capacitance/resistance change). Installation must be at the bottom of the tank.
Thermistor	Temperature	Analog	Supply, Storage, Treatment, Distribution	Electrical resistance changes with temperature. Thermistor sensors are more sensitive than thermocouple.
Thermocouple	Temperature	Analog	Supply, Storage, Treatment, Distribution	Heat creates voltage between 2 different metals. Thermocouple sensors have a wider range compared to thermistors.
Conductivity	Quality	Analog	Supply, Treatment	Small current passed between 2 electrodes. Dissolved solids change conductivity. Select unit for correct purity range of application.
pH sensors	Quality	Analog	Supply, Treatment	Two silver electrodes with one in water and one in glass. Difference in hydrogen ($H+$) ions shows pH. Sensors must be calibrated properly. High-temperature applications can affect lifespan.
Oxidation reduction potential	Quality	Analog	Supply, Treatment	Oxidizers steal electrons from other elements, which causes current. Uses two electrodes similar to pH probe.
Free chlorine sensors	Quality	Analog	Supply, Treatment	One silver electrode in water, one gold/platinum electrode in glass with membrane, measure resulting voltage to give Cl reading. Units need a continuous "sample" stream of water.
Turbidmeters	Quality	Analog	Supply, Treatment	Light is applied at 90 degrees to water flow. Light reflection/scattering is measured to find turbidity. Probes need to be cleaned periodically.
UVC light meters	Quality	Analog	Supply, Treatment	Photometer applies 254nm wavelength and energy creates voltage/current. Light intensity is measured. Install in "clean" water filtered to a minimum of 5 microns. Probes need to be cleaned periodically.
Moisture leak detector	Leaking	Digital	Storage, Distribution	Two electrodes sense water to complete the circuit to alarm. Use to shut down expensive equipment and turn off water supply. Install at bottom of application (floor, drain pan, etc.).

2.3 Configuration Options

An optimal configuration of a water microgrid may vary in terms of size, cost, and components due to the adaptable nature of the concept. A site with limited water use functions may only require a few water microgrid components. A site with many varied water end-uses and peak demands may require a wider range of equipment at different costs. Water microgrids can be configured at differing scales, ranging from simple to complex, which are highly dependent on local conditions such as installation critical water demands, site size, and potential natural hazards that could impact the site. The critical water demands and access to on-site water sources will drive the water microgrid system scale and infrastructure options. There are two basic configurations of a water microgrid: self-contained and microgrid islands (Figure 5). In both cases, the site will have on-site redundant water supply.

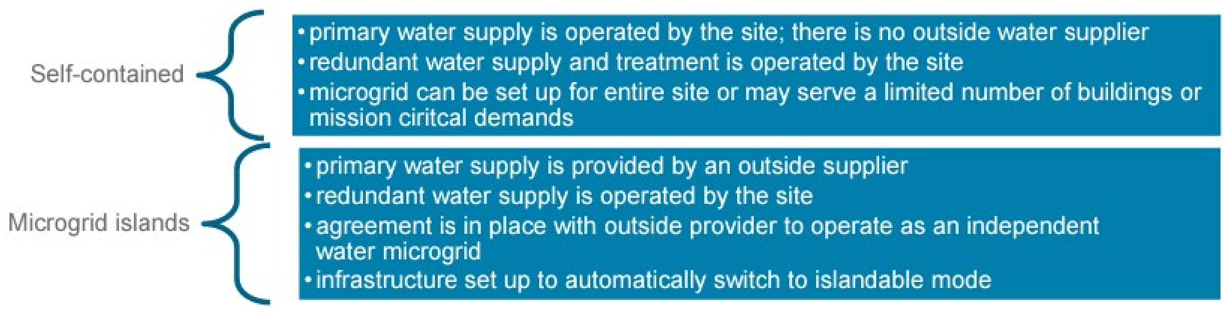

Figure 5. Water Microgrid Scales

A self-contained water microgrid has on-site water sources, treatment, and distribution, which are independent of the primary provider, and connects to wastewater treatment. Self-contained water microgrids provide water from an on-site supply and all associated infrastructure is owned and operated by the site's staff or contractor. These systems include the primary water supply and redundant water supply, treatment equipment, and distribution systems. Self-contained water microgrids may include strategies to safeguard against compromised water supply such as alternative water sources and water storage. Air Force installations that source and treat water on-site may be good candidates for self-contained microgrid deployments. Improvements to the existing systems, especially the addition of controls, are likely needed to fully realize the concept of a water microgrid and to satisfy energy and water resilience requirements.

Conversely, a microgrid island involves an agreement with the off-site primary provider to operate the site's water microgrid independently if needed via valves and controls to enable this independent operation under close coordination with the off-site utilities. In this case, where the primary water supply is from off-site water infrastructure owned and operated by local utilities, the water microgrid will have the ability to "island" in the event of compromised or disrupted off-site supply. Several additional components are required to island from an off-site water supply, which are not required in self-contained arrangements. Valves should be installed in the primary supply mains to cut off the primary water supply line in the case of threats to quantity or quality. In an islanding scenario, the supply would automatically switch to the redundant water supply as shown in Figure 3. This can be accomplished automatically when the monitors sense a change in the flow that meets the logic designed for protection, or manually in response to reports of incoming catastrophic weather (or other) events. The local utility may require additional infrastructure to preclude backflow to the off-site distribution system. Further, water treatment systems and standards must be defined for on-site water distribution system operators in coordination with off-site water utilities to ensure the sanitation of water upon resumption of service. Section 2.2 provides further details on the necessary on-site components of a water microgrid.

2.4 Operational Considerations

This section explores many operational considerations of water microgrids, to include operation and maintenance (O&M) requirements, cybersecurity considerations, and statutory requirements.

2.4.1 Operations and Maintenance

Water microgrid systems require regular O&M. It is vital that the water microgrid system be maintained by on-site personnel or maintenance contractors who are fully trained and certified to maintain the system. Generally, the components of the system are made to last with regular upkeep, and manufacturers will often provide several years of warranty, anywhere from 15 to 30 years for storage tanks and pipework, and typically 2 to 10 years for pumps. Other components requiring regular O&M include treatment systems, backflow prevention devices, and automated controls including meters and sensors. Important O&M considerations include the following:

Operator training: Water microgrid operators need the appropriate training, and possibly certifications, for the site-specific systems to ensure required regular testing is provided to keep the system operating as designed. Communicating with the site's personnel is important to inform them of the water microgrid and its functions.

Curtailment plans: A site considering a water microgrid should have a curtailment plan in place that provides specific procedures for curtailing non-critical water demands during times of disruption. A curtailment plan specifies the applications that are suspended and designates the roles and responsibilities of installation personnel responsible for executing the plan.

Emergency planning: Along with curtailment planning, emergency planning is an important function at an installation with a water microgrid. An emergency plan provides the installation with the procedures and personnel that are in place to respond to a water emergency. A comprehensive emergency plan includes identification of essential functions, roles and responsibilities, delegation of authority, and testing and training program. Emergency drills should be conducted regularly to ensure that personnel are well trained to respond to an event.

2.4.2 Cybersecurity Considerations

The addition of new automation controls infrastructure will incur the use of digital assets, remote communications, and controllers, which are subject to cyber breaches. This is currently one of the most highly visible threats to water infrastructure on a national level, as evidenced by the 2021 hacking of the water treatment system in Oldsmar, Florida.[1] As a result of this attack, the Federal Bureau of Investigation, Cybersecurity and Infrastructure Security Agency, EPA, and National Security Agency issued a Joint Cybersecurity Advisory warning U.S. water and wastewater systems of threats by "known and unknown" malicious actors (CISA 2021).

Water microgrids employ digital assets and thus are vulnerable to cyber-attack. System hardening, network segmentation, and antivirus management are all important elements of a

[1] https://www.cnn.com/2021/02/08/us/oldsmar-florida-hack-water-poison/index.html

cyber defense strategy for water microgrids. Ultimately, if the water microgrid does not have the proper cybersecurity, it may not matter how islandable the infrastructure is configured to operate.

Not all cyber-attacks can be prevented. At a minimum, the water microgrid should be capable of detecting that an attack has taken place. Trained staff will be needed to verify secure operations through operational monitoring, log reviews, and independent system health checks. Systems to help detect and prevent cyber-attacks should be investigated. Example systems include network intrusion prevention systems, intrusion detection systems, and intrusion protection systems. Cyber security protection plans should also be crafted around frameworks such as the North American Electric Reliability Corporation Critical Infrastructure Projection (NERC CIP), the Center for Internet Security Critical Security Controls (CIS CSC 18), or other such protocols.

2.4.3 Metering and Statutory Requirements

Federal agencies are required to meter buildings for water per the Energy Act of 2020, codified in 42 U.S.C. § 8253(e) (FEMP n.d. (a)). Management of water-efficient facilities and operations can be enhanced by the application of advanced water meters and timely analysis of the reported data. These actions provide critical information for facility managers to analyze water use and identify trends and operational issues that can help target water efficiency measures. This information should be incorporated into the Water Dashboard to enhance installation resiliency and tracking of potential vulnerabilities and outages.

Selecting the appropriate water meter technology/type and size requires identifying and addressing the unique requirements of each application. The primary considerations include meter size, water demand profile, accuracy, pressure loss, location, space, networking, communications, and cost. Installation and testing/calibration carry their own sets of considerations.

Water meters have three basic components: a coupling to the water line, a metering element that reacts proportionately, and a register that converts the signal into volume. There are different categories of water meters, including positive displacement, velocity, compound, electronic, and differential pressure.

The purpose of installing advanced water meters at federal buildings is to collect data to analyze and act upon. Agencies can use detailed water use data measured hourly or more frequently (15-minute intervals are desirable) and displayed in water tracking systems to identify operational issues and select conservation measures to reduce water use. Advanced meters are one component of an agency’s Advanced Metering Infrastructure, which includes an integrated network of advanced meters, communications networks, and energy management information systems. All these components work together to transform readings at the meter into actionable data for the user in combination with real property data, equipment inventories, weather data, utility information, and maintenance records.

The proper use of meters allows for leak detection, identifying improvements, and benchmarking water use, among other benefits. Detailed information can be found in Water Metering Best Practices (Cejudo et al. 2022).

3.0 Technical Considerations

Water microgrids involve many different types of technology that are all at different stages of maturity, including the advanced monitoring and controls technology that connects all the technologies together. There are some limiting factors to the adoption and operation of the technology, including specification and sourcing of appropriate and compatible equipment as well as the lack of full-scale demonstrations or case studies to demonstrate the potential of such a new concept.

3.1 Limiting Factors and Constraints (other than siting characteristics)

The key limiting factors to a water microgrid are existing infrastructure and resource availability, which are closely linked to siting characteristics as outlined in Section 7.0. Limitations to a water microgrid aside from siting characteristics include availability of water microgrid components for the particular needs of the site, compatibility of different components, and the associated costs. Examples include availability of on-site water supply, distribution configurations, and complexity of treatment technology. Since water microgrids are a framework rather than a specific piece of technology, the specifications may be different at different sites. Thus, appropriate system components and sensors and controllers must be sourced for the needs of the specific application. Possibly, the need for niche alternative water treatment equipment that is still compatible with the SCADA system could make the costs of water microgrid implementation prohibitively high. This possibility would have to be investigated when designing the water microgrid system for a new location with unique characteristics.

Natural disasters, equipment failures, and malicious acts (such as cyberattacks) require a reliable supply chain to provide both equipment and chemicals needed for water treatment. The EPA offers direct technical assistance and also recommends maintaining communication and coordination with primary and alternate suppliers in the case of supply chain issues (EPA 2022b). Due to the many components of a water microgrid, multiple suppliers may need to be kept in contact for the highest component availability.

3.2 Technology Maturation

Individual components of a water microgrid (water source, storage, treatment, distribution, and controls) are highly mature and are common in most water systems (Cejudo Marmolejo et al. 2021). Many of the associated meters, valves and sensors are well developed and are readily available off-the-shelf. IoT is becoming increasingly ubiquitous, with recent advances in wireless technology allowing sensor networks to monitor and control many types of information. Applying IoT to “smart” water systems is a recent area of research, with many studies focused on large-scale municipal water systems with high connectivity for fault detection. The automated monitoring and controls equipment and software tied into IoT sensing capabilities is the leading edge in the water sector and may not be widely adopted by DoD installations, in large part due to the cybersecurity requirements and challenges.

The structure of an IoT-connected system involves hardware (such as sensors and actuators), controllers (that can use Bluetooth or Wi-Fi to communicate), and the internet or network itself. With sensors and controllers communicating in real-time with a network, compatibility is an important consideration when looking at the different possible communications protocols, e.g., hypertext transfer protocol (HTTP), message queuing telemetry transport (MQTT), or wireless application protocol (WAP), and the possible programming languages (C, Python, MATLAB). The integration of many different existing components into a cohesive water microgrid system by adopting recent advances in connectivity and communications technology is the next step toward using this new IoT technology to increase water resilience.

3.2.1 Successful Pilots or Demonstrations

The individual components of a water microgrid are outlined in Section 2.2, with some examples of available technologies. Each component has been demonstrated individually in the past and is highly mature. While there have not been many full water microgrids developed for study, there have been demonstrations of individual components that would be present in a water microgrid such as in on-site alternative water applications.

Water microgrids are not commonly found at Air Force installations or similar facilities. But there is an example that shows the general concept of a water microgrid in action. Camp Rilea, an Army National Guard site located in Clatsop County, Oregon, has a self-contained water system that produces all water on-site from a local aquifer, treats water to potable standards, and stores and distributes water for critical and non-critical demands. Camp Rilea has an advanced SCADA system that monitors water quality and water distribution throughout the facility. The installation also includes alternative water from an indirect potable reuse (IPR) system, where wastewater is injected through rapid infiltration basins into the groundwater, which is then treated and reused for potable applications. Camp Rilea meets the key characteristics of a water microgrid of being self-sufficient, reliable, and automated.

Systems that meet the required microgrid attributes of being self-sufficient, reliable, and automated are rare. Most of the non-DoD projects identified focused on sustainability goals that provide on-site sources of alternative water to reduce the demand for freshwater but were not designed to meet critical missions under disruption scenarios. There is an example of a functioning water microgrid that meets the required attributes, however. A collaborative research project between the University of Arizona's Biosphere 2 Facility and the National Renewable Energy Laboratory was conducted as a case study for an "energy-water microgrid" (Daw, et al. 2018). The Biosphere 2 Facility has unique features that enable the operation of energy and water systems in an island mode or connected to the electric grid and/or water infrastructure. Furthermore, the Biosphere 2 Facility's water systems include an on-site water supply from local groundwater wells, a potable treatment system, and 500,000 gallons of storage in water tanks. An interesting lesson learned from this case was that energy and water efficiency improvements were needed before establishing a microgrid to reduce demand and storage requirements.

A few interesting examples of systems that provide on-site alternative water treatment include systems at Pepperdine University,[1] the University of Connecticut,[2] and WaterHub® installations at Philip Morris USA,[3] Emory University,[4] and Atlanta Piedmont Hospital. These systems provide a sustainable source of alternative water to the campus such as reclaimed wastewater or harvested rainwater. The alternative water is used for specific applications such as cooling, irrigation, or toilet flushing to offset freshwater consumption and provide a secondary source. For example, WaterHub (a NextEra Distributed Water Product) is an on-site water recycling system that treats wastewater for non-potable uses. WaterHub is capable of recycling up to

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[1] https://www.pepperdine.edu/sustainability/current-practices/water.htm
[2] https://www.hazenandsawyer.com/projects/uconn-wastewater-reuse-project
[3] https://www.distributedwater.com/content/dam/distributedwater/us/en/pdf/CASE_STUDY_PMUSA.pdf
[4] https://sustainability.emory.edu/programs/the-waterhub-at-emory-university/

40% of Emory University's total campus water needs, about 400,000 gallons per day (Emory Office of Sustainability Initiative 2021). The treated wastewater is recycled as process make-up water in the university's steam and chiller plants and for toilet flushing in select residence halls. The WaterHub reduces Emory University's use of Atlanta's municipal water supply by up to 146 million gallons annually. Upon the occurrence of any disruption in water availability, the WaterHub has a 50,000-gallon emergency water reserve that will allow the Emory University HVAC systems to function for up to 7 hours (Emory Office of Sustainability Initiative 2021). However, these systems do not meet the key attributes of a water microgrid, i.e., providing self-sufficient and reliable water to meet critical demands with an automated control system.

3.2.2 Market Penetration

While many of the components of a water microgrid are well developed and commercially available, there is a need for high connectivity and communications systems and processes to ensure successful operation of the whole water microgrid system. Previous research and application of this advanced monitoring and control technology has focused on large municipal water systems and irrigation in agricultural applications. The integration of advanced monitoring and controls equipment with existing water infrastructure into a cohesive water microgrid system is the next step toward using this technology to increase water resilience.

3.2.3 Key Challenges and Barriers to Adoption

O&M upkeep and training are key challenges for water microgrid adoption. Water systems at several Air Force installations currently use alternative water sources, including dedicated treatment components and distribution piping (purple pipe). However, these systems may be considered separate infrastructures that must be maintained in addition to the existing conventional water systems. In-house personnel may not have the required expertise to maintain and operate these alternative water systems and may need to contract an outside licensed water operator(s) to meet regulatory requirements. Installations considering a water microgrid system should consider training in-house personnel in appropriate O&M and regulatory requirements.

3.3 Optimal Use Cases and Scenarios

Water microgrids can range from simple to complex systems that are highly dependent on local conditions. The critical water demands and access to primary water sources will drive the water microgrid system scale and infrastructure options. Table 9 provides a few examples of different scales and complexities of a water microgrid. These scales focus on the types of critical water demands and existing components. Not included in the table are other potential considerations such as various system and network topography elements (e.g., number of pressure zones and layout of the distribution system), which can impact the system configuration of a water microgrid. A site's most recent installation energy plan (IEP) may help determine the critical water demands, existing infrastructure, and recommendations for additional components required to provide a completely self-sufficient, reliable, and automated water microgrid.

Table 9. Examples of Water Microgrid System Scale

System Complexity	Example Water Critical Demands	Example Existing Components/Supply Types	Additional Components Needed
Simple	Maintains limited potable critical demands only • Office: Drinking, toilet flushing • Residential: Drinking, cooking, bathing, toilet flushing	• Local utility connection • Building-level isolation valves • Off-site redundant supply • Single pressure zone	• Redundant utility connections • New storage tanks • Limited treatment per local regulations • New controller with automated valves & sensors to isolate critical buildings • Reliable power system
Medium	Maintain moderate potable and limited non-potable critical demands • Office: Drinking, toilet flushing, cooling tower • Residential: All uses	• Local utility connection • Off-site primary supply • Small on-site well • Pumps and storage tanks for multiple pressure zones (2-3) • Reliable power system • Building management system	• Redundant utility connections • On-site alternative water source • Larger storage tanks • Moderate to enhanced treatment • Additional automated valves and sensors to isolate critical demands within a building • Additional fuel for the reliable power system
Complex	Maintain all potable and non-potable critical demands • Hospital • Data center • Office • Residential • Industrial processes	• Local utility connection • Off-site and on-site primary supplies • Storage tanks • Reliable power system • Building management system • Pumps and storage tanks serving multiple pressure zones (>3)	• On-site alternative water source • Large redundant source and potable water storage, moderate treated non-potable storage • Enhanced treatment • Enhanced automation • Installation of purple pipe for non-potable critical demands • Dedicated reliable power system hardened to withstand hazards

3.4 Overlapping/Complimentary Technologies

Some components of a water microgrid are implemented as standalone technologies. Alternative water is a central subsystem of a water microgrid and includes much of the same infrastructure. An emerging alternative water technology is reclaiming wastewater and treating it to potable standards, which is commonly referred to as potable water reuse. Potable water reuse can be direct or indirect, and both types of systems use advanced treatment processes. The deployment of direct potable reuse (DPR) and indirect potable reuse (IPR) systems is still emerging in the United States, but the technologies typical of DPR and IPR systems are well proven in municipal water systems. More detailed information on alternative water reuse can be found in the forthcoming AFCEC emerging technologies review of water reuse for cooling towers report, which will be published summer of 2023.

Another overlapping technology is the energy microgrid, which can be related to a water microgrid in two ways. The need for reliable power in a water microgrid is discussed in Section 2.2.5, and energy microgrid concepts can be implemented to increase the resilience of the energy system supplying the water microgrid. In this way, an energy microgrid can complement a water microgrid. Energy microgrids also relate to water microgrids on a more conceptual level. The ideas of redundancy, distributed resources, and advanced monitoring and control in a connected energy system are very similar to the same ideas that make up a water microgrid. Distributed energy could include backup generators, solar power, and wind energy. Distributed water could include rainwater, wastewater, and surface water. Thus, there are equivalent functions of components between the energy and water domains. Energy microgrids have been studied and implemented far more than water microgrids, so the results of past research and implementation could provide insights into water microgrids. The concept of an energy microgrid is much more complex than outlined in this report.

4.0 Regulatory Overview

Water supplied and treated on-site will require regulatory approvals at the local, state, and federal levels. Careful consideration is needed to ensure that the necessary approvals are initiated at the beginning of the process and maintained throughout the operation.

4.1 Federal Requirements: Safe Drinking Water Act

For water microgrids that produce potable water, the requirements of the SDWA must be met (EPA 2022a). The SDWA is administered by the EPA and establishes standards to ensure the safety of public water systems (see definition in Appendix A; EPA 2022c).

A certified operator is required for each public water system to ensure the potable water system is operating properly and following SDWA standards. For each public water system, it is required that a certified operator performs maintenance on that system and has the authority to make decisions about water quality and quantity. The requirements to become a certified operator vary by state, but the basic requirements include:

I. Education: Most states require at least a high school diploma or general equivalency degree.

II. Experience: Some level of on-the-job experience, set by the state.

III. Examination: Pass a certification test that covers mandatory capabilities and decision-making skills.

In addition to certified operators, if it is determined that a water system needs to be tested, the public water system should have certified laboratories test the water quality and report their results. Laboratories test samples for contaminant type and level to demonstrate compliance with both primary and secondary standards. Other best practices to which public water system operators should comply are EPA standards that include the following:

1. Apply treatment technologies that allow for regulated contaminant levels to be achieved.
2. Keep updated on the Contaminant Candidate List (CCL) to be aware of what contaminants are being monitored and may be regulated in the future. (The CCL is a list of contaminants that may be found in public water systems but are currently not being regulated by the EPA. The current EPA CCL can be found at https://www.epa.gov/ccl.)
3. Maintain disinfecting protocols to ensure that water is treated properly and that the process does not exceed regulation levels.

If testing of water quality determines that contaminant levels are higher than levels allowed by the EPA, the water must be treated. For small water systems, it is suggested that point-of-use devices (used for single location contaminant reduction) and centralized treatment be applied. The basic treatment options involve granular activated carbon, packed tower aeration, and multi-stage bubble aeration. But other treatment options exist, such as reverse osmosis, which may be applicable. Treatment technologies should be evaluated by a subject matter expert to determine the proper treatment required to ensure the water is safely treated.

In addition to treatment, public water system operators are also required to disinfect water to ensure that any biological contaminants still existing in the water are eliminated. The SDWA regulates disinfectants by setting a maximum residual disinfectant level (MRDL). This means that any chemical remaining as a result of disinfection must not exceed the MRDL within the drinking water. Disinfectants that have an MRDL and are among the most commonly used chemicals include chloramine, chlorine, and chlorine dioxide. In addition, while not enforced by the SDWA, the Centers for Disease Control and Prevention recommends a minimum level of free chlorine (the amount of chlorine left after initial chlorine has reacted with other organic material) in water from the tap.

4.2 State and Local Regulatory Activity

State and local regulatory structures relating to water resources vary a great deal. The SDWA provides a regulatory “floor” for the minimum level of potable water quality required throughout the nation. Alternative water may be a key water microgrid component as a source of both potable and non-potable water. States and local jurisdictions in water-stressed areas have implemented additional requirements for alternative water to augment available freshwater sources. For example, the City of San Francisco requires on-site alternative water systems for new development projects of 100,000 gross square feet or greater (San Francisco Water, Power, Sewer n.d.).

Due to the increased water risk faced by many communities throughout the nation, a National Blue Ribbon Commission (NBRC) for Onsite Non-potable Water Systems was established in 2008 to advance “best management practices to support the use of onsite non-potable water systems within individual buildings or at the local scale” (U.S. Water Alliance 2022). The NBRC aims to provide tools and guidance to support communities looking to implement on-site water reuse within a regulatory environment based on risk-based science.

Given the fast-moving regulatory landscape of alternative water systems, Air Force installations interested in implementing a water microgrid should research state-specific requirements when suitable sites are identified and evaluated.

5.0 Risks

5.1 Social Considerations

Community outreach is a critical step in the successful deployment of a water microgrid system. Communicating with the installation's on-site personnel and their families to inform them of the water microgrid and its functions is important. Communication and education within the community can lead to greater acceptance and integration of the technology as well as more effective operations since all those involved will understand the purpose of the water microgrid.

5.1.1 Social Impact

Distributed water resources and a community-wide connected control system allow for localized water disruptions to be addressed by a communal water system. With multiple sources of water and multiple paths for water to be distributed, disruptions can be dealt with equitably by drawing from the community's water resources in the most effective way. Thus, the adverse effects of disruption can be mitigated and do not fall solely on the affected parties.

5.1.2 Public Perception Barriers

Community perception and buy-in are potential barriers to deploying a full water microgrid system. Reclaimed wastewater has had the largest hurdles regarding public perception of water reuse. There is a need to present the selected alternative water collection and treatment methods to show the public that the technology is mature and safe. The communication should make clear that a water microgrid is not the first deployment of water treatment technology, but rather is a unique configuration of highly tested and regulated technology.

5.2 Environmental Considerations

Aside from the economic and resilience benefits of a water microgrid, water reuse and reduction in waste present environmental benefits related to climate impacts. Water and energy use intensity can potentially be reduced through water microgrid system design.

Water microgrids require energy to operate and are therefore at the intersection between water, energy, and climate (Figure 5). Water networks and treatment use about 10% to 15% of national power production. Energy is necessary for pumping, treating, and distributing water. Climate change imposes additional pressures on water systems, including deeper and more frequent droughts, highly variable precipitation patterns, and rising temperatures. These climate change impacts lead to increased competition among water demands, and more frequent – and more severe – weather events that threaten sanitary supply and critical infrastructure.

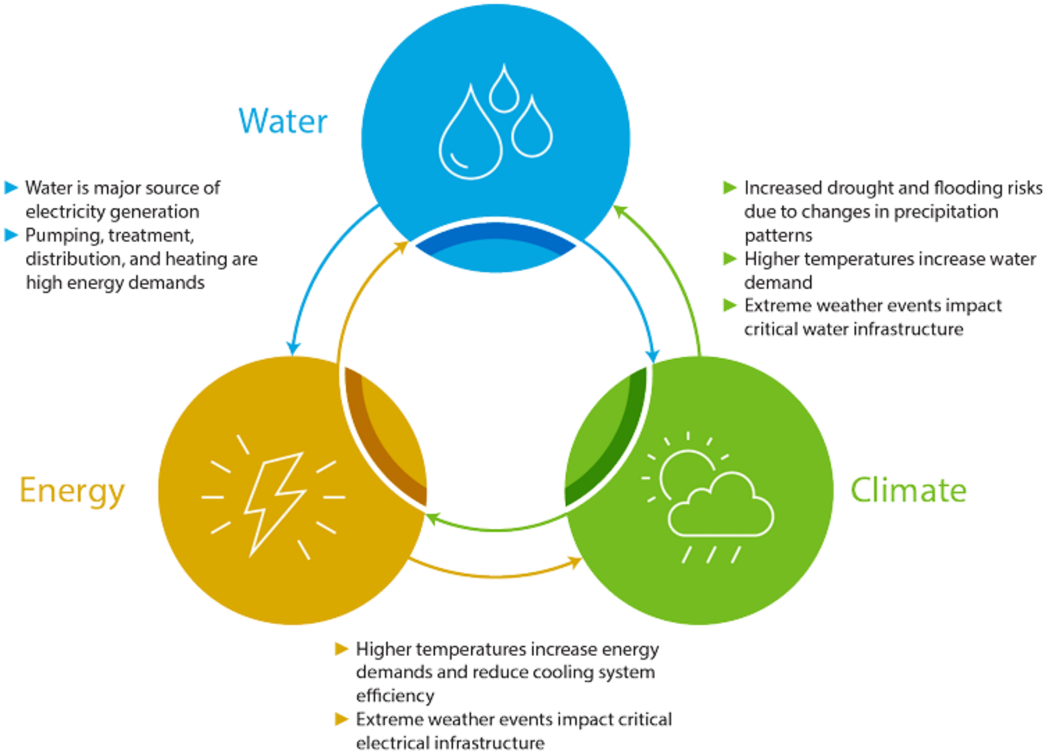

Figure 6. Water-Energy-Climate Nexus

Implementing a water microgrid shifts energy use for pumping, treating, and distributing water from the local utility to the site. Increased electricity demand due to water microgrid infrastructure is unlikely to be significant, but sites should consider the energy use intensity of different water supply, treatment, and distribution options, particularly if systems need to function on backup power.

Decarbonization is an increasing priority for federal facilities. Sites should consider how water microgrid components may affect plans to reduce energy use or achieve net zero carbon. On-site water sourcing and treatment may be more or less energy intensive than existing methods but does shift the burden and cost to the site. Water scarcity due to climate change means water may have to be pumped from greater distances or from deeper in the groundwater table, or from saltwater or brackish water, which requires an energy-intensive desalination process to remove salts and minerals. Section 2.2.5 provides an overview of reliable power systems required for a water microgrid.

Water sites that are interested in reducing energy use and/or greenhouse gas emissions should source water from local and lower energy use intensity sources (Table 10). Sites should only treat water to the level necessary. Water for flushing toilets, cooling, and irrigation does not need to be treated to potable standards. Sites should use gravity-fed storage and distribution and should consider using renewable energy to support water microgrid components. Small systems like rainwater harvesting and captured condensate can be packaged with PV and inverter/battery systems. Many in-line components outside of buildings can be supported with small, dedicated PV panels and independent direct current (DC) backup batteries.

Table 10. Energy Use Intensity by Water Source Type

	Water Source Type		Qualitative Energy Use Intensity (EUI)
Freshwater	Local surface water		Low - Medium
	Local groundwater (EUI increases with depth)		Medium
	Distant watershed (EUI increases with distance and elevation)		High
Alternative Water	Desalination	Brackish	Medium
		Seawater	High
	On-site harvested rainwater/stormwater		Low
	On-site captured condensate		Low
	Purchased reclaimed wastewater		High
	On-site reclaimed wastewater (pressurized, gravity fed)		High
	On-site reused process discharge water		Medium

6.0 Economic and Funding Considerations

The costs associated with water microgrids are widely variable based on location and needs, and therefore are not detailed in this report. A typical life cycle cost assessment is not appropriate for a water microgrid, as there is not a traditional savings stream compared to an energy efficiency measure due to the low price of water and wastewater services. Potential Funding Mechanisms

It is common for Air Force installations to have some, if not all, of the essential components of water microgrids, including on-site water supply, storage, and treatment. But many sites lack the automated metering and operational technology necessary for microgrid monitoring and control. Such technology can be deployed through funding streams that focus on water and climate resilience, including the Energy Resilience and Conservation Investment Program (ERCIP). Upgrades or enhancements to existing water infrastructure can be funded through utilities modernization funding mechanisms. Larger infrastructure investments may require military construction funds.

No specific incentives were found for this type of technology. If looking to explore further, the Air Force should conduct research to see if local incentives are available for a specific installation, especially in water-constrained locations.

7.0 Implementation and Siting Considerations

A water microgrid is best applied to advance an Air Force installation's water infrastructure and water resilience posture by being readily available to meet critical missions during a utility outage. Water microgrids have wide applicability across the DoD portfolio and are most applicable for installations with mission-essential functions, existing water infrastructure, high water risk, and water infrastructure reliability concerns. These criteria should be considered to strategically deploy water microgrids at Air Force installations.

Water microgrids can contribute to the water-inclusive requirements outlined in the Air Force's Installation Energy Strategic Plan and the Climate Action Plan. Sites should be selected for water microgrid implementation based on a few key considerations. These considerations relate to the following characteristics of a site:

- Water risk
- Water demand
- Existing infrastructure
- Potential water and energy cost savings

Priority should go to sites where water microgrid implementation will mitigate risk, reduce a large quantity of water and energy use, reduce waste, and take advantage of existing infrastructure for the lowest installation costs. Sites with a critical mission presence should also be considered for a higher priority.

The concept of a water microgrid can be applied to any site. Installations with significant existing infrastructure and advanced metering can likely implement a water microgrid without too much extra effort or funding, making them a desirable location for implementation of the technology. Sites with high levels of water use (especially unaccounted water use) are also good candidates for implementation since the water microgrid will offer a higher magnitude of water and energy cost savings.

There are several factors to consider to identify and prioritize installations that may be well-suited for water microgrid implementation. The criteria described below could used for the selection of potential water microgrid sites.

High mission priority: Installations that provide critical mission functions that require water may be good candidates for a water microgrid. Sites that are a part of the Office of Secretary of Defense's Mission Assurance, Power Projection Platform, or are a Mobilization Force Generation Installation may be given a higher priority ranking for a water microgrid site.

High water risk: Many sites across the U.S. face water risks, such as drought and increased demand for water. These risks have the potential to significantly impact water availability. These risks can affect the DAF's ability to secure adequate water supplies for critical functions and processes. Water microgrids may help to reduce these risks, providing a more reliable source of water for critical demands.

Existing on-site water supply: Installations with existing water supply through freshwater sources (such as wells) or alternative water may make the deployment of a water microgrid more feasible. Real property data can be used to identify installations with on-site potable water sources, and data from the DAF meter consumption reporting system can be used to identify installations using alternative water sources for non-potable water. Installations with both of these water sources should be ranked higher than installations with one or none of the water sources described.

Existing water treatment and storage infrastructure: Installations with existing treatment and storage infrastructure in place provide key infrastructure important for the operation of a water microgrid. Real property data can be used to identify installations with on-site potable water treatment facilities and on-site potable water storage tanks. Installations with both of these infrastructure components should be ranked higher than installations with one or none of the infrastructure present.

High water consumption: Installations with relatively high water use should be ranked above installations with lower water consumption because installations with lower water use may be able to meet their water needs using simpler solutions such as water buffalos and bottled water.

Harvested rainwater availability: The availability of rainwater to harvest as an alternative water source could provide an additional redundant water source for a water microgrid. The Federal Energy Management Program's rainwater harvesting potential map (https://www.energy.gov/femp/femp-rainwater-harvesting-map) can be used to identify installations with high potential to harvest rainwater.

Water supply unreliability: Frequent unexpected water outages may indicate an unreliable water supply to an installation. These installations may be good candidates for a water microgrid, which can help to ensure a redundant supply is available to meet critical demand. Reported installation water outage data (excluding planned maintenance events) should be considered to identify any additional installations for consideration.

It is recognized there are other important criteria to consider for prioritizing sites for water microgrids, such as specific threat and hazard probabilities. The Air Force will need to consider other factors to use for prioritization.

8.0 Recommendations and Path Forward

Moving forward in the deployment of water microgrids at Air Force installations, it is recommended that AFCEC conduct a prioritization assessment using the desirable siting characteristics noted above. Once a list of potential sites is developed, AFCEC can consider conducting a water microgrid pilot. This pilot effort can be a small-scale effort that includes a single building or a collection of several buildings. A small-scale demonstration may be sufficient to pilot the basic functions of a water microgrid. These buildings should be able to incorporate on-site water source from a freshwater and/or alternative water source and include on-site storage, treatment, and automated controls.

A second approach could be to broadly advance the topic across several installations, implementing in-line storage systems and valves to isolate critical water uses and controllers to operate them, and associating specific water demand with the most readily available water sources and treatment standards to meet system requirements. All these steps lead toward a water microgrid while improving overall water resilience. Both of these approaches hold measurable resilience gains for the DAF and should be considered in greater detail in support of overall mission resilience.

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Appendix A Glossary

Alternative water: Supplied from sustainable sources that are NOT freshwater. Alternative water examples include harvested rainwater, reclaimed wastewater, and process reuse. See Table 1 for more examples.

Critical water demand: The water end-uses required to enable the installation's critical operations.

Energy microgrid: A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode (AFCEC 2017).

Freshwater: Water supplied from surface or groundwater sources. Surface water includes reservoirs, lakes, rivers, streams, and wetlands. Groundwater is found underground in cracks and spaces in soil and rock.

Island or islandable: The ability to disconnect and operate independently from a local utility.

Non-potable water: Water that is not of sufficient quality for human consumption is considered non-potable.

Potable water: Water consumed by humans and used for personal hygiene as well as washing applications such as healthcare sanitation, dish cleaning, and laundering. Potable water is tested, permitted, and approved for human consumption directly and thus carries a higher quality burden.

Public Water System: A public water system provides water for human consumption through pipes or other constructed conveyances to at least 15 service connections or serves an average of at least 25 people for at least 60 days a year. A public water system may be publicly or privately owned (EPA 2022c).

Primary water supply: Main water supply for an installation that provides the water necessary to maintain all water requirements. Primary water supply may be produced off-site or on-site.

Reclaimed wastewater: Treated wastewater to acceptable levels for reuse.

Redundant water supply: A secondary water supply that provides backup water to support specific requirements. For the purposes of a water microgrid, a redundant water supply is on-site and serves critical water demand.

Water microgrid: A local water system that supplies, treats, and distributes water, with the capability to operate independently of an existing primary water system, and includes a layer of sensing capability that provides the necessary monitoring and controls to operate the water microgrid.

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