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Emerging Technologies Review: Water Reuse Systems for Cooling Tower Applications

August 2023

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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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Executive Summary

A majority of missions in the Department of the Air Force (DAF) depend on both water and energy. The 2021 US 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 provide guidance for making key considerations when implementing technologies that are resilient and alternative sources to the traditional methods used in the Air Force today.

This report explores the concept of water reuse systems for cooling tower water makeup, specifically focusing on the use of alternative water sources, and the viability of these systems for Air Force installations and operations. Cooling is a critical requirement for DAF operations, and alternative water supplies that enable cooling tower use during a disruption of utility-supplied water increase Air Force resilience.

The components of a water reuse system for cooling towers include alternative water supplies, storage, treatment, and distribution in addition to the cooling tower itself. Alternative water sources are not derived from fresh surface water or groundwater and can provide a redundant water supply to utility supply or to fresh water produced on site. Alternative water sources include the following, as shown in Figure ES.1:

- **Heating, ventilation, and air conditioning (HVAC) condensate**: moisture accumulated from mechanical equipment
- **Atmospheric harvesting**: moisture harvested from the ambient air
- **Rainwater harvesting**: water collected from above ground surfaces
- **Stormwater harvesting**: water harvested from ground surfaces
- **Greywater:** lightly contaminated water from sinks, showers, or laundry
- **Reclaimed wastewater**: (aka blackwater) collected from toilets, urinals, and other high contaminant building processes
- **Cooling tower blowdown**: discharge from existing process
- **Desalinated water**: from seawater or other brackish sources

Water reuse components are generally widely available on the market, with scales ranging from small units serving a single cooling tower to large systems serving multiple buildings on an installation. Although onsite storage and distribution infrastructure may be available for these

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[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/

systems, water treatment will be needed on site for many forms of water reuse systems. The level of treatment will depend on the requirements of the cooling tower and the type of alternative water source.

Treatment can range from a simple strainer for removal of large objects, to filters that remove small to microscopic particles, to a complex series of biological, chemical and/or mechanical processes (referred to as a *treatment train*) to achieve a specific level of non-potable water quality appropriate for cooling towers.

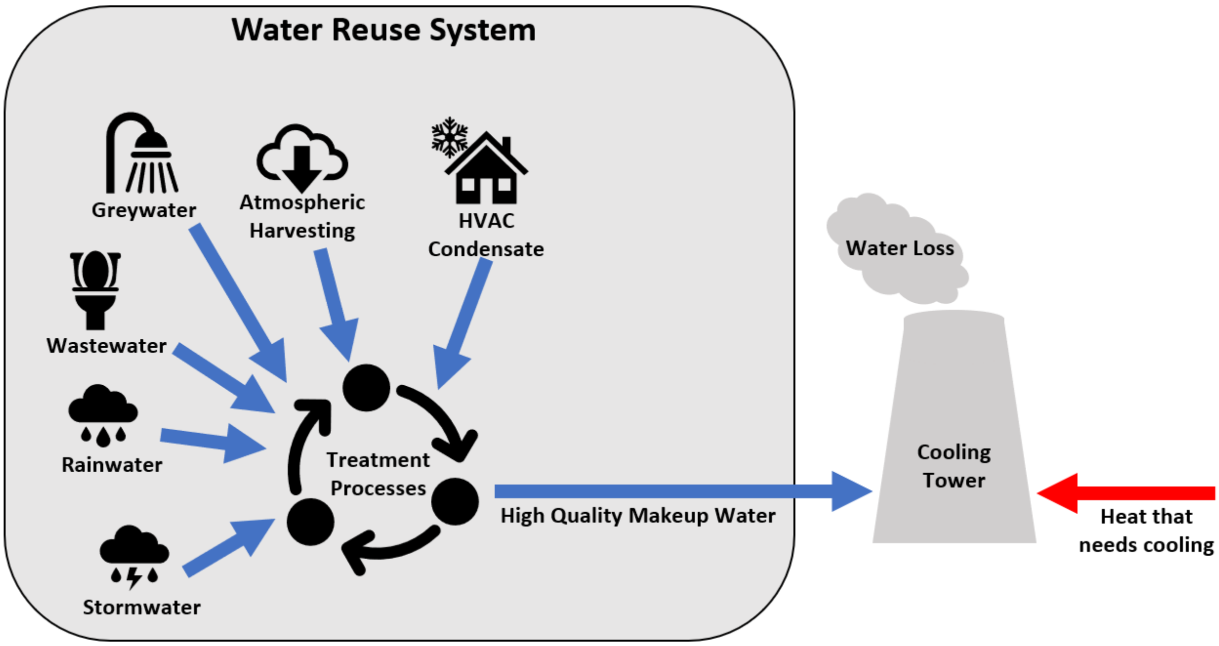

Figure ES.1. Water Reuse System for Cooling Towers

Infrastructure may be less complex in the case of alternative water sources that require minimal treatment or those that are co-located with the cooling tower. For example, an HVAC condensate or rainwater harvesting system located near the cooling tower served would require relatively little infrastructure compared to a wastewater treatment plant on the far side of the base.

Appendix A provides a list of DAF installations ranked by availability of high-quality alternative water sources applicable for cooling tower installations. It is recommended that the DAF develop a strategic approach to deploying water reuse systems across its portfolio. Key parameters to strategically target sites include installations with large cooling loads served by cooling towers, existing water infrastructure, mission critical water source deficiencies, high mission priority, and location in a state that has a supportive regulatory framework. A focus on sites with a sufficient source of high-quality alternative water (e.g., condensate capture or harvested rainwater) to meet the demand will reduce costs for additional components such as storage, treatment, and distribution.

A demonstration project of a water reuse system could illustrate technology feasibility at a relevant scale for a cooling tower application. The pilot system should be designed with specific requirements for the site using modular processes that would allow various technologies to be tested to determine the most effective and cost-efficient treatment approach. Pilot testing also would allow operators to engage with the process and develop familiarity with the alternative water source storage and treatment technologies and operations and maintenance requirements. Relevant data should be collected during the piloting process to verify efficacy, support the design process for future projects, and share lessons learned across the Air Force.

Acronyms and Abbreviations

AI	artificial intelligence
BOD	biochemical oxygen demand
DAF	Department of the Air Force
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EUI	energy use intensity
FEMP	Federal Energy Management Program
gpd	gallons per day
HVAC	heating, ventilation, and air conditioning
LEED	Leadership in Energy and Environmental Design
MBR	membrane bioreactor
MF	microfiltration
NBRC	National Blue Ribbon Commission
NPDES	National Pollutant Discharge Elimination System
O&M	operations and maintenance
PFAS	polyfluoroalkyl substances
PNNL	Pacific Northwest National Laboratory
RO	reverse osmosis
SEDS	Science and Ecosystem Support Division
TSS	total suspended solids

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1.0 Introduction

Pacific Northwest National Laboratory (PNNL) examined water reuse systems for cooling tower makeup and evaluated the applicability of this technology for use at Department of the Air Force (DAF) installations. Cooling is a critical requirement for DAF operations that uses both energy and water. Alternative water supplies that enable cooling during a disruption of utility-supplied water increase Air Force resilience.

The objective of this report is to introduce the concept of water reuse systems using alternative water sources treated to non-potable quality levels for cooling tower makeup. Cooling towers are a key component of building cooling systems whereby heat from various processes (building cooling, refrigeration, data centers) is dissipated to the environment (FEMP 2011). Cooling towers account for a significant amount of water and energy use in the U.S., averaging around 40% of a building's total water demand with over 8,000 British thermal units required to evaporate each gallon of water. Cooling towers are therefore a potential area for water reuse systems to provide moderate to significant water and energy cost savings (DOE 2016; Advantage Engineering n.d.).

Water reuse systems for cooling tower makeup water are made up of basic components including alternative water supply, storage, distribution, and treatment processes to provide non-potable quality water (Figure 1).

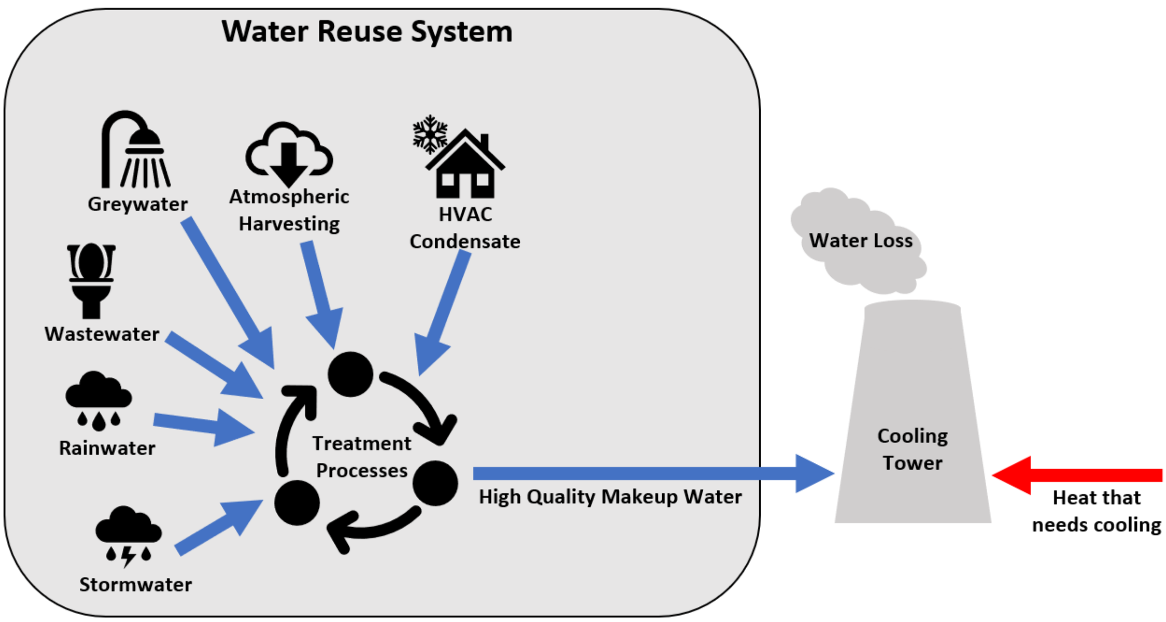

Figure 1. Water Reuse System for Cooling Towers

1.1 Background and History

In 1965, a Presidential Executive Order (H.R. 5306) created the Water Resources Council, which helped fund and drive conservation of water resources by federal government, state, localities, and private enterprises. Around the same time (in 1972), the National Pollutant Discharge Elimination System (NPDES) permit program led to increased pressure on nutrient management, disinfection by-products, and effluent guidelines (EPA 2023). These programs, along with green building certification programs such as Leadership in Energy and Environmental Design (LEED) and Green Globes, were drivers for the early development of onsite treatment technology for water reuse systems (Bell et al. 2023).

Water reuse systems span multiple industries and applications. The pulp, paper, and textile industries were early adopters of onsite water reuse systems, and have reduced their freshwater consumption by over 95% in the last 30 years. In the early 2000s, the electronics manufacturing, food and beverage, and power production industries started to reuse water for process water, boiler feed, toilet flushing, irrigation, and cooling tower makeup (Bell et al. 2023).

An early barrier to adoption was the mismatch between inconsistent alternative water supplies and constant process demands such as the use of treated rainwater for toilet flushing. Water storage and groundwater recharge have made use of relatively constant supplies of alternative water such as municipal wastewater, which can then be drawn upon during periods of higher demand. Water reuse systems can be onsite (reusing water from an internal process) or offsite water recycling (using treated municipal effluent instead of potable supply) (Bell et al. 2023).

1.2 Drivers

As DAF planners work to enhance the energy and water security of mission critical sites, it is vital to identify proven methods and processes to produce, treat, and distribute water to meet critical mission needs. Climate change and other factors, such as drought risk and increased demand for water, have the potential to significantly impact water availability across the nation. These risks can affect the ability of DAF to secure adequate water supplies for mission critical functions and processes. Water reuse provides a source of water that can provide a redundant supply for cooling towers serving critical mission buildings, thereby improving installation readiness and resilience while supporting broader sustainment and environmental objectives.

Use of alternative water sources supports the requirements set forth in U.S. Department of Defense (DoD) Instruction 4170.11 (DoD 2018), which states that DoD components shall “take necessary steps to ensure the security of energy and water resources.” In addition, the National Defense Authorization Act of Fiscal Year 2020 (H.R. 6395), Section 226, states that “[t]he Secretary of Defense shall research, develop, and deploy advanced water harvesting technologies to support and improve water sustainment within the Department of Defense and in geographic regions where the Department operates.” Executive Order 14057, Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability (The White House 2021), directs federal agencies to strategically identify sources of alternative water to offset freshwater supply. Use of alternative water will assist federal agencies in meeting the potable water use intensity reduction goals set forth in the executive order.

The 2021 U.S. Air Force Installation Energy Strategic Plan (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 has tasked PNNL with providing information on water reuse systems and providing guidance for making key decisions when implementing alternative technologies to the traditional methods used in the Air Force today.

2.0 Technology Description

Water reuse systems collect water from appropriate alternative water sources, treat it to suitable water quality standards, store it pre- and post-treatment, and distribute it as makeup water for cooling towers. The components of a water reuse system are generally widely available on the market at scales ranging from small units serving a single cooling tower to large systems serving multiple buildings on an installation.

2.1 Components

Water reuse systems for cooling tower makeup include four main components (Figure 2):

- Alternative water supply
- Storage and distribution
- Treatment
- Cooling tower processes

Figure 2. Water Reuse System Components for Cooling Towers

2.1.1 Alternative Water Supply Source Types

Before delving into the various types of alternative water, it is important to understand basic water terminology. As shown in Figure 3, there are two types of water supply and two water treatment levels. Cooling tower makeup water supply can be from freshwater or alternative water, though the focus of this report is alternative water and its treatment to appropriate non-potable quality levels.

- **Freshwater:** Surface water and groundwater found naturally in the environment that has a total dissolved solids concentration of fewer than 1,000 milligrams per liter (1,000 parts per million). 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 reuse.

Both freshwater and alternative water 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.

Figure 3. Basic Water Terms

Alternative water is supplied from sustainable sources that offset the use of freshwater. There are several types of alternative water that may be appropriate for cooling tower makeup, listed below in order of most suitable (least amount of treatment needed) for cooling tower applications:

- **HVAC condensate** comes from humid air contacting the cold surfaces of cooling coils on mechanical equipment and condensing into liquid. This water is drained to prevent buildup and damage to the equipment, then is typically discharged to sewers or an approved location. For water reuse systems, this water can be collected in a storage tank and sent directly to the cooling tower. This water is near distilled quality (requiring minimal to no treatment) and can help to reduce the average level of dissolved solids in the cooling tower, potentially increasing cycles of concentration.
- **Atmospheric harvesting** uses a device to extract water vapor from the air. The device can use condensation (similar to HVAC condensate), desiccant capture (where desiccant materials absorb the atmospheric water), or membranes (which act like filters to separate water from air). This water is also very pure (requiring minimal to no treatment) and can help reduce the average dissolved solids in the cooling tower.
- **Rainwater harvesting** is the collection of rainwater from rooftops or other covered surfaces. This is different from stormwater runoff as the harvested rainwater is collected as it falls on elevated surfaces. The water is not as pure as condensate or atmospheric harvesting and may require some treatment, such as filtration at a minimum.
- **Stormwater harvesting** is precipitation runoff on ground surfaces that has not entered other groundwater or surface water sources. Stormwater is collected on site from hard surfaces like streets and parking lots. Stormwater requires more treatment than harvested rainwater due to the contaminants picked up from contact with the ground (oil, soils, chemicals, etc.).
- **Graywater** is lightly contaminated water from bathroom sinks, showers, or laundry machines. This water is typically sent to the municipal sewage system but can be diverted to treatment then reused after filtration and disinfection.
- **Reclaimed wastewater** (aka blackwater) can be highly contaminated, depending on the discharge source (toilets and urinals, building processes, etc.). Reclaimed wastewater is typically provided from offsite larger utility-scale systems. Wastewater can also be collected and treated on site, though this may require significant investments in treatment, storage, and distribution infrastructure.
- **Cooling tower blowdown** can be treated to remove dissolved solids rather than discharging to a sewer system. However, this water is very low quality and may require significant treatment depending on the cycles of concentration.
- **Desalinated water** is brackish water or seawater that has been treated to remove dissolved solids. Desalination processes include thermal processes like multistage flash or mechanical processes such as reverse osmosis (RO). These treatment processes result in high-quality water but are very energy-intensive and produce concentrated brine that must be disposed of properly. Desalination treatment facilities are often larger utility-scale systems.

2.1.2 Storage and Distribution

Non-potable water of suitable quality for cooling tower makeup can be provided via a direct utility connection, separate from the traditional potable water supply. Depending on the alternative water source, a water reuse system may include onsite storage at the supply (before treatment) as well as post-treatment (before distribution) to meet quality requirements. There are several options available for onsite storage, as presented in Table 1.

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 required for distribution and 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 1. 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 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 • Booster pumps lift and pressurize water for distribution

The distribution system consists of a series of pipes, valves, and pumps sized for proper velocity based on flow volume and friction losses, according to local codes or acceptable engineering practices. A properly designed water reuse system's distribution component ensures the treated water is supplied to the cooling tower equipment at the required pressure and flow rate. Piping systems are regulated by local plumbing codes and therefore applicable rules and regulations should be reviewed before selecting the appropriate piping material and labeling requirements to distinguish them from any potable water distribution system.

2.1.3 Treatment

A wide variety of readily available treatment technologies can achieve non-potable water quality levels appropriate for cooling tower applications, depending on site-specific requirements. Cooling towers have specific water quality requirements to keep the equipment properly functioning. The level of treatment will depend on the requirements of the cooling tower and the type of alternative water source.

Water treatment will be needed on site for many forms of water reuse systems. Infrastructure may be less complex in the case of water supply that requires minimal treatment or that is co-located with the cooling tower. For example, an HVAC condensate or rainwater system located near the cooling tower would require relatively little infrastructure compared to a wastewater treatment plant on the far side of the base.

Table 2 provides the relative incoming quality of alternative water supply types and general type of treatment needed for cooling tower applications.

Table 2. Relative Quality of Alternative Water Sources

Source	Relative Quality	Treatment Requirement
HVAC condensate	High	None to minimal filtration
Atmospheric harvesting	High	None to minimal filtration
Rainwater harvesting	Medium	Large particle removal, filtration, disinfection
Stormwater harvesting	Medium to Low	Large particle removal, filtration, oil removal, disinfection
Graywater	Low	Filtration and disinfection
Reclaimed wastewater	Low	Biological treatment, advanced filtration, disinfection
Cooling tower blowdown	Low	Advanced filtration, RO
Desalinated water	Low	Advanced filtration, RO

Treatment can range from simple strainers for removal of large objects, to filters that remove small to microscopic particles, to a complex series of biological, chemical, and/or mechanical processes (referred to as a *treatment train*) to achieve a specific level of water quality. The treatment technologies and processes that may be employed in a water reuse system are described below.

- **Screening:** Removes large particles from a water stream before further treatment. Coarse screen openings can range from 3 inches for wastewater treatment down to 1/4 inch to remove leaves and twigs from a rainwater gutter.
- **Filtration:** Removes particles from a water stream using a physical barrier (media). The size of the opening can vary from small and fine (less than an inch) to microscopic depending on the size of the particles that must be removed. Microfiltration (MF) can involve specialized membrane media to remove ultra fine and microscopic particles.
- **Primary treatment:** Includes physical processes such as screening and gravity settling of suspended particles.
- **Secondary treatment:** Includes biological processes such as aerobic aeration, chemical flocculation, and fine filtration for further particle removal.
- **Tertiary treatment:** An advanced treatment process that produces high-quality water. Includes removal of nutrients such as phosphorus and nitrogen and practically all suspended and organic matter from wastewater. Tertiary membrane filtration can take the effluent from a secondary process and remove the particles.
- **Biological treatment:** Includes screening, primary treatment, secondary treatment, media filter, chlorination, then de-chlorination. The unique step to biological treatment is the secondary treatment. Influent enters an aerated bioreactor where bacteria consume the organic matter. The resulting water is then separated out in a clarifier and moved to the next step in the treatment train, where the separated sludge (biosolids) is returned to the bioreactor.
- **Membrane bioreactors (MBRs):** A combination of biological treatment with a membrane filter to replace the clarifier, removing the slow gravity settling process and increasing the overall particulate and organic removal effectiveness.

- **Reverse osmosis:** A specialized membrane filter that removes dissolved constituents but requires extensive pre-treatment and creates a concentrated stream of wastewater (brine).
- **Advanced oxidation:** Highly reactive hydroxyl radicals that break down any organics that make it through the RO system. This process only takes milliseconds and is very safe.

Table 3 illustrates U.S. Environmental Protection Agency (EPA) guidelines on quality and monitoring in cooling towers (Eslamian 2016). Contaminants and quality indicators of concern include pH, biochemical oxygen demand (BOD), total suspended solids (TSS), fecal coliform, and chlorine.

Table 3. Recommended Water Quality for Cooling Towers (Eslamian 2016)

Required Treatment	Recommended Contaminant Limits	Monitoring	Protected Distance
• Primary treatment • Secondary treatment • Tertiary disinfection (chemical treatment and filtration may be required as well)	• pH: 6-9 • BOD: 30 mg/L • TSS: 30 mg/L • Fecal coliform: 200 in 100 mL • Cl_2: 1 mg/L	• pH: Weekly • BOD: Weekly • TSS: Weekly • Coliform: Daily • Cl_2: Continuous	Cooling tower should be 90 m from public access to avoid health risk due to wind-blown spray exposure. (This distance can be reduced if water is treated to high quality.)

2.1.4 Cooling Tower Processes

The last component of a water reuse system for cooling towers is the cooling tower itself. The size and design of the tower may be dictated by the process that requires cooling. (Building air cooling has different requirements than an industrial process.) There are two broad categories of cooling towers: open circuit (direct contact) and closed circuit (indirect) (FEMP 2011). In both cases, the basic mechanism of heat transfer remains the same. Recirculating water is distributed through the tower and the atmospheric air provides evaporative cooling. The categories differ in the fluid that is used to dissipate heat.

Open circuit systems use water to gather heat outside of the tower directly from the process that needs cooling. Then, this same water is distributed across the tower, where the air directly provides cooling. Thus, the return fluid (which exchanges heat with the process) is the same as the recirculating fluid (which dissipates the heat to the atmosphere). Closed circuit systems use a return fluid (which is often water) in a closed coil. This fluid gathers the process heat then flows through the cooling tower while remaining inside the coil. The recirculation water inside the tower is distributed in contact with the outside of the coils, gathering the heat. Then, the air provides cooling to the recirculation water. Thus, the return fluid stays inside closed coils while it gathers the process heat and rejects the heat to the recirculating fluid, which remains inside the cooling tower as it dissipates the heat to the atmosphere.

Cooling towers can be further grouped in terms of the air flow direction and type of draft. Counter-flow towers have upward air flow and downward water flow, providing very high thermal efficiency. Cross-flow towers have air flowing horizontally across the falling water, resulting in fewer fan power requirements due to a decreased resistance to air flow. Mechanical draft towers force air flow using a fan. Natural draft towers rely on the lower density of warm air to cause a natural upward movement of air.

Other points of differentiation between towers include the method of distribution. Distribution decks can be similar to either a sprinkler system with a series of spray nozzles or a series of holes for the water to fall through. In the lower levels, older towers use splash bars to break water into droplets while more recent designs use film fill, a tightly packed material that maximizes the surface area of the water for optimal heat transfer. Table 4 provides an overview of the terms used to categorize cooling towers.

Table 4. Types and Categories of Cooling Towers

Parameter	Categories	Notes
Tower type	Open circuit	Recirculation and return fluid are the same
	Closed circuit	Recirculation and return fluid are different
Air flow direction	Counter flow	High thermal efficiency
	Cross flow	Lower fan power. Usually use gravity-fed distribution with holes
Draft type	Mechanical	Fans at bottom (forced) or top (induced)
	Natural	Very tall “hyperbolic” towers needed
Distribution method	Nozzles	Active spray (similar to irrigation sprinklers)
	Holes	No active components
Fill type	Splash bar	Often used in old towers
	Film fill	High heat transfer at the cost of higher microbial risk

Operations and maintenance (O&M) concerns include broken nozzles and plugged orifices, fouling/scaling/microbial growth in film fill, and corrosive conditions inside the tower. These issues are not directly related to water loss, but they do impact the efficiency and operation of the tower, which in turn can require more water to achieve the same cooling.

Water loss in cooling tower systems is primarily through the evaporation process, though drift and blowdown can also be significant. Water consumed through evaporation is visible as a plume in cool climates, and “is returned to the environment as part of the natural water cycle” (Morrison 2015). Drift refers to water droplets entrained in the airstream as it passes through the top or side of the cooling tower. Blowdown refers to the water discharged due to high total dissolved solids content. Cycles of concentration describes the number of times water can be circulated through the cooling tower before it must be replaced because the dissolved solids are too high. A high concentration ratio (synonymous with cycles of concentration) means less water loss. The water supply needed to replace these losses is called makeup water. Water reuse to supplement makeup water is the focus of this report.

2.2 Configuration and Scale

The optimal configuration of a water reuse system for cooling towers has sufficient alternative water volume for all the required makeup water to the cooling tower. Both the availability of alternative water and the existing infrastructure may vary significantly from site to site. So, each base should be considered on a case-by-case basis.

Water reuse systems for cooling towers are generally done on a smaller scale than water reuse systems for other end uses like potable consumption. Some water reuse system projects involve large-scale centralized systems that provide water for large populations and include a distribution network. Yet, emerging technologies are making smaller onsite distributed systems possible. For this report, a large-scale system is defined as servicing an entire installation and includes a significant distribution network. A small-scale system is defined as servicing no more than a single or several proximate buildings' cooling tower(s) and includes either a minimal or no distribution system.

Water reuse systems can be suitable for smaller onsite applications. Minimal distribution can imply that the treated alternative water is not blended back into a mainline but can be fed directly to building end uses. These systems can be considered "skid-mounted" or "scalable" because they are mounted directly on a portable frame and/or may fit within spaces such as building mechanical rooms.

Small-scale, skid-mounted "plug-and-play" systems are readily available and can be deployed as containerized solutions. Several manufacturers, for example, sell prepackaged wastewater treatment systems with capacities rated to a low 500 gallons per day (gpd). Cooling towers are typically sized at 3.0 gallons per minute per ton over a 10°F delta-T across the cooling tower. Cooling tower makeup water demand will depend on several factors, including climate zone, building load served, and equipment efficiency.

The effluent of these systems produces water at a non-potable level that can be used for non-potable applications and/or possibly provide for a sewer credit agreement with water utilities for pre-treating the wastewater. These modular systems use modern technologies such as MBRs that combine membrane process (such as MF or ultrafiltration) with biological wastewater treatment processes (such as activated sludge) to reduce the system footprint. Combining treatment into one system also can provide cost savings associated with purchasing and operating fewer pieces of equipment and any associated energy savings. Figure 4 and Figure 5 show examples of skid-mounted solutions.

Figure 4. Example of a Skidded Microfiltration System

Figure 5. Example of a Skidded MBR Package

While skid-mounted units for all types of treatment processes used in water reuse systems are technically mature and commercially available (e.g., MF, MBR, RO, ultraviolet), similar to a large-scale system, the overall treatment train will require engineering support and guidance to implement. Regardless of the system size, all water reuse systems will ultimately be subject to the same local and federal regulations for water quality testing and permitting (see Section 5.0).

3.0 Operational Considerations

Water reuse systems require continual O&M. The size and complexity of the water reuse system will ultimately dictate the level of O&M effort. A thorough O&M plan and associated manual is critical to successfully operating any facility. Typically developed during system design and refined continually beginning with system startup, the manual documents operational duties, troubleshooting, testing, and frequency of preventative maintenance. The local permitting agency will dictate the minimum requirements of the O&M manual; commonly required topics for a complete water reuse system are found in Table 5.

Table 5. Common O&M Manual Topic Areas

Topic	Covers	Use
Organizational chart	Lays out structure and organization of treatment facility; divides work, authority, and responsibility (chain of command)	Provides information on chain of command; useful during upset conditions or equipment failure
Job descriptions	Lays out various work positions; identifies required skills and certifications	Clearly states requirements and certifications required to work in each role
Description of each process (design basis)	Process flow diagrams, as-built drawings, equipment suppliers, equipment manuals	Provides all relevant system details, process flows, and sources of replacement equipment
Normal operations	Instruction set and procedures for all equipment, processes, and testing	Provides definitive guide for system operation, required testing methodologies, and all required duties to maintain treatment system
Emergency response/ troubleshooting	Troubleshooting guide for system upset or equipment failure	Provides plans to recover from process upsets or equipment failures. Further outlines chain of command for various system conditions
Preventative	All required manufacturer preventative maintenance	Defines preventative maintenance schedule for all equipment

3.1 Operations and Maintenance Requirements

The O&M manual will provide the required frequency of maintenance and required level of effort for operational duties. However, to provide context, Table 6 outlines several of the ongoing requirements of operations and a generalized frequency of the work (FEMP 2023).

Table 6. O&M Measures for Water Reuse Systems

Component	Description	Maintenance Actions	Suggested Frequency
		Alternative Water Supply Source Types	
Potable water connection (municipal or onsite freshwater source)	Makeup water supply to meet cooling tower process needs when alternative water supply is not adequate to meet demand	Inspect potable water supply connection and backflow preventer and ensure that connections are in good condition without leaks. Comply with any regulations for testing required by local ordinances.	Annually
HVAC condensate	Water supply from humid air condensing on mechanical equipment	Inspect collection system for blockage.	As needed
Atmospheric harvesting	Water supply extracted from air	Ensure device is operating as intended.	As needed
Rainwater harvesting	Water collected from rooftops or covered surfaces	Inspect collection system for blockage.	As needed
Stormwater harvesting	Precipitation collected from ground surfaces	Ensure water is being collected as intended. Inspect collection system for blockage.	As needed
Graywater	Water supply from bathroom sinks, showers, or laundry	Ensure water is being collected as intended. Inspect collection system for blockage. Inspect connection to water supply and backflow preventer.	As needed
Reclaimed wastewater	Water supply from highly contaminated sources (toilets, building processes, etc.) typically from off site	Inspect connection to water supply and backflow preventer.	As needed
Cooling tower blowdown	Water supply from cooling tower once dissolved solids are too high to keep using	Ensure water is being collected as intended.	As needed
Desalinated water	Brackish water or seawater collected to be treated	Ensure water is being collected as intended.	As needed
		Storage and Distribution	
Controls	An electronic system that collects, monitors, and manages signals from sensors and components of the water reuse system. Controls can be part of individual components (pumps, valves, etc.) or configured to a central location	Ensure controls operate as intended, visually confirm response to control commands. Request manufacturer maintenance as needed to repair any controls issues. Check that wiring is in good condition.	Monthly
Storage tank	Vessel(s) appropriate for the application (see Section 2.1.2).	Inspect tank for cracks or leakage. Infrequent blowdown may be needed to remove sediment from the bottom of the tank. If filters are regularly maintained, sediment accrual should be minimal.	Annually
Backflow preventor	Mechanical device installed at an appropriate location in the distribution system to ensure that water cannot flow into potable water system (cross connection) under instances of negative pressure	Have an approved professional test annually or at a frequency required by local regulations.	Annually

Component	Description	Maintenance Actions	Suggested Frequency
Flow meter	A mechanical or electronic device to measure water production and/or distribution. Advanced meters include logging components to monitor over time	Ensure meter is calibrated per manufacturer instructions. Track water use regularly through meter readings automatically (with data logger) or manually with a logbook.	Monthly
Water level indicator	A mechanical or electronic device to monitor the water level in the storage tank	Ensure the indicator is functioning as intended.	Monthly
Overflow	Opening in storage tank located such that drainage connection allows for overflow if the water gets above a certain level	Visually inspect overflow to ensure it is clear of debris.	Monthly
Pump	A device to move water through the entire water reuse system to the end use	Check motor condition. Investigate excessive vibration, noise, or temperature. Perform pump maintenance, such as bearing lubrication, in accordance with manufacturer specifications.	Monthly; Manufacturer-specified intervals
		Treatment	
Power supply	Systems may use conventional or alternative power systems such as solar systems or energy microgrids.	Check power supply and equipment after power outages and ensure no damage to components. Follow manufacturer O&M guidelines for alternative standalone power supplies (e.g., solar photovoltaic panels).	As needed; Manufacturer-specified intervals
Controls	An electronic system that collects, monitors, and manages signals from sensors and components of the water reuse system. Controls can be part of individual components (pumps, valves, etc.) or configured to a central location.	Ensure controls operate as intended, visually confirm response to control commands. Request manufacturer maintenance as needed to repair any controls issues. Check that wiring is in good condition.	Monthly
Treatment system	A single component such as filtration, or a combined treatment train that treats the alternative water to required quality levels	Clean and replace filters at manufacturer-specified intervals. Ensure treatment system dosing intervals are sufficient to meet water quality requirements in the system.	Manufacturer-specified intervals
		Cooling Tower Processes	
Cooling Tower	Cooling tower that uses makeup water to provide cooling	Ensure tower is operating as expected. Check water quality and scaling issues.	As needed; Operator-specified intervals

3.2 Cybersecurity Considerations

With the development of advanced controls, including artificial intelligence (AI), cybersecurity is an increasingly important consideration (Zhao et al. 2020). 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 of threats to U.S. water and wastewater systems by “known and unknown” malicious actors (CISA 2021).

Not all cyber-attacks can be prevented. 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. Examples 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, the Center for Internet Security Critical Security Controls, or similar protocols.

3.3 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.). Management of water-efficient facilities and operations can be enhanced by the application of advanced water meters and timely analysis of the reported data. Metering of cooling towers is also a good strategy to manage water use. 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 DAF 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 related to cooling tower applications. 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 proper use of water meters allows for flow measurement of various sources (freshwater, alternative water, treated non-potable makeup water), leak detection, identifying improvement opportunities, and benchmarking water use, among other benefits. Detailed information can be found in Water Metering Best Practices (Cejudo et al. 2022).

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

4.0 Technical Considerations

Successful installation of a water reuse system requires a careful approach to selecting components that is driven by regulatory requirements and treatment needs specific to each location. For instance, a given location may suffer from extremely hard water that alters technology selection, or local regulators may have specific removal requirements that necessitate multiple treatment processes (see Section 2.1.3).

To support the technology selection, it is essential to collect site-specific data that is used to determine the specific system requirements. Table 7 identifies data types that should be collected to characterize a site and explains why each is useful for determining the appropriate water reuse system for a given location.

For installations that are considering using reclaimed wastewater and have existing wastewater treatment plants, most of the needed data will be readily available via the NPDES reporting requirements for an operating wastewater treatment system.[1] For installations where no wastewater treatment plant is present, site-specific data for other alternative water sources will need to be collected.

During the data collection process, water reuse system goals and potential technical issues must be considered. Table 7 lists key questions that can help to uncover potential issues, identify system goals, and facilitate implementation. Careful consideration of these topics will support the overall decision-making process. This list is a starting point and is not comprehensive because each installation will present unique challenges and system requirements.

[1] NPDES permit is required by the Clean Water Act and is required for any discharge of pollutants into a U.S. waterway by a "point source" such as a wastewater treatment plant. NPDES regulates discharge limits and monitoring and reporting requirements. Find more information on NPDES: https://www.epa.gov/npdes

Table 7. Considerations for Identifying Potential Issues, System Goals, and Implementation Methods

Area	Considerations	Potential Option, Action, or Target	Outcome or Result
Overall / General	What are the goals for the water reuse system for the cooling tower?	Offset/reduce demand for freshwater resources Provide redundant water source to improve resilience	Specific goals may result in different final system sizing, infrastructure, distribution, and reporting requirements.
	Who will operate and maintain the system?	Develop an operating plan and identify personnel and training needs	A well-defined O&M plan and operator training program will ensure a well-operated system that meets requirements and stays compliant with necessary regulatory requirements.
	What is the appropriate size of the system?	Very small – services a single building or cooling tower Small to medium – services several buildings/processes Large – services a central plant	The system size will affect the number of short-term disruptions and amount of engineering services required.
Water Reuse System Considerations	Is advanced treatment required?	Remove TSS via enhanced filtration/screening and coagulant dosing Reduce biological growth through process modifications or improvements (e.g., optimizing aeration)	Reduces fouling potential.
		Reduce dissolved mineral content (through softening, diluting, or other treatment technologies)	Reduces scaling potential.
	What actions can be taken to deal with unusual or troublesome constituents in the alternative water supply?	Reduce greases/oils	If grease or oil are fed to a membrane system, significant system disruption can occur; reducing the amount in the system improves water treatment efficiency.
		Consider installation of real-time water chemistry analysis systems	Allows for rapid process modification to ensure high-quality water that meets water quality criteria.
		Need to evaluate water for corrosive effects	RO water can be a very aggressive solvent and result in corrosion issues.
	How will treatment system waste streams be handled for disposal?	Add storage specifically for waste discharge Investigate options for disposal (evaporation basins, solid liquid separators, etc.)	Treatment systems will generate waste by-product that needs to be disposed of, which can be costly.
	How are system issues that may cause the system to go offline handled?	Install standby/backup power system	Allows for remote system operation in the case of a power outage, which is required for pressurized membrane systems.

4.1 Component Availability/Supply Chain Issues

Water reuse system components as described in Section 2.1, including storage, distribution, and treatment technologies, are widely available from multiple manufacturers across the U.S. The type of treatment train specified for the water reuse system has the widest range of variability. For example, high-quality incoming water may only require simple filtration while low-quality water supply will require more advanced treatment (see Section 2.1.3). It is recommended the water quality and treatment be carefully specified in advance of the project installation to give ample time for the procurement process. Over the past several years, water utilities have faced supply chain issues when purchasing these types of water system components (AWWA 2021).

4.2 Technology Maturation

Technologies that are part of a water reuse system are generally widely mature and have been on the market for many years. There are some novel technologies that are less mature, as described in this section.

The current areas of research and development that may lead to new improvements in water reuse systems are primarily controls and treatment components.

Controls: AI is an area of research in water reuse systems, with the number of publications on AI applied to water treatment technology growing significantly each year. Trends in AI-related research have application to technological performance, economic cost, and management. Artificial neural networks are the most common AI technique for water treatment and can be used to simulate, predict, confirm, and optimize contaminant removal (Zhao et al. 2020).

Membranes: These play a key role in the production of high-quality water, particularly when used for RO. Issues facing membranes include high energy consumption, membrane fouling, micropollutant/pathogen removal, and concentrate disposal. These issues are being addressed through research in novel process innovation and advanced membrane development (Tang et al. 2018). One limitation of membranes is the inability to fully reject some harmful constituents in wastewater. Use of metal-organic framework nanoflakes to create advanced membranes is an area of research that can enhance the performance of membranes and reject these constituents far beyond the ability of current state-of-the-art membranes (Wen et al. 2022). Other research in material chemistry seeks to create membranes with improved solute-tailored selectivity for better performance in water reuse systems (Sujanani et al. 2020). Rather, this research demonstrates that membrane technology is an active area of development that can continue to expect performance improvements in the future, making membrane-based processes an attractive option for state-of-the-art reuse systems.

Other work: Other current work in water reuse systems focuses on removal of harmful contaminants [such as polyfluoroalkyl substances (PFAS)] and improvement to the treatment methods used. Technologies such as adsorbents and photocatalysts are being studied for application to potable reuse, but the resulting advances in water treatment technology may be leveraged for non-potable reuses as well (Fanourakis et al. 2020). However, these technologies are more relevant for potable water reuse systems as opposed to non-potable quality water suitable for cooling tower makeup.

4.2.1 Successful Commercial Applications

A few interesting examples of onsite alternative water treatment include systems at the University of Connecticut[1] and WaterHub installations at Philip Morris USA,[2] Emory University,[3] 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 towers, irrigation, or toilet flushing to offset freshwater consumption and provide a secondary source. For example, WaterHub (a NextEra Distributed Water product) is an onsite water recycling system that treats wastewater for non-potable uses. WaterHub is capable of recycling up to 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 makeup 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 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).

A successful case study is the Air Handler Condensate Recovery at the EPA's Science and Ecosystem Support Division (SEDS) in Athens, Georgia (FEMP 2010). Due to severe drought in the southeastern U.S., SEDS installed an air handler condensate recovery system in May 2008. The rooftop cooling units cause condensation in the hot and humid climate. The condensation drips from the units into collection basins and, when the basins are full, the recovered water is pumped directly into the nearby cooling tower. This water is nearly distilled and thus does not need treatment and does not cause issues due to water quality. From May through December 2008, SEDS recovered approximately 540,000 gallons of water, representing 16% of the facility's total water use and a financial savings of $3,500. EPA spent $24,500 on the project, resulting in a simple payback period of 6 years. The project's success led to similar implementation at other facilities in the same climate.

A case study in Brazil gathered data during 2014 and 2015 about reusing petrochemical industry process water for cooling tower makeup (Hansen et al. 2016). Water sources included the industrial effluent sent to a wastewater treatment plant, water used to cool bearings in rotating equipment that required no treatment, water used to remove ashes after burning coal in boilers, and the blowdown water from the cooling towers themselves sent to other cooling towers with salt concentrations still below the maximum level. The study found savings of 385,440 cubic meters (101,822,476 gallons) per year.

Washing and disinfection of bottles before packaging is another type of industrial process that can be leveraged for water reuse systems for cooling towers. A study in Spain was performed at the lab scale then implemented at the industrial scale (Arias et al. 2021). This system treated the wastewater from the washing process, performed treatment with activated carbon, then sent the water to be used in cooling towers. Results showed water savings of 5 cubic meters per hour and met 100% of the cooling tower makeup needs. Cost of required treatment is a consideration that may affect the economic viability of a potential implementation.

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

A mall in São Paulo, Brazil, used sewage and a wastewater treatment plant to offset water consumption in air conditioning cooling towers and toilets, resulting in water savings of 797 cubic meters per month (27% of water consumption in the mall) (Papp et al. 2022).

4.2.2 Market Penetration

In the global water reuse (reclamation) market, 97.7% is used for non-potable purposes, of which 52% is used for irrigation and 20% is used for industrial process. Only 2.3% of water production is used for potable purposes, and mostly for indirect potable reuse. California was a pioneer in water reclamation, and now most states recognize the benefits of reuse. However, less than 4% of global wastewater is treated for reuse (Yang et al. 2020). The specific percentage of water reuse associated with cooling tower makeup is not readily available.

4.2.3 Key Challenges and Barriers to Adoption

Selection of the appropriate alternative water resource(s) is important to the success of a water reuse system. Implementation of an alternative water collection system for a resource that is not readily available (too far away from cooling tower served) or is intermittent (rainwater harvesting) can be costly from both a capital cost and a water efficiency perspective.

Another key challenge to adopting water reuse systems for cooling towers is ensuring that staff are properly trained to operate and maintain the system components. See Section 3.1 for more information on O&M activities that should be performed on these systems.

4.2.4 Technical Resources Available

The U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP) has resources on alternative water sources and their considerations.[1,2] The resources include maps of alternative water source potential for rainwater,[3] condensate capture,[4] and wastewater reclamation.[5] These resources are explained and used in Section 4.2.4.

WateReuse[6] has resources ranging from conferences, educational content, research reports, and legislative information.

The EPA WaterSense at Work[7] best management practices document has a section about onsite alternative water sources.

4.3 Overlapping/Complementary Technologies

Real-time monitoring is a key element in a water reuse system. A water reuse system itself can be a subsystem of a larger water microgrid system as noted in the FEMP Water Meter Best Practices (Cejudo et al. 2023). While this report focuses on the reuse of water to provide cooling tower makeup, alternative water can be used for many other applications that require non-

[1] https://www.energy.gov/femp/best-management-practice-14-alternative-water-sources
[2] https://www.energy.gov/femp/alternative-water-sources
[3] https://www.energy.gov/femp/rainwater-harvesting-tool
[4] https://www.energy.gov/femp/condensate-capture-potential-map
[5] https://www.energy.gov/femp/reclaimed-wastewater-map
[6] https://watereuse.org/
[7] https://www.epa.gov/sites/default/files/2017-02/documents/watersense-at-work_final_508c3.pdf

potable water, including irrigation, vehicle and aircraft wash, toilet and urinal flushing, and boiler makeup. Although less common, alternative water can also be treated to potable standards.

Conversely, cooling tower blowdown can be treated for reuse in other processes. Blowdown has high concentrations of dissolved solids, so the water likely cannot be reused without treatment for most applications. Some of the treatment processes that can be used to treat cooling tower blowdown include constructed wetlands (Wagner et al. 2020), membrane distillation (Koeman-Stein et al. 2016), and RO (Davood et al. 2016).

5.0 Regulatory Background

The first general guidelines for water reuse systems came from the 1980 research report by the EPA Office of Research and Development (Bell et al. 2023; EPA 1980). Next was a 1992 guidelines update intended to help states with regulatory use (EPA 1992). Then, a 2004 guidelines update incorporated ultraviolet disinfection and emerging contaminants (EPA 2004). Another guidelines update was released in 2012 (EPA 2012). In 2017, EPA released the potable reuse compendium with best practices and around 40 case studies (EPA 2017). In 2019, the EPA water reuse action plan identified important near-term actions and established some performance metrics for success (EPA 2019).

Today, there are still no federal reuse regulations on reclaimed municipal wastewater. Instead, reuse quality must rely on the Clean Water Act and Safe Drinking Water Act (Bell et al. 2023). After meeting these federal requirements, states can regulate reuse as desired. Different industries have different guidance documents written by the relevant organizations (e.g., the International Life Sciences Institute for food and beverage), which can be confusing for certain states if there is not a relevant guidance document for the process in focus. However, state regulations and industry guidelines are likely less to be an issue for internal reuse at a federal facility.

DOE recently funded $100M to the National Alliance for Water Innovation to establish frameworks by sector to help inform and evolve the thinking around different types of reuses. One of these reports identifies challenges caused by industrial reuse advancing faster than the associated regulations are being made (Bell et al. 2023), which could lead to stranded resources that were invested in before the associated regulations were set.

Non-potable reuse, such as agriculture, faces a different set of regulations than potable water quality treatment. Governing bodies such as EPA, the World Health Organization, and national governments provide regulations worldwide; most are focused on human health but are lacking in regulations for water quality and pollutants such as heavy metals and salinity. Some regulations from different sources may have discrepancies between one another, so all applicable regulations should be considered when implementing a particular technology (Shoushtarian and Negahban-Azar 2020).

Due to the increased water risk faced by many communities throughout the U.S., 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” (US Water Alliance 2022). The NBRC aims to provide tools and guidance to support communities looking to implement onsite water reuse systems within a regulatory environment based on risk-based science.

5.1 Federal Requirements

The National Defense Authorization Act of Fiscal Year 2020 (H.R. 6395), Section 226, requires that military departments research, develop, and deploy advanced water harvesting technologies to support and improve water sustainment. In addition, Executive Order 14057, Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability (The White House 2021), directs federal agencies to strategically identify sources of alternative water to offset freshwater supply. The use of alternative water for cooling tower applications could help the Air Force comply with these federal requirements.

5.2 State Regulatory Activity

Federal law does not directly address water produced from alternative water sources; instead, states and local jurisdictions dictate specific requirements and compliance (e.g., use of reclaimed wastewater). The EPA guidelines described in Section 5.0 provide guidance to states, territories, and tribes on how to implement reclaimed wastewater initiatives while complying with federal law.

Figure 6 shows regulatory activities for non-potable reclaimed wastewater in the contiguous United States as of May 2020. States are classified as having no regulations, existing regulations, or anticipated regulations that are in development.

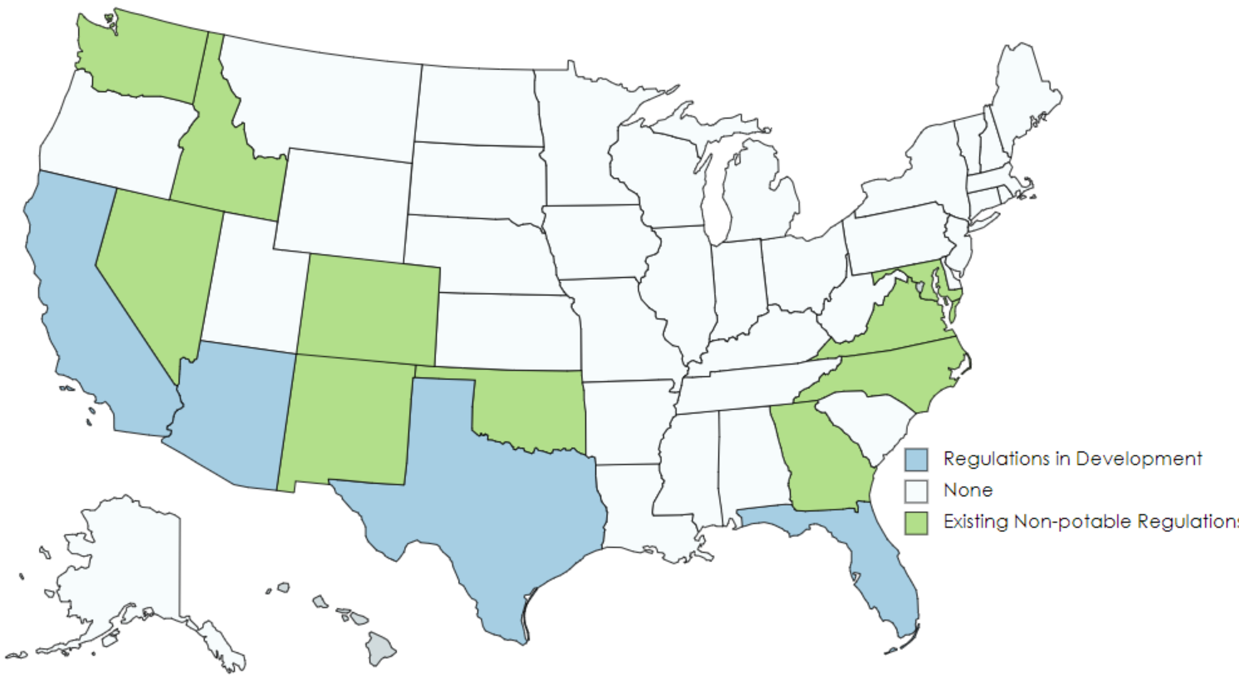

Figure 6. Reclaimed Wastewater Non-potable Regulatory Activities in the Contiguous United States

Similarly, rainwater harvesting is not regulated by the federal government and each state can dictate the requirements for harvesting rainwater. FEMP has produced an interactive map of state regulations (Figure 7) that categorizes levels of allowance as follows (FEMP 2022):

- **Very Limited**: The state has limited exemptions available for legal implementation of rainwater harvesting. For example, Colorado only allows homeowners to harvest up to 110 gallons for outdoor use only, while businesses cannot harvest rainwater.
- **Not Illegal/No Regulations**: No regulations are in place prohibiting rainwater harvesting. The state generally has no information regarding rainwater harvesting.
- **No Regulations/Encouraged**: No regulations are in place prohibiting rainwater harvesting. State-specific rainwater harvesting technical resources are available to encourage use, such as handbooks and guidelines on rainwater harvesting systems.

- **State Regulations**: Regulations are in place allowing rainwater harvesting; however, no specific technical resources or incentives are provided.
- **State Regulations/Encouraged**: Regulations are in place allowing rainwater harvesting, and state-specific technical resources are available to encourage the collection and use of rainwater.
- **State Regulations/Incentives**: Regulations are in place allowing rainwater harvesting, state incentive programs are in place, and state-specific technical resources are available.

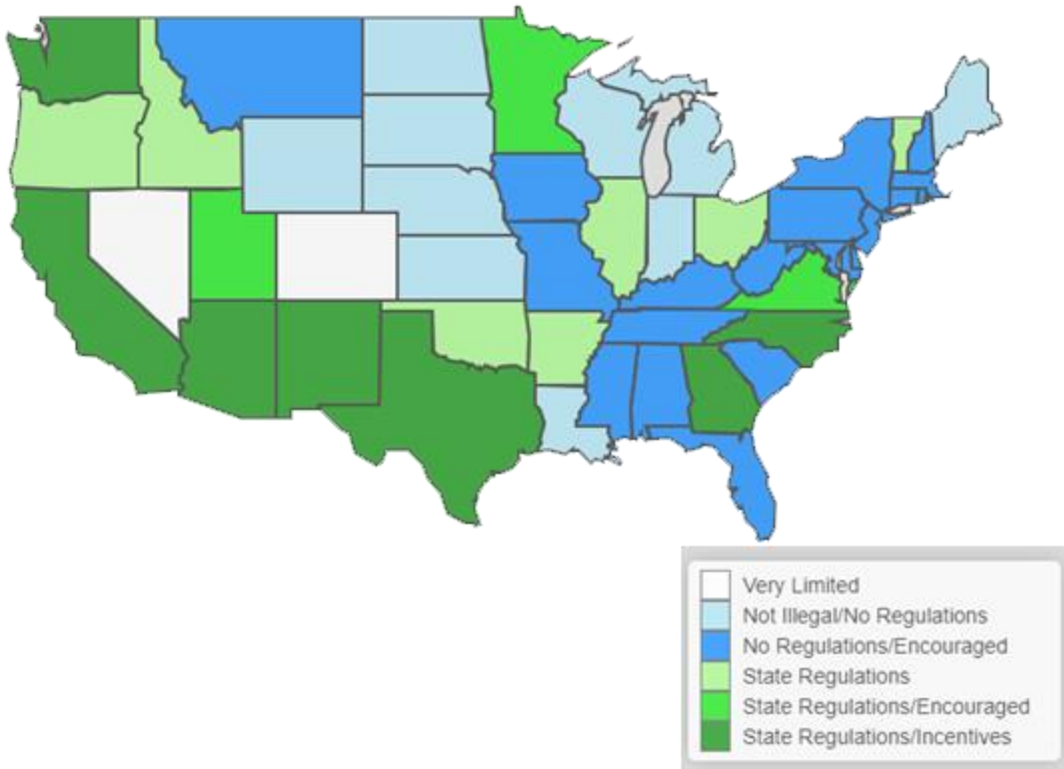

Figure 7. State Rainwater Harvesting Regulation Status

The installation should ensure that any water reuse system project pursued by the Air Force meets local and state regulations.

6.0 Siting Considerations

The most desirable siting characteristics for water reuse systems for cooling towers are installations with high availability of alternative water sources and significant cooling demand. Another characteristic that can help with implementation of a water reuse system is existing infrastructure to store, treat, and distribute the alternative water source to the application. This section reviews some of the considerations for implementing the appropriate water reuse system components at DAF base locations.

6.1 Alternative Water Resource Availability

The availability of the alternative water supply is highly dependent on the project location. The potential for condensate harvesting from air conditioning systems can be estimated from a site's annual average dew point, cooling degree days, and rainfall. The FEMP Condensate Capture Potential Map shows this potential across the U.S.[1] Figure 8 shows the results of overlaying Air Force base locations on the map. About 44% of base locations have high or the highest potential for condensate capture.

The potential for atmospheric water harvesting can be correlated to hot and humid conditions, and thus estimated from the climate zone at a base. Figure 8 shows the results of estimating potential at Air Force base locations using climate zones. Hot-humid climates were considered high potential, mixed-humid climates were considered medium potential, and all other climates were considered low potential. About 25% of Air Force base locations have high potential for atmospheric water harvesting.

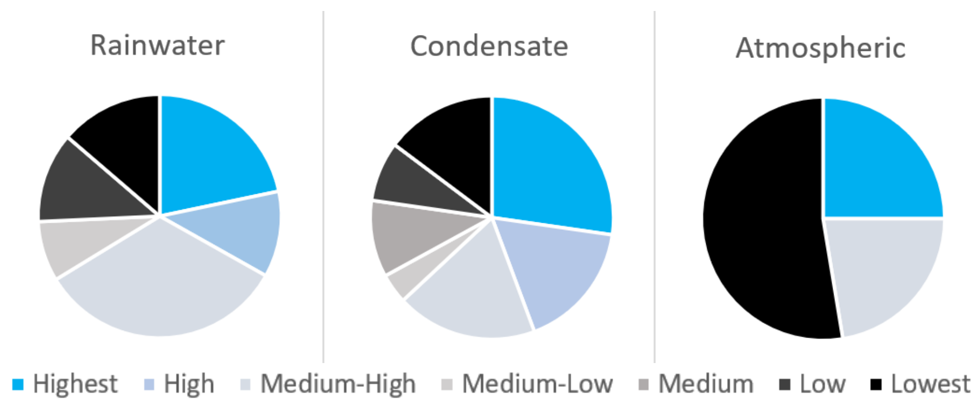

Figure 8. Potential for Various Alternative Water Sources at 192 Continental Air Force Active Duty, National Guard, and Reserve Bases

The potential to harvest rainwater at a site can be estimated from the total amount of rainfall and the months in which it occurs. The FEMP Rainwater Harvesting Tool, developed by PNNL, uses monthly rainfall data to estimate the amount of water (in inches) that can be harvested. This publicly available web tool gives the general rainwater harvesting potential at a particular ZIP code.[2] Figure 8 shows the tool results for Air Force base locations. About 33% of Air Force base locations have high or the highest potential for rainwater harvesting.

[1] https://www.energy.gov/femp/condensate-capture-potential-map
[2] https://www.energy.gov/femp/rainwater-harvesting-tool

While real property data of existing infrastructure is needed to estimate the applicability of onsite wastewater treatment required at bases, the purchase of reclaimed wastewater from nearby plants is another option. The FEMP Reclaimed Wastewater Map shows water utilities that produce and sell reclaimed wastewater in six states: California, Florida, Texas, Arizona, Colorado, and Nevada.[1] In these states, 16 Air Force bases are located within 20 miles of a water reclamation plant.

The resource availability at each Air Force base is summarized in Appendix A, where Table A.1 shows the potential for various alternative water sources according to the methodology described in this section.

6.2 Space Requirements

The space needed for water reuse systems depends on the demands of the cooling tower. Processes that require lots of cooling, such as air conditioning for large buildings, may come with large alternative water potential in the form of expansive rooftops for rainwater collection. In this example, water collection and water demand may both be positively correlated with rooftop area and building size. Other forms of reuse such as wastewater treatment are more dependent on the water consumption of the occupants rather than the size of the buildings. An onsite treatment plant may require only a fixed amount of space to provide a wide range of supply capacity. Because the storage component can take up considerable real estate (NextEra Distributed Water n.d.(a-c)), its sizing and location should be coordinated such that sufficient volumes of alternative water supply and treated non-potable water are readily accessible to adequately meet the requirements of the cooling tower equipment served.

As an example, the WaterHub system at Piedmont Atlanta Hospital takes up 5,873 ft^2 and provides 250,000 gpd of high-quality makeup water for cooling tower and boiler uses. A larger WaterHub system at the Philip Morris campus in Richmond takes up 8,200 ft^2 for the building plus a 1,200-ft^2 exterior storage tank that provides 650,000 gpd for a district energy system. A smaller WaterHub at the Emory University campus in Atlanta takes up 3,200 ft^2 and provides 400,000 gpd for district steam and chiller plants.

[1] https://www.energy.gov/femp/reclaimed-wastewater-map

7.0 Economic and Funding Considerations

When performing an economic analysis, it is important to closely evaluate all costs and potential savings streams when determining the cost effectiveness of these systems.

7.1 Installed System Costs

System costs for water reuse systems can vary widely. A major driver in system costs are the technologies selected for use and various site-specific requirements (Bailey 2013; Chalmers et al. 2013). Another factor affecting system costs is if or how existing installed equipment may be used. Sites with a significant amount of existing water treatment capacity may have lower overall costs for installation of a water reuse system. As an example, sites that already have a potable drinking water treatment facility (or additional capacity) may be able to use the same equipment to treat alternative water to lower non-potable standards. Additionally, a site that already has a tertiary wastewater treatment process with ultrafiltration or MF membranes may support a significant portion of pre-treatment, which improves the quality of some alternative sources and can potentially reduce the costs of water reuse system components.

In general, the largest capital costs result from membrane-based filtration equipment such as MF, nanofiltration, and RO, which may be considerably decreased for non-potable applications and higher quality water sources. Geographic location also can affect system capital costs. For example, locations near the ocean may have reduced or no costs for brine disposal (associated with RO reject).

Figure 9 shows the range of costs per million gallons ($/Mgal) associated with a variety of water source types compared to traditional water conservation projects. Although dated, the figure illustrates the wide range of expected costs associated with treatment of different alternative water sources including non-potable water reuse (WateReuse Association 2014).

Table 8. Relative Costs of Water Reuse System Components

Component	Notes	Relative Cost
Alternative Water Supply Source Types		
HVAC condensate	Quality is high, minimal to no treatment	$
Atmospheric harvesting	Quality is high, minimal to no treatment	$
Rainwater harvesting	Quality is medium, minimal treatment needed	$$
Stormwater harvesting	Quality is medium to low, moderate to high treatment	$$ to $$$
Graywater	Quality is low, high treatment	$$ to $$$
Reclaimed wastewater	Quality is low, high treatment	$$$
Cooling tower blowdown	Quality is low, high treatment	$$$
Desalinated water	Quality is low, high treatment	$$$
Storage and Distribution		
Controls	Can vary in complexity from basic component on-board controls to complex building-integrated building management system	Variable
Plastic storage tank above grade	Small to medium size capacity, National Sanitation Foundation-approved materials	$-$$
Metal storage tank above grade	Large, structurally reinforced for large storage capacity	$$-$$$
Underground storage tank	Steel, fiberglass, or concrete; designed to withstand groundwater and cover loads; higher installation costs due excavation	$$
Water level indicator	Monitor for each storage tank	$
Pump	Typically close-coupled inline for above grade, vertical turbine for underground; cost based on volume and head, intake and outlet locations	Variable
Treatment		
Power supply	Conventional and alternative power systems can vary widely in cost based on technology selection and size	Variable
Treatment system	Treatment cost varies based on complexity of the system and the water supply quality	Variable

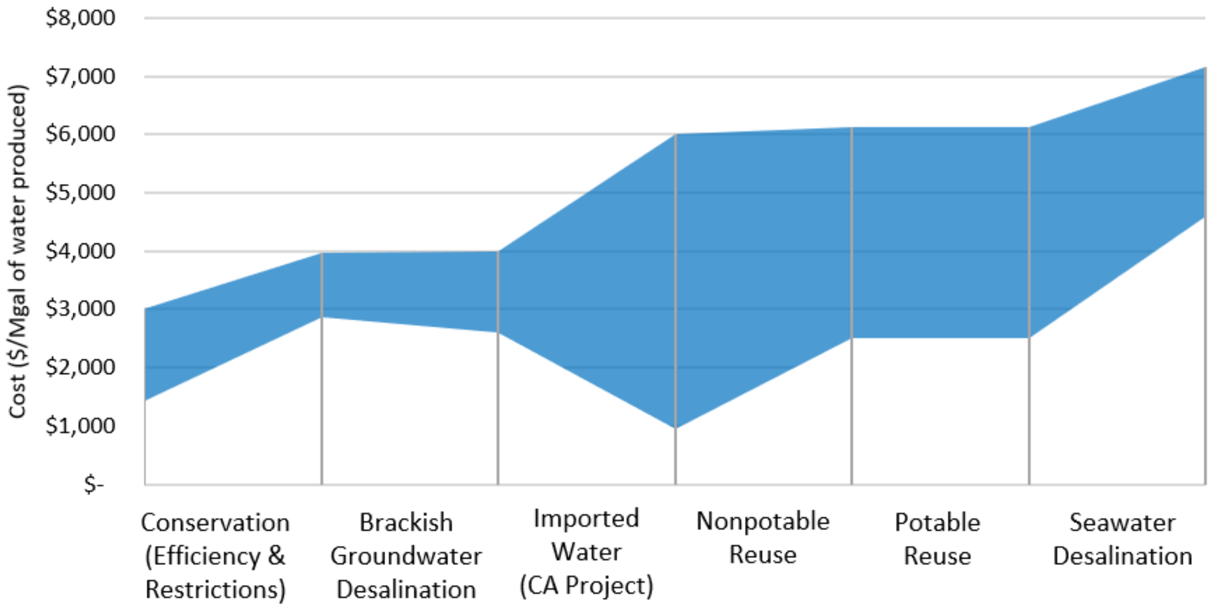

Figure 9. Cost Range of Water Reuse Treatment by Alternative Water Source

7.2 Potential Funding Mechanisms

Water reuse systems can be deployed through funding streams that focus on water and climate resilience, including the Energy Resilience and Conservation Investment Program. Third-party financing, such as energy savings performance contracts and utility energy service contracts, could be a potential source of funding to implement water reuse systems. Water reuse has the potential to be bundled into larger projects. 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 water reuse systems specific to cooling tower makeup water. The map shown in Figure 7 notes incentives for reuse of rainwater, which may be applicable and should be investigated by DAF for use in cooling tower applications. If looking to explore further, the Air Force should determine whether local incentives are available for a specific installation, especially in water-constrained locations. WateReuse has a collection of resources that may be useful in further research into incentives[1] and offers some awards and recognition programs.[2]

[1] https://watereuse.org/advocacy/state-policy-and-regulations/
[2] https://watereuse.org/news-events/awards/

8.0 Resilience and Climate Impacts

There are significant resilience benefits of a water reuse system. Water reuse systems can provide a redundant water supply for cooling towers serving critical mission building systems during times of disruption, thereby improving installation readiness and resilience while supporting broader sustainment and environmental objectives. In addition, water reuse systems can help protect against impacts due to climate change. Climate change imposes pressure on water systems via availability of alternative water supplies, 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. Water networks and treatment use about 10% to 15% of U.S. power production (IWA 2016). Energy is necessary for pumping, treating, and distributing water. Figure 10 shows the connection between climate change, water systems, and energy.

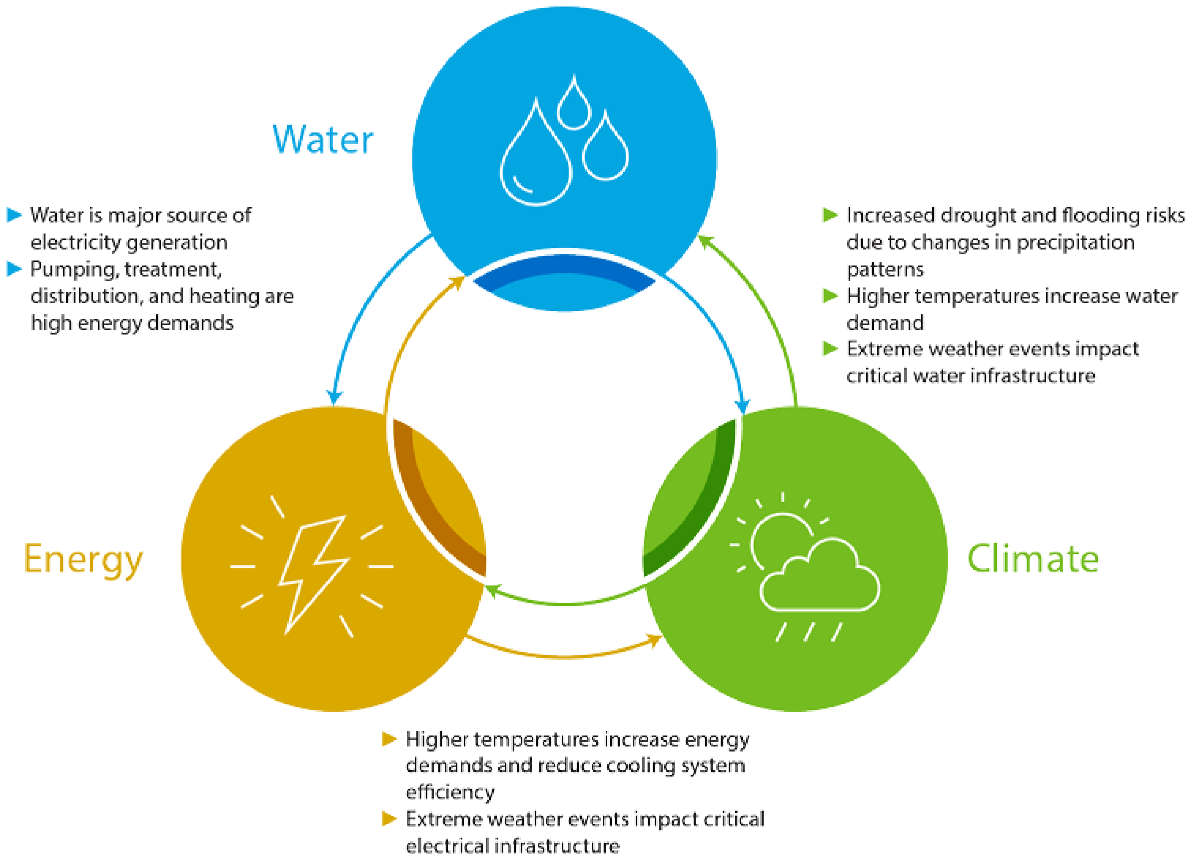

Figure 10. Water-Energy-Climate Nexus

Implementing an onsite water reuse system shifts energy use for pumping, treating, and distributing water from the local utility to the site. Increased electricity demand due to water reuse system infrastructure for a cooling tower 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.

Table 9. Energy Use Intensity by Water Source Type (Davila et al. 2020)

	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
	Onsite harvested rainwater/stormwater		Low
	Onsite captured condensate		Low
	Purchased reclaimed wastewater		High
	Onsite reclaimed wastewater (pressurized, gravity fed)		High
	Onsite reused process discharge water		Medium

9.0 Risks and Social Considerations

There are important factors other than technical requirements that should be considered when implementing water reuse systems. This section covers the potential human health risk(s) associated with water reuse and the barriers presented by public perception and community engagement throughout the implementation process.

9.1 Human Health Risk

The primary driver of human health risk associated with water reuse systems for cooling towers is *Legionella* bacteria. In improperly maintained cooling towers, *Legionella* bacteria can grow in the water. Cooling tower fans can create small droplets of water that become airborne, which can potentially cause Legionnaires' disease in people with underlying health conditions that come into contact with and breathe in the particles. Legionnaires' disease is serious type of pneumonia. The Centers for Disease Control and Prevention has developed a toolkit[1] that provides information on how to evaluate and implement measures to control for *Legionella* in cooling towers. Key recommendations related to a water reuse system provided in the toolkit include closely monitoring disinfection levels and automating chemical treatment to consistently disinfect the water supply to limit the production of *Legionella* bacteria.

9.2 Social Impact

There is no significant social impact related to water reuse for cooling towers. The water in these cooling tower systems does not come into contact with humans or with water consumed by humans.

9.3 Public Perception Barriers

A barrier to water reuse can be public perception, but this is more concentrated in the food and beverage industry or when considering potable reuse and use of wastewater. Still, public perception of water reuse in cooling towers is an obstacle that could cause barriers to project implementation. Thus, Air Force leadership should address the perceptions of families and personnel throughout the installation. Addressing public concerns is of utmost importance and no issue should be disregarded.

Community engagement can also act as a powerful tool to drive development of reuse projects. Positive messaging about reclaiming and reusing water, particularly from personal channels such as family, friends, colleagues, and leadership, is important to the acceptance of these water sources. Previous experience with water restrictions (familiarity with living in drought or disaster-stricken areas) increases the likelihood of acceptance and should inform the nature of the communication message that is likely to be most effective. Studies have concluded that messages emphasizing the real problem of water scarcity (e.g., by showing examples of current water scarcity in the geographical proximity of where people live) will have a higher likelihood of improving acceptance (Harris-Lovett et al. 2015).

Ultimately, findings have shown that the most likely ways to increase public acceptance are to provide information and conduct communication campaigns that include the following considerations (Harris-Lovett et al. 2015). It is essential that people understand that water from

[1] https://www.cdc.gov/legionella/wmp/control-toolkit/cooling-towers.html

alternative sources is a necessity. Examples of restrictions on current potable water supplies can be useful for providing perspective. It also is crucial to craft a targeted and proactive outreach program that reflects specific communication objectives. Proactive communication efforts can manage the narrative to avoid potential media misperception and subsequent pushback.

Also, suggesting voluntary and accessible ways for people to experience reclaimed water may be a useful strategy for increasing public acceptance and usage. Voluntary opportunities, such as tasting recycled water or filling public swimming pools with recycled water, could help garner public acceptance. These techniques are likely to be more effective than public announcements stating that recycled water would be added to water supplied to households. Such announcements have been perceived as threatening and have resulted in public rejection of water augmentation schemes in the past (Dolnicar et al. 2011).

9.4 Environmental Considerations

Water reuse systems have both environmental benefits and impacts. Section 8.0 discusses the primary environmental benefit of water reuse systems in the context of resilience and climate change. Sections 6.0 and 7.0 discuss the environmental impacts and regulatory requirements, which are more site-specific than the potential benefits. The main environmental impact of a water reuse system is the greenhouse gas emissions related to the energy required to treat the water to the acceptable standard and distribute it to the required location. A secondary impact is the waste streams that may be generated from the treatment process, which need to be discharged to an appropriate location. Table 9 summarizes the relative energy use intensity needed to treat each water source type to reveal the impact of greenhouse gas emissions associated with energy required.

10.0 Recommendations and Path Forward

It is recommended that the DAF develop a strategic approach to deploying water reuse systems across its portfolio. Key parameters to strategically target sites include installations with large cooling loads served by cooling towers, existing water infrastructure, mission critical water source deficiencies, high mission priority, and location in a state that has a supportive regulatory framework. A focus on sites with available high-quality alternative water sources will reduce costs for additional components such as storage, treatment, and distribution.

There are essential steps that should be taken to help ensure the successful deployment at individual bases, including:

- Identify available sources of alternative water.
- Conduct a detailed review of site-specific considerations, alternative water supply availability and quality, and treatment options that will ensure that the system meets site-specific requirements for cooling tower makeup water.
- Plan for required O&M activities.
- Understand and comply with federal, state, and local legislation pertaining to the operation of a water reuse system.
- Assess system costs, which vary widely and are driven primarily by the technologies selected and various site-specific requirements and existing infrastructure.

A demonstration project of a water reuse system could illustrate technology feasibility at a relevant scale for a cooling tower application. The demonstration should be targeted at a site with a large cooling load with a sufficient source of high-quality alternative water (e.g., condensate capture or harvested rainwater) to meet the demand. The pilot system should be designed with specific requirements for the site using modular processes that would allow various technologies to be tested to determine the most effective and cost-efficient treatment approach. Pilot testing also would allow operators to engage with the process and develop familiarity with the alternative water source storage and treatment technologies and O&M requirements. Relevant data should be collected during the piloting process to verify efficacy, support the design process at future installations, and share lessons learned across the enterprise.

11.0 Glossary

Advanced water treatment: Advanced treatment technology (for wastewater) refers to processes capable of reducing specific constituents in wastewater not normally achieved by other treatment options. It covers all unit operations that are not considered to be mechanical or biological, for example, chemical coagulation, flocculation and precipitation, break-point chlorination, stripping, mixed-media filtration, micro-screening, selective ion exchange, activated carbon absorption, RO, ultrafiltration, and electroflotation. Advanced treatment processes may be used in conjunction with mechanical and biological treatment operations.

Biochemical oxygen demand: BOD is the amount of dissolved oxygen used by microorganisms to metabolize organic material in water; BOD_5 is typically used as a wastewater treatment metric and represents the amount of dissolved oxygen consumed in 5 days of testing.

Disinfection: This is the removal of microorganisms (bacteria, virus, fungi, yeast, protozoa, rotifer, and/or algae) through the implementation of one or more of the following: chemical agents, physical agents, mechanical means, and/or radiation (Metcalf and Eddy 2003).

Filtration: Filtration is the process of removing particles from a water stream using a physical barrier. The sizes of the opening can vary from small to large depending on the size of the particles that must be removed.

- *Nanofiltration:* A membrane filtration-based process that used nanometer sized membrane through-pores. Nanofiltration uses a smaller membrane pore than microfiltration or ultrafiltration but typically larger than RO membranes.
- *Ultrafiltration:* A membrane filtration-based process that uses roughly 0.01 to ~0.1 µm sized through-pores. Ultrafiltration membranes are generally discussed in terms of molecular weight cutoffs in Daltons that describe the mass of filtered compounds.
- *Microfiltration*: A membrane filtration-based process that uses 0.1 to 10µm sized membrane through-pores.

Freshwater: Water obtained from a surface or groundwater source that has a total dissolved solids concentration of less than 1,000 milligrams per liter (1,000 ppm).

Large particle removal (screening): Screens are used to remove large particles from a water stream before further treatment. Coarse screens can have openings on the order of 0.25 inches, for example, to allow leaves to be screened from rainwater from a gutter.

Non-potable water: Water that is not of sufficient quality or been treated for human consumption.

Primary treatment: Primary water treatment is the first step of a water treatment system. This step includes physical processes such as screening and settling of suspended particles.

Point source: Any conveyance from which pollutants are or may be discharged; this term does not include agricultural stormwater discharges and return flows from irrigated agriculture (in Section 502(14) of the federal Clean Water Act) (EPA 2018, accessed on 10 February 2020 at https://www.epa.gov/cwa-404/clean-water-act-section-502-general-definitions).

Potable water: Water from public or on-site water systems that is classified, permitted, and approved for human consumption.

Reverse osmosis (RO): Physicochemical separation process in which water flows through a semipermeable membrane due to the application of an external pressure in excess of the osmotic pressure (the pressure required to balance the difference in chemical potential between two solutions separated by a semipermeable membrane); monovalent ions are excluded and low molecular weight compounds are not excluded (<200 g/mole) (MWH Global Inc. 2005).

Secondary treatment: Secondary water treatment is the second step of a water treatment process. This step includes biological processes such as aeration and fine filtration for further particle removal.

Tertiary wastewater treatment: Tertiary treatment is the advanced treatment process, following secondary treatment of wastewater. Tertiary treatment produces high-quality water. Tertiary treatment includes removal of nutrients such as phosphorus and nitrogen and practically all suspended and organic matter from wastewater. Tertiary membrane filtration can take the effluent from a secondary process and remove the particles

Treatment train: A series processes to achieve a specific level of water quality.

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Appendix A – Air Force Base Ranking: Alternative Water Supplies for Cooling Tower Water Reuse System

Table A.1 provides a list of Department of the Air Force installations ranked by availability of high-quality alternative water sources applicable for cooling tower installations.

Table A.1. Potential for Various Alternative Water Sources at Air Force Base Locations

Installation Name	Climate Zone	HVAC Condensate Potential	Atmospheric Harvesting Potential	Rainwater Harvesting Potential
Air Station Barbers Point	Hot-Humid	Highest	High	Highest
Brunswick Air Guard Station	Hot-Humid	Highest	High	Highest
Camp Beauregard	Hot-Humid	Highest	High	Highest
Camp Blanding Joint Training Center	Hot-Humid	Highest	High	Highest
Columbus Air Force Base	Hot-Humid	Highest	High	Highest
Dannelly Field	Hot-Humid	Highest	High	Highest
Eglin Air Force Base	Hot-Humid	Highest	High	Highest
Eglin Air Force Base (Duke Field)	Hot-Humid	Highest	High	Highest
England Air Park	Hot-Humid	Highest	High	Highest
Hall Air Guard Station	Hot-Humid	Highest	High	Highest
Hammond Air Guard Station	Hot-Humid	Highest	High	Highest
Hilo Air National Guard Communications Station	Hot-Humid	Highest	High	Highest
Homestead Air Reserve Base	Hot-Humid	Highest	High	Highest
Hurlburt Field	Hot-Humid	Highest	High	Highest
Jackson Air National Guard Base	Hot-Humid	Highest	High	Highest
Jacksonville Air National Guard Base	Hot-Humid	Highest	High	Highest
Joint Base Charleston	Hot-Humid	Highest	High	Highest
Joint Base Pearl Harbor Hickam	Hot-Humid	Highest	High	Highest
Macdill Air Force Base	Hot-Humid	Highest	High	Highest
Maui Air National Guard Communications Station	Hot-Humid	Highest	High	Highest
Maxwell Air Force Base	Hot-Humid	Highest	High	Highest
Moody Air Force Base	Hot-Humid	Highest	High	Highest
Naval Air Station Joint Reserve Base	Hot-Humid	Highest	High	Highest
Patrick Space Force Base	Hot-Humid	Highest	High	Highest
Savannah Air National Guard Base	Hot-Humid	Highest	High	Highest
Seymour Johnson Air Force Base	Hot-Humid	Highest	High	Highest
Tyndall Air Force Base	Hot-Humid	Highest	High	Highest
Wheeler Army Airfield	Hot-Humid	Highest	High	Highest
Barksdale Air Force Base	Hot-Humid	Highest	High	High
Robins Air Force Base	Hot-Humid	Highest	High	High
Camp Mabry	Hot-Humid	Highest	High	Medium-High
Dallas Air Guard Station	Hot-Humid	Highest	High	Medium-High

Installation Name	Climate Zone	HVAC Condensate Potential	Atmospheric Harvesting Potential	Rainwater Harvesting Potential
Fort Worth Naval Air Station	Hot-Humid	Highest	High	Medium-High
NAS JRB Fort Worth	Hot-Humid	Highest	High	Medium-High
Joint Base San Antonio - Lackland	Hot-Humid	Highest	High	Medium
Joint Base San Antonio - Randolph	Hot-Humid	Highest	High	Medium
Camp Pendleton	Mixed-Humid	Highest	Medium	Highest
Ellington Field Joint Reserve Base	Mixed-Humid	Highest	Medium	Highest
Gulfport Combat Readiness Training Center	Mixed-Humid	Highest	Medium	Highest
Keesler Air Force Base	Mixed-Humid	Highest	Medium	Highest
Key Field	Mixed-Humid	Highest	Medium	Highest
McEntire Joint National Guard Base	Mixed-Humid	Highest	Medium	Highest
Shaw Air Force Base	Mixed-Humid	Highest	Medium	Highest
Alabama Air National Guard Base	Mixed-Humid	Highest	Medium	High
Dobbins Air Reserve Base	Mixed-Humid	Highest	Medium	High
Little Rock Air Force Base	Mixed-Humid	Highest	Medium	High
Pope Air Force Base	Cold	Highest	Low	Highest
Pope Army Air Field, Fort Bragg	Cold	Highest	Low	Highest
Arnold Air Force Base	Hot-Humid	High	High	High
Horsham Air Guard Station	Hot-Humid	High	High	High
Volunteer Air National Guard Station	Hot-Humid	High	High	High
Laughlin Air Force Base	Hot-Humid	High	High	Low
Joint Base Langley-Eustis	Mixed-Humid	High	Medium	Highest
Ebbing Air National Guard Base	Mixed-Humid	High	Medium	High
Louisville Air National Guard Base	Mixed-Humid	High	Medium	High
McGhee Tyson Air National Guard Base	Mixed-Humid	High	Medium	High
Memphis Air National Guard Base	Mixed-Humid	High	Medium	High
New London Air National Guard Base	Mixed-Humid	High	Medium	High
Tulsa Air National Guard Base	Mixed-Humid	High	Medium	High
Whiteman Air Force Base	Mixed-Humid	High	Medium	High
Yeager Air National Guard Base	Mixed-Humid	High	Medium	High
Berry Field	Mixed-Humid	High	Medium	Medium-High
Charlotte Air National Guard Base	Mixed-Humid	High	Medium	Medium-High
Delaware Air National Guard Base	Mixed-Humid	High	Medium	Medium-High
Dover Air Force Base	Mixed-Humid	High	Medium	Medium-High
Joint Base Andrews	Mixed-Humid	High	Medium	Medium-High
Scott Air Force Base	Mixed-Humid	High	Medium	Medium-High
Tinker Air Force Base	Mixed-Humid	High	Medium	Medium-High
Warfield Air National Guard Base	Mixed-Humid	High	Medium	Medium-High
Will Rogers Air National Guard Base	Mixed-Humid	High	Medium	Medium-High
Hulman Field	Cold	High	Low	Medium-High
Jefferson Barracks Air Guard Station	Very Cold	High	Low	Medium-High

Installation Name	Climate Zone	HVAC Condensate Potential	Atmospheric Harvesting Potential	Rainwater Harvesting Potential
Mcconnell Air Force Base	Cold	High	Low	Medium-High
Salina Air National Guard Detachment	Cold	High	Low	Medium-High
Springfield Air National Guard Base	Cold	High	Low	Medium-High
Stout Field	Cold	High	Low	Medium-High
Vance Air Force Base	Cold	High	Low	Medium-High
Sheppard Air Force Base	Cold	High	Low	Medium
Fort Dodge Air Guard Station	Hot-Humid	Medium-High	High	High
Blue Ash Air National Guard Station	Hot-Humid	Medium-High	High	Medium-High
Shepherd Field	Hot-Humid	Medium-High	High	Medium-High
Dyess Air Force Base	Hot-Humid	Medium-High	High	Medium
Des Moines Air National Guard Base	Mixed-Humid	Medium-High	Medium	Medium-High
Forbes Field	Mixed-Humid	Medium-High	Medium	Medium-High
Mansfield Lahm Air National Guard Base	Mixed-Humid	Medium-High	Medium	Medium-High
Rickenbacker Air National Guard Base	Mixed-Humid	Medium-High	Medium	Medium-High
Springfield-Beckly Air National Guard Base	Mixed-Humid	Medium-High	Medium	Medium-High
Toledo Express Air National Guard Base	Mixed-Humid	Medium-High	Medium	Medium-High
Wright-Patterson Air Force Base	Mixed-Humid	Medium-High	Medium	Medium-High
Altus Air Force Base	Mixed-Humid	Medium-High	Medium	Medium
Port Clinton Air National Guard Base	Mixed-Humid	Medium-High	Medium	0
Rosecrans Air National Guard Base	Cold	Medium-High	Low	High
Air Station Fort Indiantown Gap	Cold	Medium-High	Low	Medium-High
Air Station Middletown	Cold	Medium-High	Low	Medium-High
Bradley Air National Guard Base	Cold	Medium-High	Low	Medium-High
Fort Wayne Air National Guard Base	Cold	Medium-High	Low	Medium-High
Francis S. Gabreski Air National Guard Base	Cold	Medium-High	Low	Medium-High
Grissom Air Reserve Base	Cold	Medium-High	Low	Medium-High
Nebraska Air National Guard Base	Cold	Medium-High	Low	Medium-High
North Smithfield Air Guard Station	Cold	Medium-High	Low	Medium-High
Offutt Air Force Base	Cold	Medium-High	Low	Medium-High
Orange Air National Guard Station	Cold	Medium-High	Low	Medium-High
Peoria Air National Guard Base	Cold	Medium-High	Low	Medium-High
Pittsburgh Air National Guard Base	Cold	Medium-High	Low	Medium-High
Pittsburgh IAP Air Reserve Station	Cold	Medium-High	Low	Medium-High
Youngstown Air Reserve Base	Cold	Medium-High	Low	Medium-High
Zanesville Air National Guard Base	Cold	Medium-High	Low	Medium-High
Goodfellow Air Force Base	Hot-Dry	Medium-High	Low	Medium
Sioux City Air National Guard Base	Cold	Medium-High	Low	Medium
Los Angeles Air Force Base	Hot-Dry	Medium-High	Low	Lowest
San Diego Air National Guard Station	Hot-Dry	Medium-High	Low	Lowest

Installation Name	Climate Zone	HVAC Condensate Potential	Atmospheric Harvesting Potential	Rainwater Harvesting Potential
Johnstown Air National Guard Station	Cold	Medium	Low	High
Air Station State College	Cold	Medium	Low	Medium-High
Barnes Air National Guard Base	Cold	Medium	Low	Medium-High
General Mitchell Field	Cold	Medium	Low	Medium-High
Hancock Field	Cold	Medium	Low	Medium-High
Niagara Falls Air Reserve Station	Cold	Medium	Low	Medium-High
Stewart Air National Guard Base	Hot-Dry	Medium	Low	Medium-High
Stratton Air National Guard Base	Cold	Medium	Low	Medium-High
Truax Field	Cold	Medium	Low	Medium-High
Westover Air Reserve Base	Cold	Medium	Low	Medium-High
Minneapolis IAP Air Reserve Station	Cold	Medium	Low	Medium
Minneapolis/St. Paul Air National Guard Base	Cold	Medium	Low	Medium
Selfridge Air National Guard Base	Cold	Medium	Low	Medium
Volk Field	Very Cold	Medium	Low	Medium
Joe Foss Field	Cold	Medium	Low	Low
Channel Islands Air Guard Station	Marine	Medium	Low	Lowest
March Air Reserve Base	Hot-Dry	Medium	Low	Lowest
Sepulveda Air Guard Station	Hot-Dry	Medium	Low	Lowest
South Portland Air Guard Station	Cold	Medium-Low	Low	Medium-High
Alpena Combat Readiness Training Center	Cold	Medium-Low	Low	Medium
Cannon Air Force Base	Mixed-Dry	Medium-Low	Low	Low
Davis-Monthan Air Force Base	Hot-Dry	Medium-Low	Low	Low
Tucson Air National Guard Base	Hot-Dry	Medium-Low	Low	Low
Luke Air Force Base	Hot-Dry	Medium-Low	Low	Lowest
Phoenix Air National Guard Base	Hot-Dry	Medium-Low	Low	Lowest
Camp Rilea	Marine	Low	Low	High
Portland Air National Guard Base	Marine	Low	Low	Medium-High
Portland Air National Guard Station	Marine	Low	Low	Medium-High
Beale Air Force Base	Hot-Dry	Low	Low	Medium
Duluth Air National Guard Base	Very Cold	Low	Low	Medium
Hector Field	Cold	Low	Low	Low
Moffett Federal Airfield	Marine	Low	Low	Low
North Highlands Air Guard Station	Hot-Dry	Low	Low	Low
Travis Air Force Base	Hot-Dry	Low	Low	Low
Vandenberg Space Force Base	Marine	Low	Low	Low
Fort Bliss	Cold	Low	Low	Lowest
Fresno Air National Guard Base	Hot-Dry	Low	Low	Lowest
Holloman Air Force Base	Mixed-Dry	Low	Low	Lowest
Kingsley Field Air National Guard Base	Cold	Low	Low	Lowest
Camp Murray Air Guard Station	Hot-Humid	Lowest	High	Medium-High

Installation Name	Climate Zone	HVAC Condensate Potential	Atmospheric Harvesting Potential	Rainwater Harvesting Potential
Joint Base Lewis-Mcchord	Hot-Humid	Lowest	High	Medium-High
Mountain Home Air Force Base	Hot-Humid	Lowest	High	Lowest
Ellsworth Air Force Base	Mixed-Humid	Lowest	Medium	Low
Nellis Air Force Base	Mixed-Humid	Lowest	Medium	Lowest
Buckley Space Force Base	Cold	Lowest	Low	Low
F. E. Warren Air Force Base	Cold	Lowest	Low	Low
Grand Forks Air Force Base	Very Cold	Lowest	Low	Low
Greeley Air Guard Station	Cold	Lowest	Low	Low
Joint Base Elmendorf-Richardson	Very Cold	Lowest	Low	Low
Minot Air Force Base	Very Cold	Lowest	Low	Low
Peterson Space Force Base	Cold	Lowest	Low	Low
Schriever Space Force Base	Cold	Lowest	Low	Low
U.S. Air Force Academy	Cold	Lowest	Low	Low
Wyoming Air National Guard Base	Cold	Lowest	Low	Low
Creech Air Force Base	Cold	Lowest	Low	Lowest
Edwards Air Force Base	Hot-Dry	Lowest	Low	Lowest
Eielson Air Force Base	Subarctic	Lowest	Low	Lowest
Fairchild Air Force Base	Cold	Lowest	Low	Lowest
Gowen Field	Cold	Lowest	Low	Lowest
Hill Air Force Base	Cold	Lowest	Low	Lowest
Kirtland Air Force Base	Mixed-Dry	Lowest	Low	Lowest
Malmstrom Air Force Base	Cold	Lowest	Low	Lowest
Montana Air National Guard Base	Cold	Lowest	Low	Lowest
Nevada Air National Guard Base	Cold	Lowest	Low	Lowest
Utah Air National Guard Base	Cold	Lowest	Low	Lowest
Quonset Air National Guard Base	Hot-Humid	#N/A	High	0
Atlantic City Air National Guard Base	Mixed-Humid	#N/A	Medium	0
Battle Creek Air National Guard Base	Mixed-Humid	#N/A	Medium	0
Joint Base Mcguire-Dix-Lakehurst	Mixed-Humid	#N/A	Medium	0
McGuire Air Force Base	Mixed-Humid	#N/A	Medium	0
Andersen Air Force Base	#N/A	#N/A	Low	0
Bangor Air National Guard Base	Cold	#N/A	Low	0
Burlington Air National Guard Base	Cold	#N/A	Low	0
Hanscom Air Force Base	Cold	#N/A	Low	0
Muñiz Air National Guard Base	#N/A	#N/A	Low	0
Northfield Air National Guard Station	Cold	#N/A	Low	0
Otis Air National Guard Base	Cold	#N/A	Low	0
Pease Air National Guard Base	Cold	#N/A	Low	0
Punta Borinquen Radar Site	#N/A	#N/A	Low	0
Punta Salinas Air Guard Station	#N/A	#N/A	Low	0
St Croix Air Guard Station	#N/A	#N/A	Low	0

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