Pacific Northwest
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Water Savings Potential of Implementing Alternative Cooling Technologies

June 2022

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Principal Investigator: Brian K Boyd
Project Manager: Kate LM Stoughton

U.S. DEPARTMENT OF ENERGY

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Prepared for
the Alliance for Water Efficiency
under PNNL Agreement No. 71685

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Richland, Washington 99354

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Acronyms and Abbreviations

AWE	Alliance for Water Efficiency
HSC	hygroscopic cooling
HVAC	Heating, ventilation, and air-conditioning
MPM	Market penetration model
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
SAWS	San Antonio Water System
TMD	thermal membrane distillation
TSC	thermosyphon cooling
UND	University of North Dakota

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Executive Summary

Removing heat for occupant comfort or process cooling purposes is an important function in many commercial buildings and industrial locations. The physical properties of water make it an attractive and efficient working fluid in comparison to air-based cooling systems. Historically, the perception of water as an endless resource and the general ease of access have allowed water to be relatively inexpensive. Our built environment has taken advantage of the heat transfer and evaporative cooling properties and low cost of water for mechanical cooling systems. Large cooling towers are a common feature of these systems and are a hidden workhorse of our industrialized society. Water scarcity and water conservation have become more of a priority in recent years, and a single cooling tower system for a 100,000 square foot office building can use over a quarter-million gallons per year even in a mild climate region. For a community of 200,000 this can add up to over 250 million gallons of water used per year.

Pacific Northwest National Lab (PNNL) teamed up with the Alliance for Water Efficiency (AWE) in an effort to help quantify the number of cooling towers in a utility service territory and to identify conservation opportunities of these cooling tower systems on a community scale. Our subject matter experts and research teams at PNNL worked with industry experts at AWE to complete a variety of research tasks towards these ends. As a result of this collaboration a first of its kind Cooling Tower Estimating Model (CTEM) was developed using publicly available data to estimate the number, size, and usage of cooling towers in a community based on basic input data. CTEM also allows the user to adjust key model parameters as well as determine water savings potential from increasing system efficiency. Alongside CTEM, the teams at PNNL and AWE produced a guidebook to help a community understand and identify cooling towers, and to use CTEM to estimate cooling tower water use in the region and begin to establish an inventory of locations likely to have cooling towers.

As a follow on to CTEM, the sustainability engineers at PNNL established a market penetration model (MPM) to evaluate water savings potential from deploying alternative technologies to cooling towers proposed by AWE and their member organizations. The four most promising alternative cooling tower technologies at or near ready for market deployment at the time of the study were thermosyphon cooling (TSC), hygroscopic cooling (HSC), adiabatic cooling (AC), and thermal membrane distillation (TMD). This document outlines the alternative cooling tower technologies chosen for analysis, provides an overview of the CTEM and market penetration methodology, and details an example case study for the San Antonio metropolitan area.

The San Antonio case study was completed using a total service population of 2 million with CTEM showing an estimated cooling tower water use at 5.4 billion gallons per year. With those CTEM results estimates entered in the MPM, two technology mix scenarios (equal distribution and optimized) were then compared. Both technology mix scenarios showed similar water savings potentials around 7% (or 400 million gallons per year) by 2030, however, the optimized scenario showed an estimated investment cost over $10 million less than the equal distribution scenario. The MPM was designed such that other locations can enter their CTEM results, adjust the technology mixes in the two scenarios, and tailor their own market penetration estimates.

It must be noted that with substantial savings in water use in cooling systems tradeoffs such as capital and reoccurring expenses and increases in energy use are expected. These studies did not perform rigorous economic evaluations such as life cycle costing (LCC) or techno economic analysis (TEA), therefore we recommend additional economic analysis be completed before any programs are established. However, plans for future iterations of both CTEM and its companion

MPM and guidebooks to include energy use estimates for cooling tower systems and their alternative technologies is underway.

1.0 Introduction

The Alliance for Water Efficiency (AWE) contracted with Pacific Northwest National Laboratory (PNNL) to explore the potential for water conservation in urban areas through improvements to cooling tower systems. The overarching purpose of this study is to gain foundational knowledge needed to create effective, targeted, and appealing incentive and outreach programs to improve efficiency in cooling tower systems.

The five main objectives of the study are as follows:

1. Develop best practices for identifying water-cooled facilities in urban areas
2. Develop best practices for estimating consumptive and non-consumptive water demands for cooling
3. Determine the conservation potential for improvements to traditional cooling technologies such as cooling towers
4. Determine the water savings potential of alternative cooling technologies
5. Develop practical guides, incorporating study results, to increase the effectiveness of cooling water use efficiency incentive and outreach programs.

This document focuses on the fourth objective—determining the water savings potential of alternative cooling technologies. The study aims at informing the adoption of alternative cooling technologies in a water supplier's service territory, to create effective and targeted incentive and outreach programs for reduced water use of cooling towers in their area. The analysis included the following elements:

- Review of commercially available cooling technologies that could offset or replace traditional cooling towers
- Selection of the top four alternative cooling technologies
- Construction a market penetration model to evaluates the adoption of the alternative cooling technologies and estimates the associated the water savings potential.
- Estimation of water savings potential of the four selected technologies for San Antonio Water System (SAWS) service territory as a case study provide an example of the analysis model

The document provides an overview of the four selected alternative cooling technologies, description of the market penetration model that was developed, and the results of the SAWS case study.

1.1 Cooling Tower Basics

To understand the potential benefits of the selected alternative cooling technologies, it is useful to understand the basics of a cooling tower. A cooling tower takes the heat rejected from an air conditioning compressor/chiller or an industrial process and dissipates that heat by evaporating water in the cooling tower. The cooling tower takes warm water, heated by waste heat from buildings or industrial processes, and evaporates that water using pumps, fans, and special media designed to expose the warm water to cool air. It then collects the cool water condensate and returns it to the heat source for another round of cooling (Figure 1). This evaporative cooling process is essentially the same cooling effect when getting out a pool or lake on a windy day. The instant sensation of getting colder is due to water evaporating off your skin when the air blows across the water droplets, lowering the water's temperature.

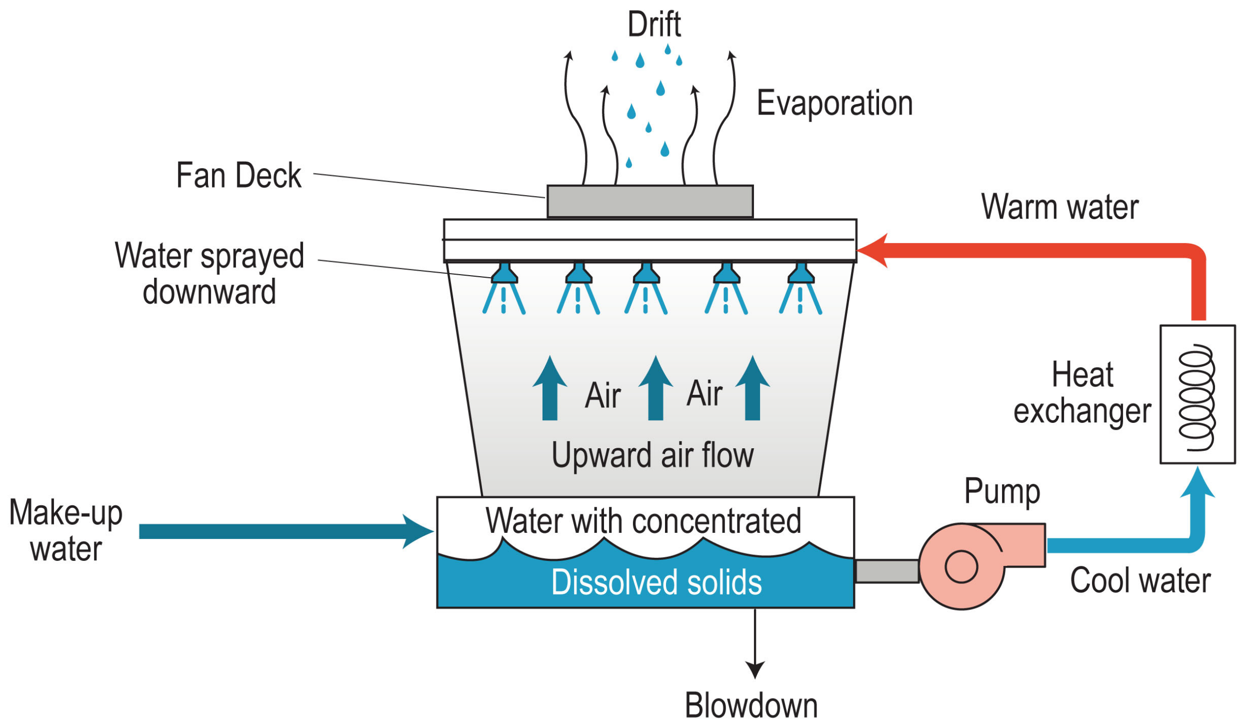


Figure 1. Cooling Tower Diagram

Water must be discharged (blowdown) to keep the minerals and salts, that remain behind as the water evaporates, from building to levels that cause both scaling (hardness) and corrosion of metal components of the cooling tower. Water must be continuously added to make up for the evaporation and blowdown.

Related to make-up and blowdown, another important concept to understand is cycles of concentration. Cycles of concentration is the ratio of concentration of dissolved solids in the blowdown water to that of the make-up water. Cycles of concentration measures the approximate number of times a given amount of water of a certain quality can circulate through the cooling tower before the mineral concentration accumulates such that the evaporation of additional water would leave unwanted deposits of minerals and other material on cooling tower system components, thereby reducing its overall efficiency.

2.0 Alternative Cooling Technologies

A variety of alternative cooling technologies were recommended for consideration for this task. Ultimately, four technologies that met the high-level criteria were selected through iterative conversations between PNNL and AWE team members for the initial analysis in the MPM. This section of the report provides an overview of this process and a technology description, appropriate applications, water savings potential, and cost data for the selected technologies.

2.1 Technology Selection

PNNL and AWE requested suggestions for alternative cooling technologies from the utility partners to formulate an initial list of candidate alternative cooling technologies. The three criteria requirements for these technologies were that they must be:

- Commercially available
- Verified water savings performance
- Published capital costs

The utility partners recommended the following alternative technologies for further consideration (listed alphabetically):

- Adiabatic cooling
- Air cooled direct expansion and variable refrigeration flow/volume systems
- Air side economizer
- Building load reduction
- Desiccant systems
- District cooling
- Dry cooling
- Electrochemical
- Geothermal
- Non-evaporative single-pass with indirect reuse
- Passive cooling systems
- Plume abatement
- Radial deionization
- Radiative cooling
- Recovery of compressor heat to heat water for domestic use
- Solar assisted cooling systems
- Solid-state cooling
- Thermal membrane distillation with geothermal energy pairing
- Thermosyphon hybrid cooling

- Tree canopy to provide shading
- Water side economizer

PNNL researched available published data on these technologies to determine if there was adequate data available, had significant water savings potential, and broad applicability for replacing or augmenting traditional cooling tower systems. PNNL researchers documented their findings and discussed them with the AWE team to identify the best candidate technologies to initially analyze in the MPM. Through this process, the following four alternative cooling technologies were selected:

- Thermosyphon hybrid cooling
- Hygroscopic cooling
- Thermal membrane distillation
- Adiabatic cooling

Plume abatement was also researched and found to have a good potential for water reduction but did not make the final selection. A short description is included on plume abatement to provide an overview of the technology, but is it not included in the market penetration model.

2.2 Thermosyphon Cooling

A thermosyphon cooling (TSC) is an advanced dry cooler that uses refrigerant in a passive cycle to dissipate heat. This type of technology is a hybrid heat-rejection system, which optimizes the use of two cooling technologies—one wet (an open cooling tower) and one dry (a thermosyphon cooler unit)—in a single, integrated operating system.

Figure 2 shows a thermosyphon system and schematic. The system precools heated water through a passive heat exchanger based on natural convection. As shown in Figure 2 schematic, the refrigerant liquid sinks to the bottom of the system and the refrigerant vapor “floats” to the top, whereby natural convection moves the warmer vapors up (“heat rises”). This process allows the refrigerant to cool as it circulates naturally between the unit’s evaporator and condenser without the need for any compressors or pumps.

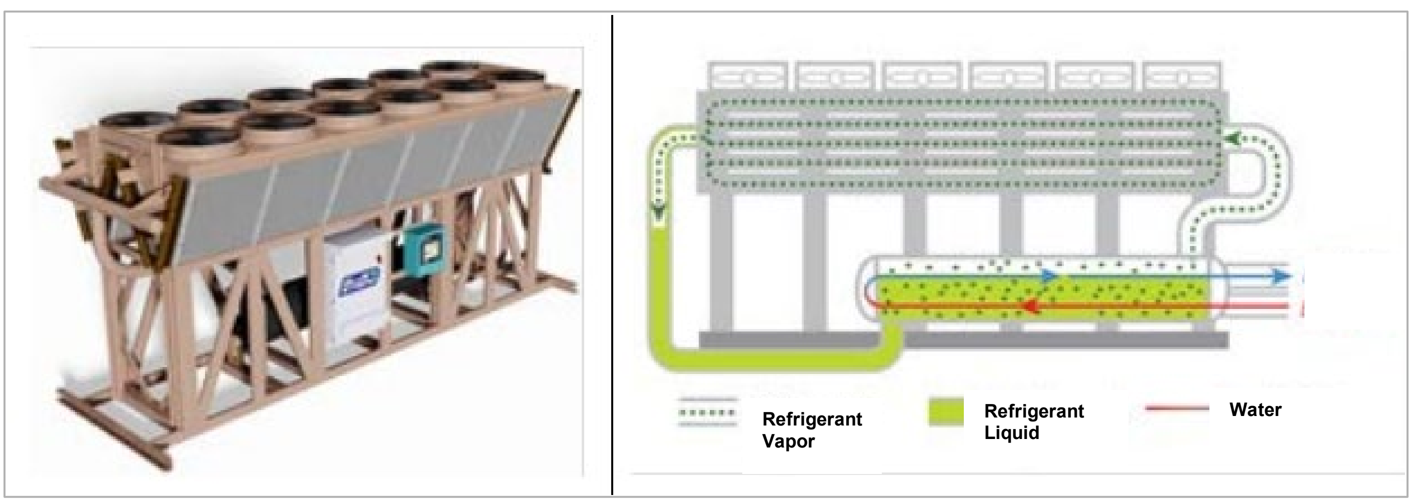


Figure 2. TSC System and Schematic (Source: NREL 2018)

The TSC fans automatically modulate to use the most efficient combination of water and air-cooled systems in response to utility rates, ambient and system temperatures, and system loads. This allows the TSC to operate in a highly efficient manner across a vast range of weather and load conditions. The system's modular design is highly scalable, with the ability to incrementally add multiple units in parallel to handle the largest cooling requirements, therefore appropriate for many applications. The TSC can also be used as an efficient dry water-side economizer in combination with a traditional cooling tower or deployed as a stand-alone dry cooler.

TSC can reduce total annual water volume consumption when used in combination with a traditional cooling tower. A study was conducted by the Electric Power Research Institute to examine water saving potential for hybrid systems that combine traditional cooling towers with thermosyphon technology. The study found that in a mild climate (San Luis Obispo, California), total water volume savings ranges from 30% to 88%. In a hot and arid climate (Yuma, Arizona), total water volume savings ranges from 15% to 71% (Carter *et al.*, 2013). The substantial range of water savings potential is due to wide variance in the control strategy, including the maximum allowable system pressure and the thermosyphon fan speed.

2.3 Hygroscopic Cooling

A hygroscopic cooling (HSC) works similarly to a traditional cooling tower, but instead of pure water as the cooling fluid, a hygroscopic liquid desiccant fluid is used, such as calcium chloride (CaCl2) mixed with water. In a traditional cooling tower, most of the heat is transferred through evaporation, mainly driven by outdoor conditions such as relative humidity. Hygroscopic coolers however transfer more heat through convection rather than evaporation when the outdoor air is cooler than the temperature set point of the system. When outdoor air temperature exceeds this threshold, the system switches to evaporative cooling. The system can be controlled to optimize this process, thereby reducing water use by reducing the amount of evaporation (Figure 3). HSC systems also save water through the elimination of blowdown. Unlike traditional cooling towers, hygroscopic coolers remove dissolved solids by precipitating and then filtering the solids out of the fluid for reuse.

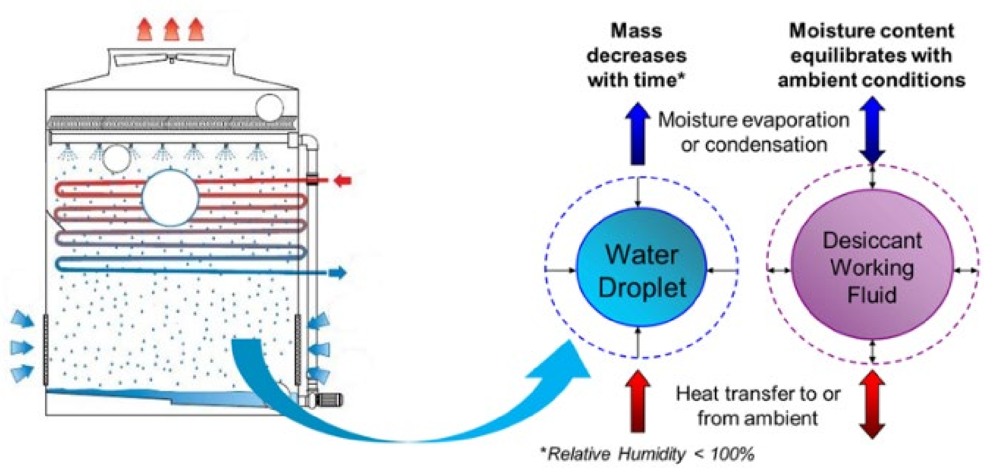


Figure 3. HSC Tower Diagram (Source: University of North Dakota, 2018)

The University of North Dakota performed a study of HSC towers for the Department of Defense Environmental Security Technology Certification Program. The study aimed to test this technology to determine the water savings potential. The study found that by increasing the cycles of concentration from 4 to 20, a hygroscopic cooler can theoretically achieve a 30%-50% water savings, and case study findings of 36% water savings in a mild climate (Monterey Bay, California) and 31% water savings a warm-dry climate (Fort Irwin, California).

The study found that HSC systems provide the biggest water savings to areas with poor water quality, where cycles of concentration higher than 5 are hard to achieve. Also, these systems were found to be most appropriate in applications that require operation when ambient air temperatures drop below system's set point. In other words, the application requires cooling even when the outdoor temperature is cooler than the set point. This is typically caused by internal loads in the building, called "latent loads", such as people and equipment that produce heat. If cooling it typically only required during peak outside temperatures, these systems will have lower water savings potential. (University of North Dakota 2018)

2.4 Adiabatic Cooling

Adiabatic cooling systems work by using evaporation to pre-cool the air flowing through a closed loop coil. Adiabatic coolers run in two modes: wet (or "pre-cooler") operation and dry operation Figure 4. Wet operation is only activated during peak demand conditions (e.g. times of high outdoor temperatures and/or during high internal cooling loads conditions). A fan draws warm air through an adiabatic unit where humidity is added to the air. When the humidity comes into contact with the warm air, water evaporates and heat is dissipated, similar to how a swamp cooler works. When outdoor temperatures are low and cooling loads are minimal, the system operates in dry mode, operating similar to a conventional finned dry cooler where heat is dissipated to the ambient air via convection.

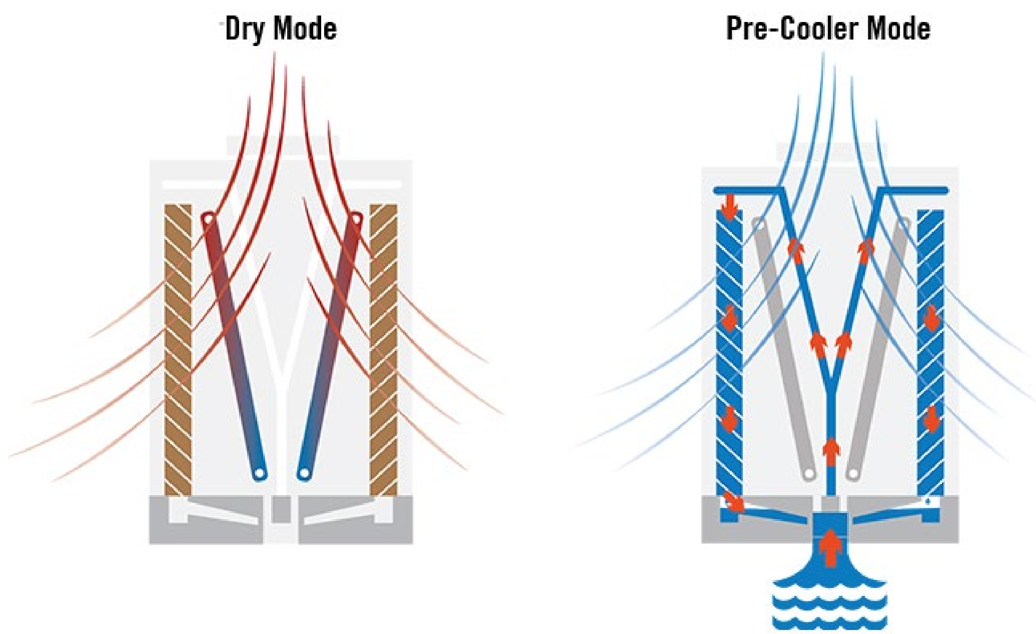


Figure 4. Adiabatic Cooling Schematic (Source: BAC)[1]

[1] Image from Baltimore Cooling Company: http://www.baltimoreaircoil.com/english/products/hybrid/trilliumseries/modes-of-operation

Adiabatic systems can be closely controlled, which optimizes the system between the two operation modes. Water is only used when conditions require evaporative cooling, thereby reducing water demand compared to traditional cooling towers. Adiabatic cooling systems have a wide range of water savings because water use is heavily influenced on the operating conditions and how the system is controlled. The expected range of water savings is between 25% to 75% (Cohen, 2019). These systems do not circulate water, which has the added benefit of no water treatment reducing operation costs.

2.5 Thermal Membrane Distillation

Thermal membrane distillation (TMD) is a water treatment option for cooling-tower blowdown water, which can be reused in cooling-tower makeup thereby reducing the use of freshwater supply. Membrane distillation is a separation process that works by filtering water through a hydrophobic membrane, which only allows the passage of water vapor through the membrane's pores. The process works by heating the blowdown water, which causes a phase change from vapor to liquid, resulting in a pressure change that drives the vapor across the membrane. The vapor condenses to clean liquid water as "product water", which can be reused in the system. Figure 5 shows the use of geothermal production wells that provide low temperature geothermal energy (<90ºC) to heat the source water. This geothermal energy can be used to power the TMD process in areas where geothermal energy is available[1]. Membrane distillation systems can be configured for a single pass or with source-water recirculation to achieve high recovery.

[1] The cost to install a production well for geothermal energy was not included in the market penetration analysis.

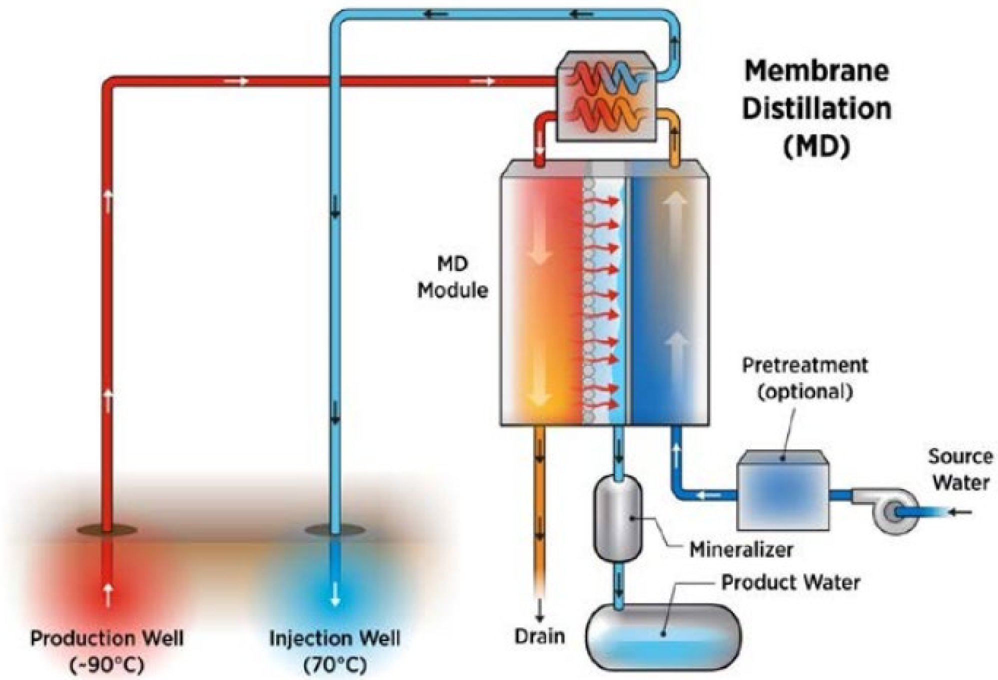


Figure 5. Thermal Membrane Distillation with Geothermal Energy (Source: NREL 2016)

Yu et al. performed an experiment using direct contact membrane distillation in cooling towers. This research reported a water savings potential range of 68% to 87%, without and with the use of additional chemical treatment respectively (Yu 2013). Ma *et al.* built a cooling tower simulation model that reported 29% makeup water volume savings by implementing TMD in a cooling tower system (Ma 2018). The large range in water savings between the two studies is due to the 2013 Yu study is a theoretically achievable water savings potential while the 2018 Ma study is based on industry practices and case study averages.

2.6 Plume Abatement

Plume abatement was not selected as one of the top four alternative cooling technologies because adequate data was not available from academic resources to run the market penetration model. However, this technology may be a viable option for water suppliers to adopt, therefore this information is meant to provide an overview of the technology for consideration.

Plume abatement is a technology that captures water vapor from a cooling tower's plume. A plume is formed when the relative humidity of the air leaving the tower is greater than 100%. The excess water vapor condenses into fine droplets that are suspended in the air to form fog, otherwise known as a visible plume. Evaporation from cooling towers is a predominant cause of plume formation (Wang *et al.*, 2019). Plume abatement technology cools the plume through an air-to-air heat exchanger to condense the water vapor to liquid water, which is then collected in the tower's basin. An auxiliary fan introduces cooler ambient air across the cooling tower to cool and condense the plume (Figure 6). This technology is also called a "hybrid" or wet/dry cooling tower because an air-to-air heat exchanger is used.

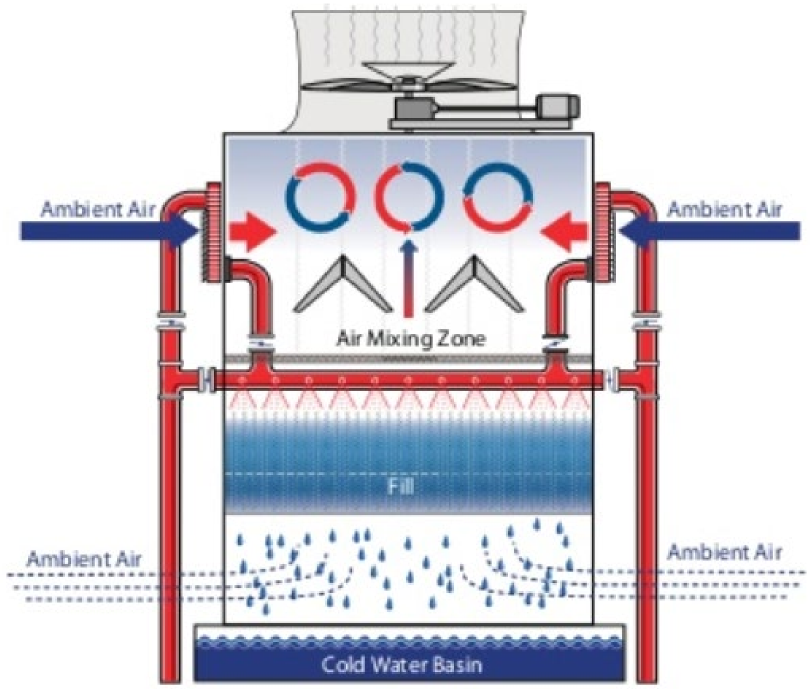


Figure 6. Cooling Tower Plume Abatement Diagram (Source: Cooling Tower Depot)[1]

Deziani et al conducted a study to determine the potential reduction of evaporative losses from plume abatement technology. The study was conducted in a laboratory by implementing an air to air heat exchanger that contacted warm-wet air released from a cooling tower with relatively drier and cooler ambient air. The laboratory results indicate about 35% of evaporation (plume) reductions, depending on the ambient air conditions (Deziani 2017).

[1] Image is from the Cooling Tower Depot Capabilities Brochure: http://www.coolingtowerdepot.com/content/free-tools/library_full

2.7 Water Savings and Cost Data

Based on the published, third party resources the water savings potential for the selected alternative cooling technologies are presented in Table 1.

Table 1. Water Savings Potential and Investment Cost of Alternative Cooling Technologies

Alternative Cooling Technology	**Capital Cost ($/ton)**	**Climate**	**Water Savings Potential**	**Operating Costs – Non-Electricity Related ($/ton/year)**	**Primary Data Source**
Thermosyphon Cooling – Hybrid System	$518	Hot & Arid	15%-71%	Undetermined	Carter et al. 2013
		Moderate	30%-88%	Undetermined	Carter et al. 2013
Hygroscopic Cooling – Hybrid System	$344	Hot & Arid	31%	$66	UND 2018
		Moderate	36%	$85	UND 2018
		Theoretical	30%-50%		UND 2018
Adiabatic Cooler	$640	Lab	50	Undetermined	Cohen 2019
Thermal Membrane Distillation – Hybrid System	$26	Modeled, Lab	29%-87%	$10	Ma 2018, Yu 2019

3.0 Market Penetration Model

The study's main objective is to assess the adoption of alternative cooling technologies and associated water savings potential in a water supplier's service territory. To this end, the sustainability engineering research team at PNNL used their previous experience developing novel market penetration methods. The analysis also included using technical diffusion, production and consumption growth curve models, and a sensitivity analysis.

- Market penetration is the measurement of how much a product is being adopted in a market compared to the total market of that product.
- Technical diffusion is a process that examines the how innovative products are adopted by a population over time.
- Growth curve models studies a data over time to predict the patterns or behaviors of the dataset.
- Sensitivity analysis is a technique that is used to compare different analysis results by changing variables, which helps to reveal the impact of the variable to the results.

These methods were used in combination to develop a systems-level modeling framework. The results of the of the analyses show that the likely size of the market penetration by these alternative cooling technologies is 27% of the total cooling tower market in any given water utility. The range of market penetration was 3% to 63%, based on the growth curve model results. See the Appendix for more information on the analyses.

Based on the outcomes of the analyses, PNNL built an Excel based model for estimating the water savings potential of the four selected alternative water technologies over time for a given utility's service territory. The market penetration model uses outputs from the Cooling Tower Estimating Model (CTEM)[1]: the number of cooling towers and estimated associated water use in a water provider's service territory. These outputs form the baseline for the Market Penetration Model. Figure 7, below, provides an example of these inputs.

[1] CTEM is a model produced by PNNL as part of the AWE Cooling Tower Study, which is an Excel based model that estimates the number of cooling towers and associated water use for a given water supplier's service territory.

	Units	Large/Industrial Facilities w/CTs	Commercial Facilities w/CTs	Total Facilities w/CTs
Number of Facilities with Cooling Towers in 2021 (CTEM output)	*# facilities*	209	3,283	3,492
Expected Number of Cooling Tower Facilities in 2031 (Rough Estimate)	*# facilities*	209	3,283	3,492
Number of Cooling Towers in 2021 (CTEM output)	*# towers*	1,755	6,481	8,236
Expected Number of Cooling Towers in 2031 (Rough Estimate)	*# towers*	1,755	6,481	8,236
Capacity of Cooling Towers in 2021 (CTEM output)	*cooling tons*	575,436	2,124,626	2,700,062
Expected Cooling Tower Capacity in 2031 (Rough Estimate)	*cooling tons*	575,436	2,124,626	2,700,062
Annual Load of Cooling Towers in 2021 (CTEM output)	*cooling ton-hours/year*	443,350,033	1,636,942,010	2,080,292,043
Expected 2030 Cooling Tower Annual Load (Rough Estimate)	*cooling ton-hours/year*	443,350,033	1,636,942,010	2,080,292,043
Annual Consumptive Water Use of Cooling Towers in 2021 (CTEM output)	*Mgal/year*	724	2,827	3,551
Annual Non-Consumptive Water Use of Cooling Towers in 2021 (CTEM output)	*Mgal/year*	279	835	1,114
Annual Total Water Use of Cooling Towers in 2021 (CTEM output)	*Mgal/year*	1,003	3,662	4,665
Expected 2030 Cooling Tower Annual Water Use Without Intervention (Rough Estimate)	*Mgal/year*	1,003	3,662	4,665

Figure 7. Example Market Penetration Inputs

The tool also allows the user to specify the anticipated growth (expressed as a percentage) of the cooling demand met by cooling towers for their service territory. For example, an anticipated growth of 0% for a starting year of 2023 would mean the overall cooling demand would remain unchanged (no increase or decrease), and a 20% increase would correlate directly to a 20% increase in water use to meet the user input cooling demand increase. The example 20% increase is shown in Figure 8, below, graphically illustrating the numbers from Figure 7, above.

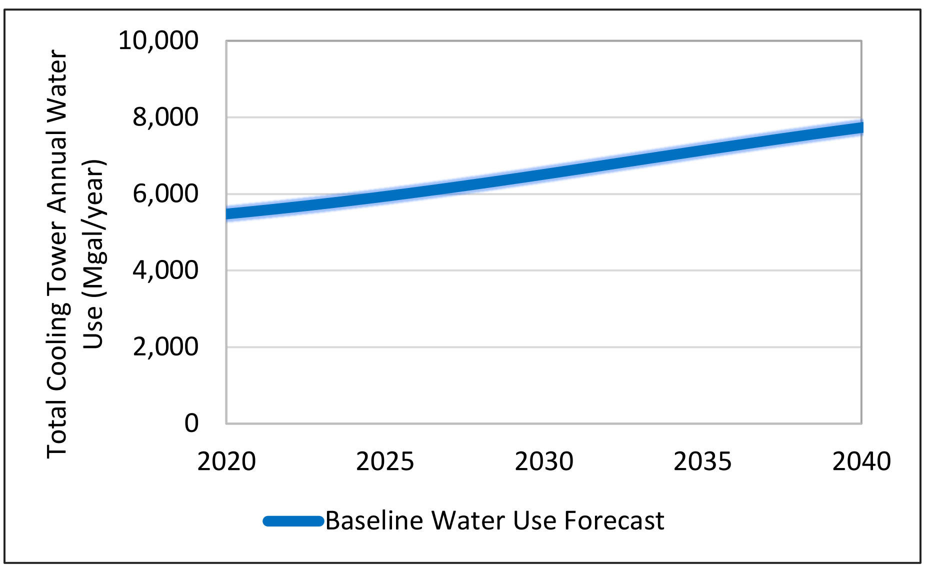


Figure 8. Example Baseline Water Use Forecast

With this baseline, the model allows the user to investigate four different alternative cooling technologies at a time, as selected from the drop-down menu at the top of the Alt Techs Details tab (highlighted in the red box in Figure 9).

Technologies for Reducing Cooling Tower Water Use **Select from Dropdown Menus Below** (Model can process only 4 technologies at a time)	Capacity (tons)	Water Savings (mid)	Water Savings (low)	Water Savings (high)
Adiabatic Cooler (AC)	500	50%	25%	75%
Water Recapture System	500	20%	10%	30%
Salt-Based Ion Exchange	500	24%	23%	24%
Continuous Monitoring and Partial Water Softening	500	15%	14%	16%

Technologies for Reducing Cooling Tower Water Use (For use in table above for model inputs) (Add details for additional technologies for use in model in blank rows)	Capacity (tons)	Water Savings (mid)	Water Savings (low)	Water Savings (high)
Thermosyphon Cooler (TSC) – Hybrid System	500	50%	11%	87%
Hygroscopic Cooler (HSC) – Hybrid System	500	34%	28%	40%
Adiabatic Cooler (AC)	500	50%	25%	75%
Thermal Membrane Distillation (TMD)	500	58%	29%	87%
Continuous Monitoring and Partial Water Softening	500	15%	14%	16%
Water Recapture System	500	20%	10%	30%
Salt-Based Ion Exchange	500	24%	23%	24%
Advanced Oxidation	500	26%	23%	30%
N/A				
*add addition alt-tech data here				
*add addition alt-tech data here				
*add addition alt-tech data here				

Service Territory CT Baseline | **CT Alt-Tech Details** | CT Market Penetration Worksheet

Figure 9. Alternative Technology Selection Illustration

The tool compares the projected savings and overall impact of the selected technologies for two adoption rate scenarios in the Market Penetration Worksheet tab. On this page of the model, the user enters the adoption goal for each alternative cooling technology for both large facilities and commercial buildings. Table 2, below, provides an example of two variations of a 20% overall adoption rate. Scenario 1 applies a 5% uniform or equal adoption rate for each of the four alternative technologies, while scenario 2 targets only salt-based ion exchange for the same overall adoption rate. The inputs can be altered iteratively and varied to optimize the outputs.

Table 2. Adoption Rate Scenario Example

	Scenario 1: Equal Adoption		**Scenario 2: Focused Adoption**	
Alternative Technology	**Large Facilities**	**Commercial Facilities**	**Large Facilities**	**Commercial Facilities**
Adiabatic Cooler	5%	5%	0%	0%
Water Recapture System	5%	5%	0%	0%
Salt-Based Ion Exchange	5%	5%	20%	20%
Continuous Monitoring and Partial Water Softening	5%	5%	0%	0%
Total Adoption Rate	20%	20%	20%	20%

Based on these inputs, the tool provides graphic trends for water savings projections and energy impact for the selected scenarios and provides a summary table for the forecast results.

The output of the model provides the estimated water use of cooling systems under these scenarios. Main model outputs include: (See Section 4.0 for example inputs and outputs from the SAWS case study.)

Water Use Over Time Chart: A chart is generated by the model that provides the baseline water use of the water supplier's cooling towers without adoption of alternative cooling technologies compared the water use for both scenarios 1 and 2. The chart shows these water use patterns from 2020 through 2050. The market penetration curve of the alternative technologies show water use is impacted by the adoption of the technology under the two scenarios.

Technology Investment Over Time Chart: A second chart is generated by the model that provides an estimated investment requirement to implement the alternative technology from 2020 through 2050. This chart is a growth curve that reveals the impact of the investment and how it relates to the water consumption over the same time period.

The outputs of the market penetration model can help water suppliers in determining the impact of investments made for specific alternative cooling technologies. Comparing the water use over time and investments over time under each scenario, the water supplier can select the technology that will make the largest impact on water use and the required investment needed to produce the outcome. This information can help to inform the most effective rebate or incentive programs for these specific technologies.

4.0 Case Study Results

PNNL conducted a test of the market penetration model using the SAWS's service territory (using Bexar County, Texas data) to estimate the water savings potential of the four selected technologies. First, PNNL used CTEM to determine the number of cooling towers and estimated associated water use in Bexar County. Figure 10 shows the inputs used in the CTEM for SAWS. Figure 11 shows the outputs generated by CTEM, which are needed to estimate water savings of the four selected technologies.

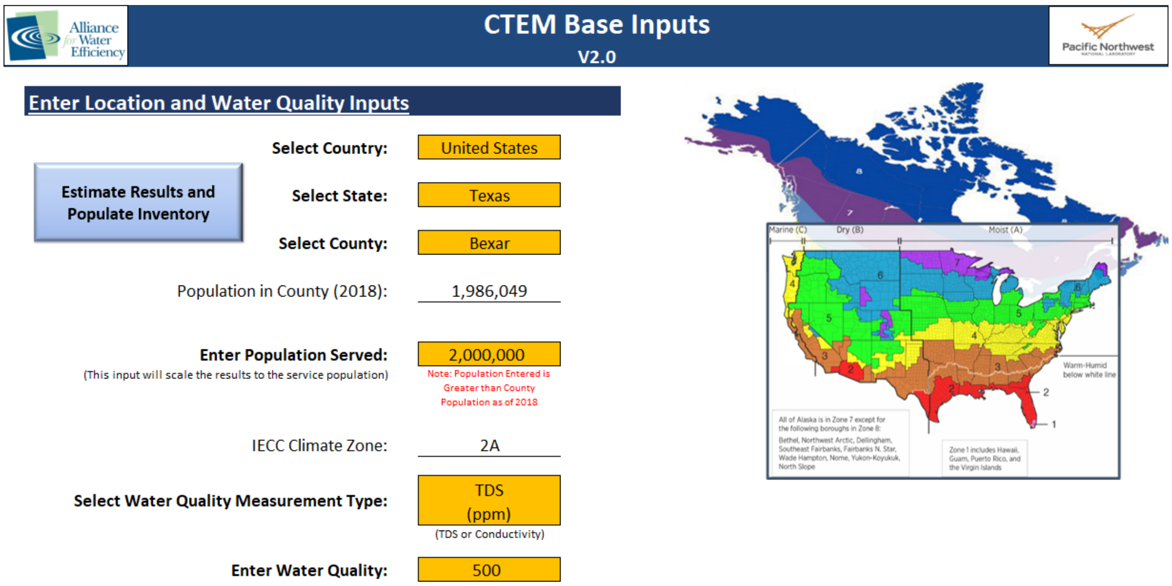
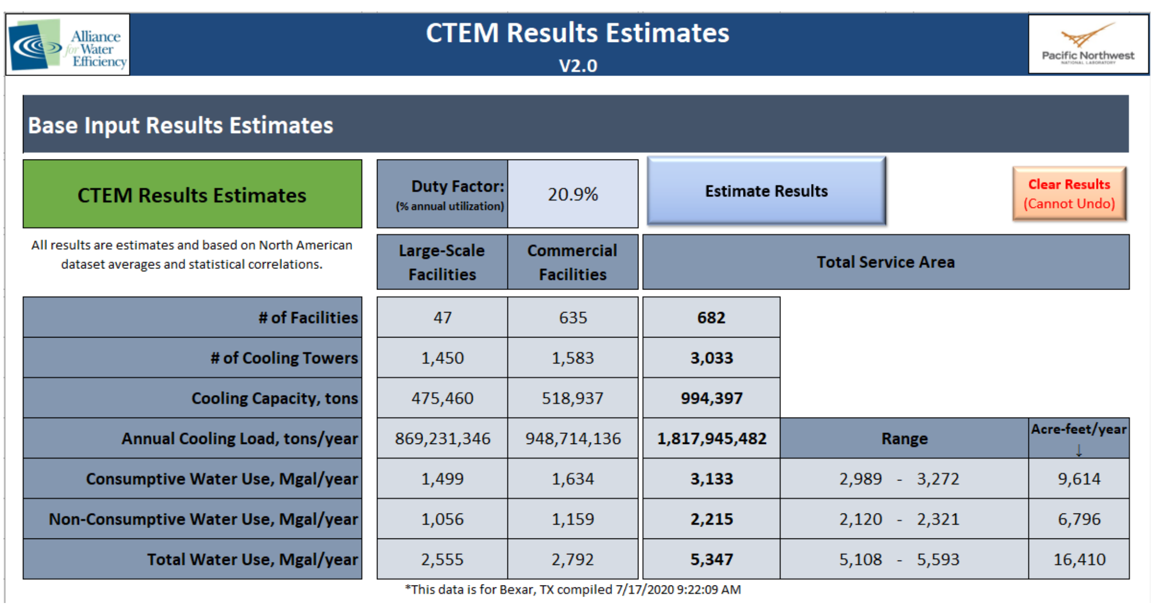


Figure 10. SAWS CTEM Inputs



	Large-Scale Facilities	Commercial Facilities	Total Service Area	Range	Acre-feet/year ↓
# of Facilities	47	635	**682**		
# of Cooling Towers	1,450	1,583	**3,033**		
Cooling Capacity, tons	475,460	518,937	**994,397**		
Annual Cooling Load, tons/year	869,231,346	948,714,136	**1,817,945,482**		
Consumptive Water Use, Mgal/year	1,499	1,634	**3,133**	2,989 - 3,272	9,614
Non-Consumptive Water Use, Mgal/year	1,056	1,159	**2,215**	2,120 - 2,321	6,796
Total Water Use, Mgal/year	2,555	2,792	**5,347**	5,108 - 5,593	16,410

*This data is for Bexar, TX compiled 7/17/2020 9:22:09 AM

Figure 11. SAWS CTEM Outputs

The outputs of CTEM were entered into the market penetration model. Two hypothetical scenarios were run to demonstrate different implementation strategies of the selected technologies. As mentioned previously, the adoption scenarios can be altered iteratively to optimize the results.

Table 3 and Table 4 are the assumptions that were used for the adoption rate for each alternative cooling technology in scenario 1 and 2 respectively.

Table 3. Model Assumptions for SAWS Scenario1

		Scenario 1		
		% Large Facility to Alt-Tech	% Commercial to Alt-Tech	% Total to Alt-Tech
Thermosyphon Cooler (TSC) – Hybrid System	% TSC Market Segment Adoption Goal	7%	7%	7%
	% water savings from TSC (midrange estimate)	3%	3%	3%
	% water savings from TSC (low-range estimate)	1%	1%	1%
	% water savings from TSC (high-range estimate)	5%	5%	5%
	Cost per Ton to TSC (USD2020)	$518	$518	$518
Hygroscopic Cooler (HSC)- Hybrid System	% HSC Market Segment Adoption Goal	7%	7%	7%
	% water savings from HSC (midrange estimate)	2%	2%	2%
	% water savings from HSC (low-range estimate)	2%	2%	2%
	% water savings from HSC (high-range estimate)	2%	2%	2%
	Cost per Ton to HSC (USD2020)	$298	$298	$298
Adiabatic Cooler (AC)	% AC Market Segment Adoption Goal	7%	7%	7%
	% water savings from AC (midrange estimate)	3%	3%	3%
	Cost per Ton to AC (USD2020)	$640	$640	$640
Thermal Membrane Distillation (TMD) – Hybrid System	% TMD Market Segment Adoption Goal	7%	7%	7%
	% water savings from TMD (midrange estimate)	4%	4%	4%
	Cost per Ton to TMD (USD2020)	$235	$235	$235
	% CT to Total Alt-Tech Goal	27%	27%	27%
	% water savings from Alt-tech (midrange estimate)	13%	13%	13%
	% water savings from Alt-tech (low-range estimate)	11%	11%	11%
	% water savings from Alt-tech (high-range estimate)	15%	15%	15%
	Cost per Ton to Alt-Tech (USD2020)	$423	$423	$423

Table 4. Model Assumptions for SAWS Scenario 2

		Scenario 2		
		% Large Facility to Alt-Tech	% Commercial to Alt-Tech	% Total to Alt-Tech
Thermosyphon Cooler (TSC) – Hybrid System	% CT to TSC Goal	27%	0%	13%
	% water savings from TSC (midrange estimate)	13%	0%	6%
	% water savings from TSC (low-range estimate)	4%	0%	2%
	% water savings from TSC (high-range estimate)	22%	0%	10%
	Cost per Ton to TSC (USD2020)	$518	$0	$518
Hygroscopic Cooler (HSC)– Hybrid System	% HSC Market Segment Adoption Goal	0%	27%	14%
	% water savings from HSC (midrange estimate)	0%	9%	5%
	% water savings from HSC (low-range estimate)	0%	8%	4%
	% water savings from HSC (high-range estimate)	0%	10%	5%
	Cost per Ton to HSC (USD2020)	$0	$298	$298
Adiabatic Cooler (AC)	% AC Market Segment Adoption Goal	0%	0%	0%
	% water savings from AC (midrange estimate)	0%	0%	0%
	Cost per Ton to AC (USD2020)	$0	$0	$0
Thermal Membrane Distillation (TMD) – Hybrid System	% TMD Market Segment Adoption Goal	0%	0%	0%
	% water savings from TMD (midrange estimate)	0%	0%	0%
	Cost per Ton to TMD (USD2020)	$0	$0	$0
	% CT to Total Alt-Tech Goal	27%	27%	27%
	% water savings from Alt-tech (midrange estimate)	13%	9%	11%
	% water savings from Alt-tech (low-range estimate)	4%	8%	6%
	% water savings from Alt-tech (high-range estimate)	22%	10%	16%
	Cost per Ton to Alt-Tech (USD2020)	$518	$298	$403

The results of SAWS case study using the model are shown in Figure 12 and Figure 13. Figure 12 displays the range of cooling tower water use with and without the market penetration of alternative cooling technologies overtime from 2020 through 2050. The results of the model provide growth curves. Growth curves are commonly bell-shaped and s-shaped curves. In Figure 13, the water use growth curves are s-shaped, revealing that the market penetration of the alternative technologies ramps up quickly at first and then slowly levels out over time showing full adoption of the technology.

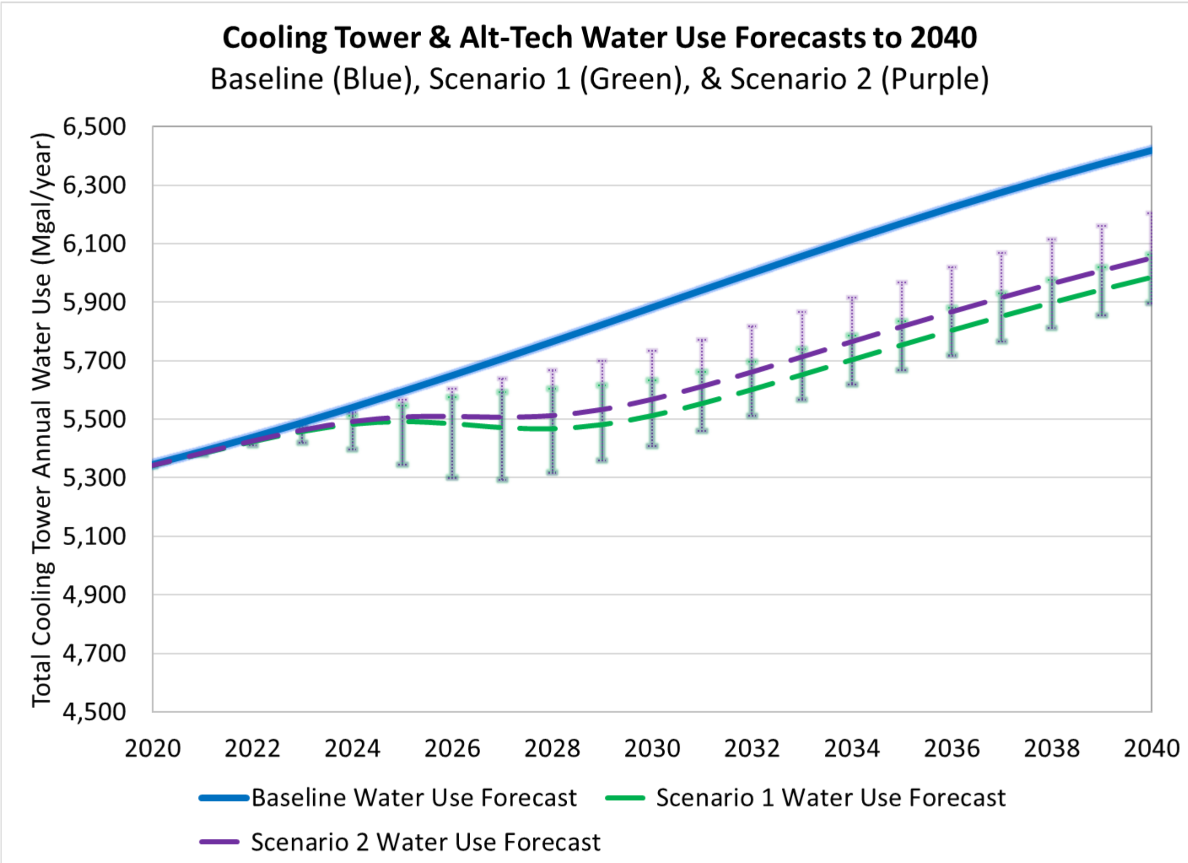
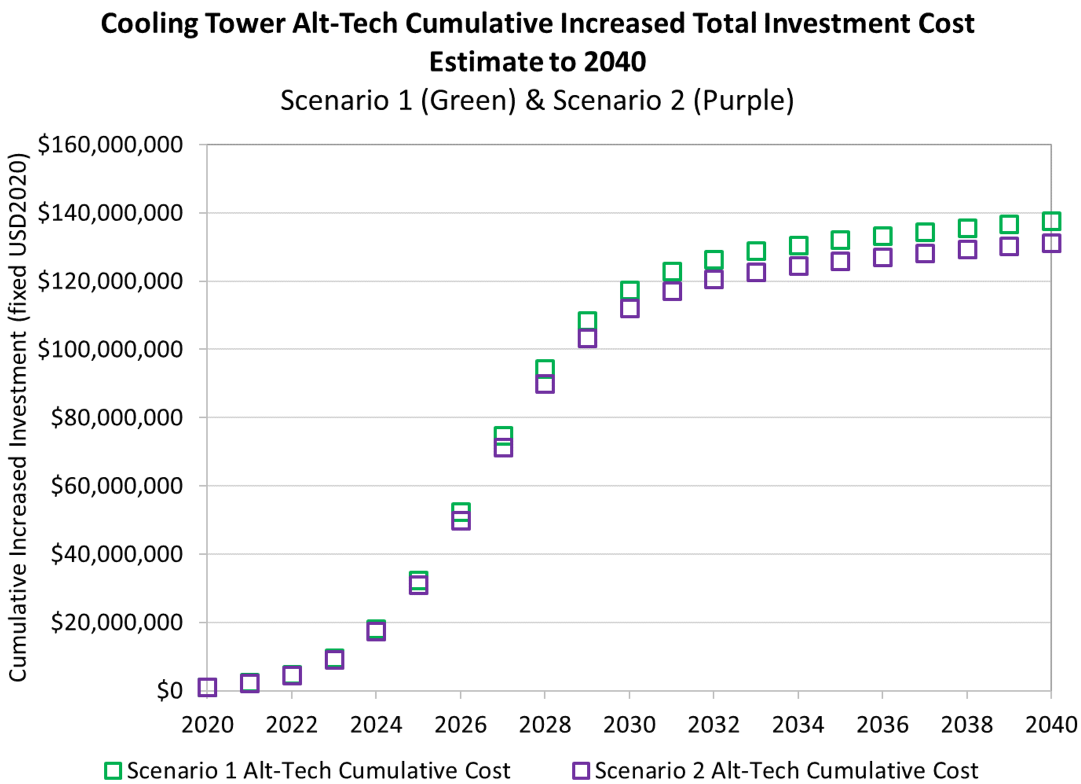


Figure 12. SAWS Estimated Water Use for Scenarios 1 and 2

In Figure 13, the investment growth curves are both s-shaped and bell-shaped. The bell-shaped curves in the annual investments reveal a peak in investments approximately halfway through the alternative technology market penetration cycle, while the cumulative capital investment curve follows the s-shaped trend, showing that investments level off after full adoption of the technology.



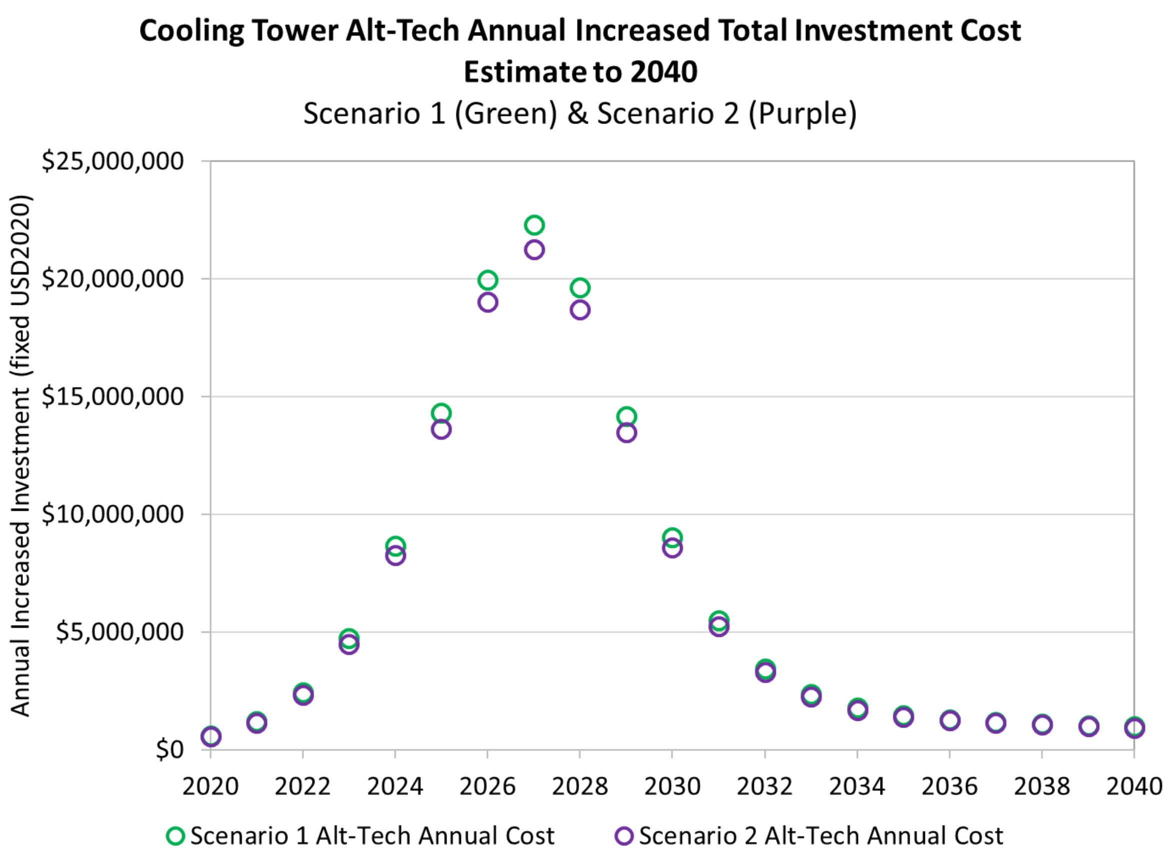


Figure 13. SAWS Cumulative and Annual Investments

Table 5 displays the results summary of the market penetration forecast for alternative cooling technologies. The results show in each category that while the water savings are substantially larger for Scenario 1 in comparison to Scenario 2, the costs are also substantially higher in each category, respectively. This means that a utility will need to review the market penetration data and choose incentives that, upon implementation, would generate optimal water savings.

Table 5. Summary Results of SAWS Case Study

Forecast Results Summary Table (SAWS)	Units	Scenario 1	Scenario 2
Annual Water Savings Estimate in 2030	*Mgal/year*	**369**	**314**
% Water Savings in 2030	*%*	**6%**	**5%**
Annual Water Savings Estimate by 2040	*Mgal/year*	**432**	**367**
% Water Savings in 2040	*%*	**7%**	**6%**
Cumulative Water Savings Estimate to 2030	*Mgal*	**1620**	**1376**
Cumulative Water Savings to 2040	*Mgal*	**5762**	**4895**
Mid Alt Tech Annual Cost at 2030	*USD2020*	**$9,014,896**	**$8,594,542**
Mid Alt Tech Annual Cost at 2040	*USD2020*	**$979,592**	**$933,915**
Mid Alt Tech Cumulative Cost at 2030	*USD2020*	**$117,488,303**	**$112,009,950**
Mid Alt Tech Cumulative Cost at 2040	*USD2020*	**$137,608,123**	**$131,191,605**

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Appendix – Market Penetration Model (MPM) Methodology

To assess the water saving potential of alternative cooling technologies, PNNL developed a growth curve model based on previous work by the PNNL team (Harris et al. 2018). PNNL's model is based on a four-parameter logistic multi-cycle growth curve modeling method which provides a highly parameterizable growth curve analysis to measure the change in a dynamic quantity (e.g. production/consumption) over time. This type of analysis is commonly used to forecast the response of a population to adopt technologies and is referred to as technological diffusion. Market penetration modeling is a form of technological diffusion modeling focused on a product or service diffusing into or penetrating a given market base.

Technological diffusion modeling was first developed by Fisher and Pry in 1971 (Fisher & Pry, 1971) and has been used regularly thereafter (Grübler, 1996; Grübler, Nakićenović, & Victor, 1999; Rao & Kishore, 2010; Vanston & Hodges, 2004). We used this approach to determine market penetration parameters that represent the cooling tower industry in North America. Our PNNL team then used these parameters to perform a cooling tower alternative technology market penetration case study worksheet in Excel to form the basis of the market penetration model. We built the model to perform a scenario analysis that allows for a combination of the 4 alternative cooling tower technologies to compare and build an optimized investment estimation given the adoption rate and water savings potential parameters entered into the model. A sensitivity analysis was then performed to determine the parameters with the greatest effect on the adoption, cost, and water savings forecasts.

Technological diffusion and thereby market penetration growth cycles illustrate and model the typical trends in the adoption of a product or service by a population over time. These curves have the same general shape as cumulative distribution functions (CDFs) that form an s-shaped curve and probability density functions (PDFs) that form a bell-shaped curve. Most market penetration trends follow the s-shaped curve (Giaccherini et al., 2019; Vanston & Hodges, 2004) and such was the case found for the cooling tower market (CTI, 2020). The carrying capacity is the intended maximum level of total market saturation and is the upper plateau of the s-shaped curve (Figure 14). Sensitivity analysis changes specific variables and then compares different analysis results to reveal the impact of the variable to the results.

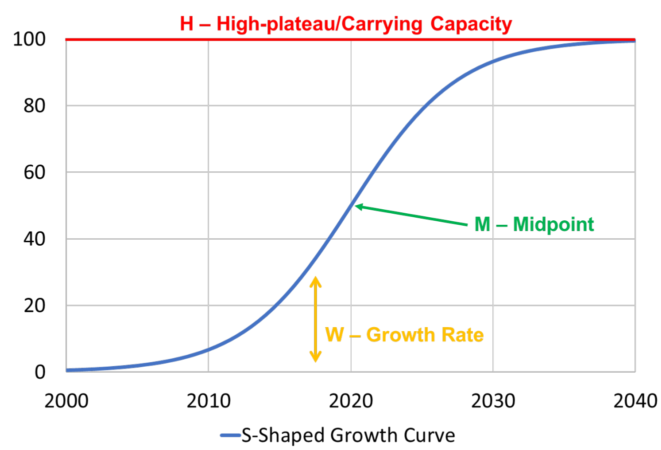

Figure 14. S-shaped growth curve representing technological diffusion and market penetration

The following is a high-level description of the underlying calculations built into the MPM. The four-parameter equation used for this s-shaped model is given by equation 1:

$$P(t) = H + \frac{L-H}{1+e^{\frac{t-M}{W}}} \quad (1)$$

Where *P(t)* is the quantity produced (in this case water) in time period *t* (years), *H* is the high plateau or carrying capacity of the market, *L* is the low plateau or starting capacity (set to 0), *e* is Euler's number, and *W* is the width factor where the growth rate factor *r = 1/W*. *M* is the midpoint time period of the growth cycle (year, *t*) such that:

$$\frac{dP}{dx}(M) = 0$$

The PNNL team used basic Excel solver functionality for parameter regression of cooling tower industry historical time-series data made publicly available by the Cooling Technology Institute (CTI, 2020). The CTI time-series data from 1990 to 2019 includes the number of cooling tower manufactures, certified cooling tower product lines, and certified cooling tower models. We used these datasets to fit this four-parameter multi-cycle growth curve model (Figure 15) and establish the descriptive statistics required for the MPM. These parameters represent how cooling tower technology has been adopted overtime and we used them to produce the market penetration forecast results.

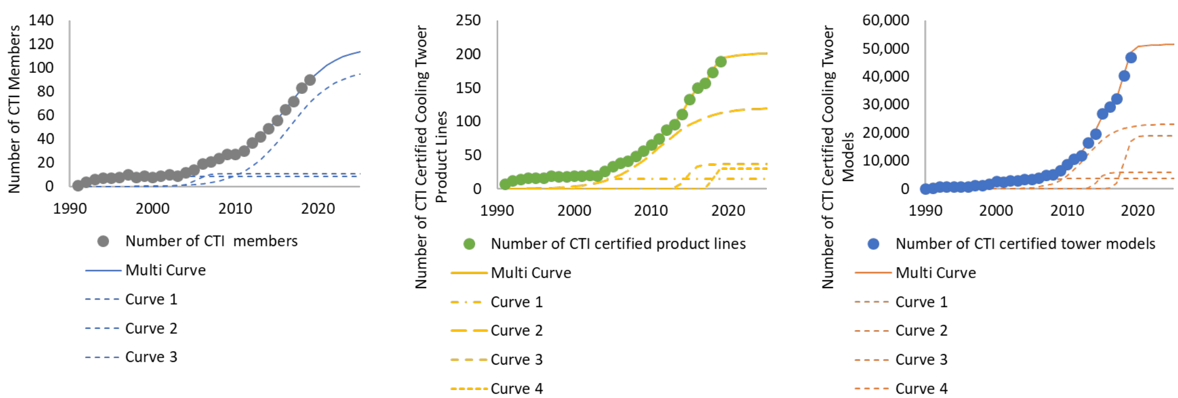

Figure 15. Growth curve fits to CTI data.

These curves show a near perfect fit to the expected growth curve established by Fisher and Pry. The growth curves show that at first there is a slow adoption period, followed by a steep acceptance, and an eventual leveling out. However, when s-shaped growth curves are followed by additional concurrent s-shaped market growth, an uneven step-like shape in the trend emerges. The individual growth cycles are plotted starting from zero while the sum of all the curves produces the overall step-shaped trend that follows the data points.

Table A.1 provides the average, low, and high number of years observed for cooling tower technology or services to diffuse across the North American market from 1% to 75% of the carrying capacity for the alternative cooling tower technology.

Table A.1. Cooling Tower Market Penetration Values for Sensitivity Analysis

	Market Segment	**Years from 1% to 75%**	**Years from 1% to 99%**
Average	**27%**	**9.9**	**15.2**
Small	**7%**	5.6	9.0
Large	**84%**	15.9	25.7
Fast	37%	**2.7**	**4.3**
Slow	7%	**18.4**	**29.7**

Growth Curve Parameters	**Average**	**Fast**	**Slow**
L	0	0	0
H	User Input	User Input	User Input
W	1.4	1.0	1.7
M	2008.4	1991.2	2018.0
Years from 1% Growth to M	2002.1	1986.4	2010.0

For the alternative cooling technology market penetration model, these growth curve factors were used to forecast the adoption of the alternative cooling tower technology over time. Water savings potential (presented in Section 2.7) for each technology was then integrated into the model estimate the water savings over time resulting from the market penetration of each technology.

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