Clean Water Production in Cooling Towers

DOE Award Number: DE-FE0032057

Final Technical Report
Grant Period: 07/02/2021-09/30/2025

Principal Investigator: Karim Khalil, PhD
9083424545
kkhalil@infinite-cooling.com

Infinite Cooling
121 Madison Street, Malden MA 02148
DUNS 080777013

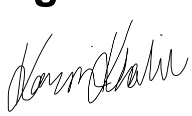
Submitted to

U.S. Department of Energy
National Energy Technology Laboratory

Project Manager: Omer Bakshi
Omer.Bakshi@netl.doe.gov

Submission Date
9/30/25

Signature:



Karim Khalil, PhD
CTO, Infinite Cooling

Abstract/Executive Summary:

According to studies by the United Nations and the United States Department of State, global water resources are on track to face severe shortages by 2030. In the United States, power plants account for about thirty nine percent of all freshwater withdrawals, most of which are used for cooling. Cooling towers are the dominant cooling technology and fossil plants in particular are highly water intensive. In addition to high water use, the performance of cooling towers has a direct impact on plant heat rate since the cooling tower determines the condenser pressure and therefore the overall thermal efficiency of the steam cycle. When cooling towers operate below optimal performance, they raise condenser backpressure, increase heat rate, reduce net output and can create operational bottlenecks that limit production during periods of high demand or high ambient temperature. Cooling tower plumes also create operational constraints that reduce efficiency, limit output and restrict flexibility. Addressing both water consumption and plume related limitations is essential for maintaining the competitiveness of fossil generation in an increasingly water constrained world. Our technology addresses all these common problems optimizing cooling operations, capturing liquid water from exhaust plumes, and re-utilizing the water on site for high value applications such as boiler feed.

This project developed and demonstrated a novel technology that produces clean water from cooling tower recirculating water by using the natural evaporation and condensation cycle inside cooling towers. The system captures the escaping plume and converts blowdown quality water into high purity water suitable for on-site reuse such as boiler feed. The technology uses electric fields to ionize exhaust plumes, charge the entrained droplets, and direct them toward collection electrodes where they coalesce and flow downward. This allows water recovery at a low energy cost while reducing visible plume emissions.

Over the course of this award, the technology advanced from TRL four to TRL six. Through continued engineering and commercial development by our company, it is now at TRL 9. A full-scale prototype was built and operated at the Fox Energy Center, where it was successfully integrated with plant controls. Building on this demonstration, we developed modular versions of the system that can be scaled to any

cooling tower size, from about five feet to over five hundred feet in exhaust diameter across mechanical draft and natural draft towers that are factory assembled or field erected. These modules provide a robust, repeatable and cost-effective architecture that can be mass produced and deployed globally. Capture efficiency of 85 to 90 percent has been maintained across configurations.

In addition, we developed a complementary software platform that improves overall cooling tower performance. The system uses wireless sensors and physics-based machine learning algorithms to optimize key parameters of the cooling process. For power generation facilities, this increases the thermal efficiency of the cooling loop and condenser, resulting in measurable cycle efficiency gains. Improvements of one percent or more can deliver significant increases in electricity production for the same fuel input. The platform is applicable to a wide range of evaporative cooling systems including power plants, industrial facilities, chiller plants and data centers. Together, the plume capture technology and optimization platform provide operators with a comprehensive suite of tools to increase efficiency, reduce water use and improve operational performance.

Technical Summary:

The overall objective of this project was to design, build and test a full-scale prototype of a clean water production technology from cooling tower water in a real power plant environment and scale. The prototype was installed on a large-scale natural gas power plant. The performance and durability of the equipment was monitored after installation utilizing site visits + instrumentation that was placed to monitor the water capture equipment as well as the cooling tower itself.

The program began with a conceptual study to study the cost/benefit for the host site, which led to the go-decision for the project. Once the project began, the full engineering process took our previous smaller scale prototypes and scaled them up to the full cooling tower size – in this case, a 35+' field-erected cooling tower. This was followed up with procurement, fabrication and then site-assembly and installation of the system. Integration into the host plant by routing the water and automating controls was completed as well prior to commissioning. The deliverables of the project are outlined in the below table:

Deliverables:

Task/ Subtask number	Deliverable Title	Status
1.1	Project Management plan	Completed
1.2	Technology Maturation Plan	Completed and in Appendix
2	Conceptual study	Completed with partner site in 2022
3	Techno-Economic Analysis (TEA)	Completed and in Appendix
7	Technology Gap Assessment	Completed and in Appendix
8	Commercialization plan	Completed and in Appendix

Prototype Design & Installation at Fox Energy Center:

Initial WaterPanel™ Design: During the time of designing our system for the demonstration for this award, Infinite Cooling would create custom-designed large scale water capture systems that would fit to the cooling tower fan exhaust fan shroud as shown in the below images of Figure 1. These custom-designed units would require Infinite Cooling to completely re-size every component on the internals of the system including our electrodes, collecting plates and drainage systems.

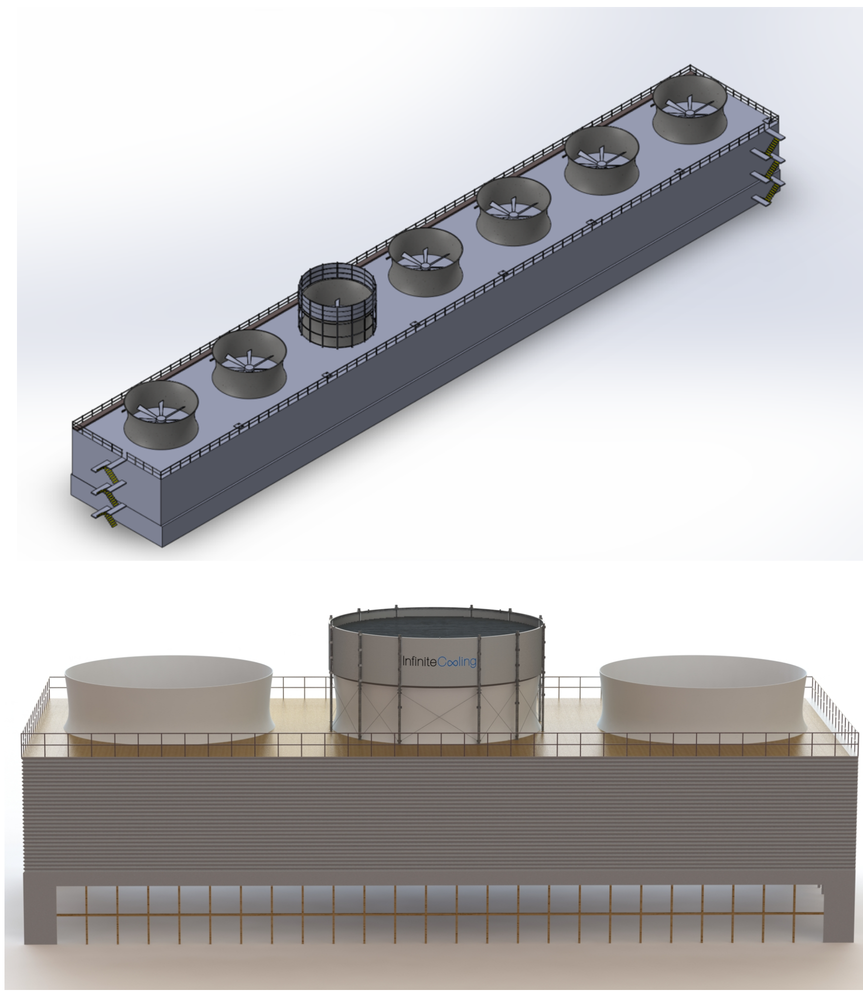


Figure 1 - WaterPanel™ initial full-scale designs utilized for project prototype demonstrations

After design completion, the 35+’ custom design of the WaterPanel™ was fabricated with partners and then shipped to our partner host site in parts for field installation.

Figure 2 - The WaterPanel™ unit was assembled on the ground, lifted into place utilizing a crane to install the columns to mount the unit over the fan exhaust of the cooling tower

Figure 3 - WaterPanel™ system installed on the fan exhaust of the cooling tower at our partner site

After installation of the collector on the cooling tower – integration of all mechanical and electrical systems were completed. This included powering the power supply of the collector with 3-phase 480V power and finalizing the mechanical interfaces of the collector to the cooling tower for structural and plumbing. Infinite Cooling then commissioned the WaterPanel™ collector by running through an electrical diagnostics check to verify that all electrodes were properly insulated and the unit was operational. Despite being able to scale a prototype of our cooling tower water capture technology from lab-scale, to a 12+’ prototype in prior years, and most recently here with a 35’+ prototype for a field-erected mechanical draft cooling tower at a power plant, it became clear that the path to scalability for this technology was through modularity to a common-sized smaller unit that could be bolted together to fit an arbitrarily large cooling tower size. This allows the technology to maintain peak robustness & performance in all applications as well as allowing for manufacturing cost-targets to be met with the economies of scale of common parts and designs. The following section of the report elaborates on this design and it’s performance metrics in full-scale installations of our technology.

Modular Collector Design and Path Forward for Technology:

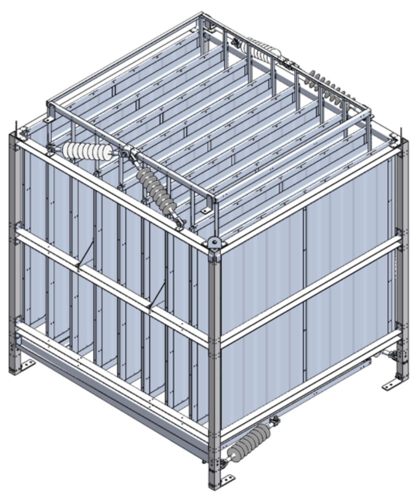


Figure 4 - Standard WaterPanel™ Module. 6’x’6’ coverage area

The standard WaterPanel™ module is approximately 6’x6’x6.6’ and is typically comprised of either marine-grade aluminum or stainless steel alloys (see Figure 4). Each unit weighs less than 400 lbs., and has the ability to support a water flow of up to 2-10 m^3/s per module. Each unit is designed to capture 85-90% of the liquid water mass available in the cooling tower plume it’s being installed in, while maintaining an extremely small pressure drop of 1-2% of the entire cooling tower pressure drop. This pressure drop has been experimentally validated in cooling towers where there has been an immeasurable impact on the thermal efficiency and airflow of the cooling tower with and without our system being installed.

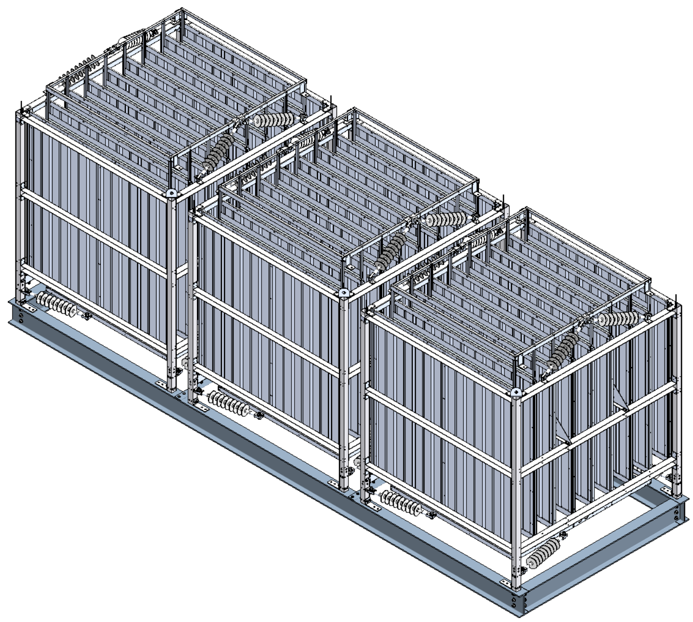


Figure 5 - WaterPanel™ modules installed on standard 3-module FRP skid. Skids can be installed directly into cooling towers. Skid size selection depends on cooling tower structural framing layout

Additionally – to simplify installation, WaterPanel Modules are pre-assembled into support skids (see Figure 5), made from pultruded fiberglass-reinforced plastic (FRP). This material is typically used as the structural material of field-erected mechanical draft cooling towers. By pairing modules into ready-made support skids, this can simplify installation into logical common units that fill up the available space in the cooling tower support structure (see Figure 3). This common unit is typically decided upon during the engineering phase of the project when structural loads are being confirmed. Manufacturing begins and all modules are fabricated to the spec, and then pre-assembled onto the FRP skids and then shipped to site.

Once the materials are onsite they can be installed into the plenum of the cooling tower (see Figure 6), or above the fan on a grid of FRP members with a similar layout as inside the cooling tower. Installation of these pre-assembled module units into the cooling tower can be completed with existing equipment on site, typically done with a large forklift or small truck-crane. With the modest weights of our technology

+ the limited reach required to get to these heights, these pieces of equipment are sufficient for installation.

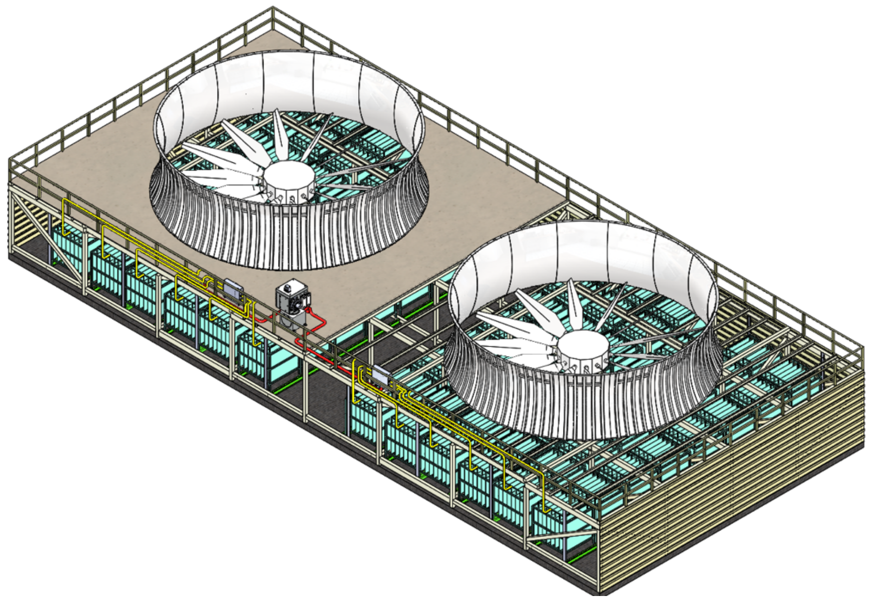


Figure 6 - WaterPanel™ modules installed in a field-erected mechanical draft cooling tower, in-plenum

Infinite Cooling has now supported several installations of our modular technology in the industry. The section below on performance and modeling capabilities discusses real data of our technology deployed in these applications.

Performance and Modeling Capabilities for New Sites & Customers:

Infinite Cooling now has the ability to predict the performance of our modular water capture technology with a high-degree of accuracy. Figure 7 shows data from a deployed WaterPanel™ module that has been installed in cooling tower plenums on large industrial facilities (nuclear power plants, chemicals facilities etc.). The x-axis represents the measured collection rate, and the y-axes represents the modeled collection rate of water of this module. Experimental data points are in good agreement with the modeling, demonstrating the clear and expected dependence on ambient humidity and temperature that Infinite Cooling has demonstrated in prior awards. The key distinction here is that these experimental results are now being obtained in a full-scale setting, in cooling towers that are fully operational on large industrial sites.

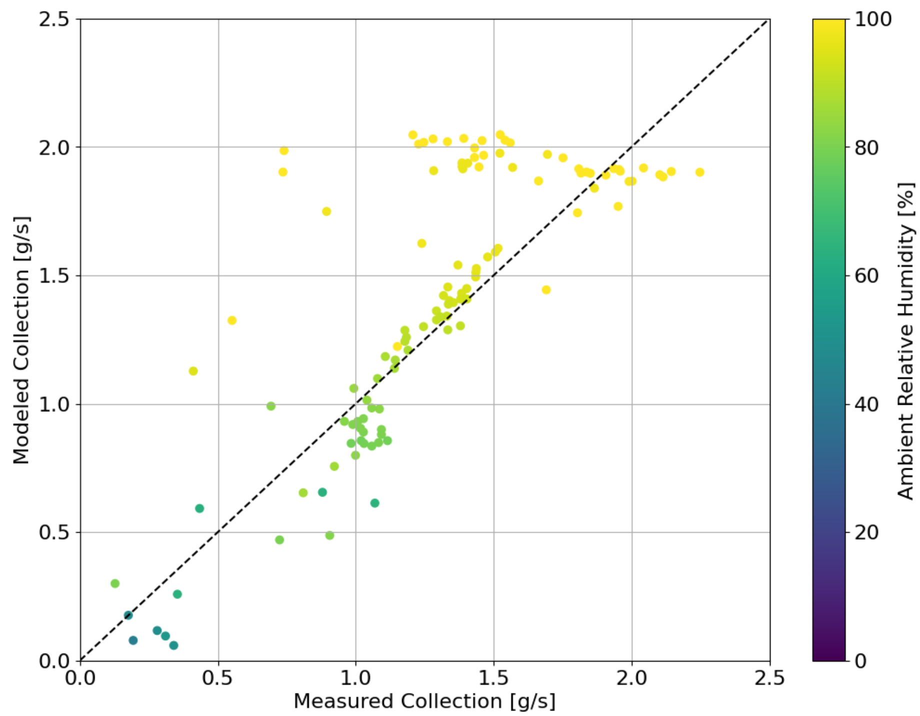


Figure 7 – Measured Module performance versus modeled performance

The modeling framework utilized by Infinite Cooling to compare and predict results for a given site includes the following: 1. Electrostatic performance modeling (droplet capture physics + flow characterization) 2. Plume formation and mixing physics modeling. The combination of these two modeling frameworks allows Infinite Cooling to model the performance of the WaterPanel™ modules accurately and provide detailed information for value modeling of this technology in a variety of applications.

For example, see the below plot in Figure 8 – that demonstrates the dependence of available liquid water in the plume as a function of ambient dry bulb temperature and ambient relative humidity for a sample site/cooling tower. This graph can be populated for any cooling tower in any environment by Infinite Cooling and is typically utilized during the early stages of project validation. These two parameters, in addition to the cooling tower airflow characteristics (fan dynamics) + the heat load on the cooling tower all are critical to modeling this plume formation and mixing physics modeling.

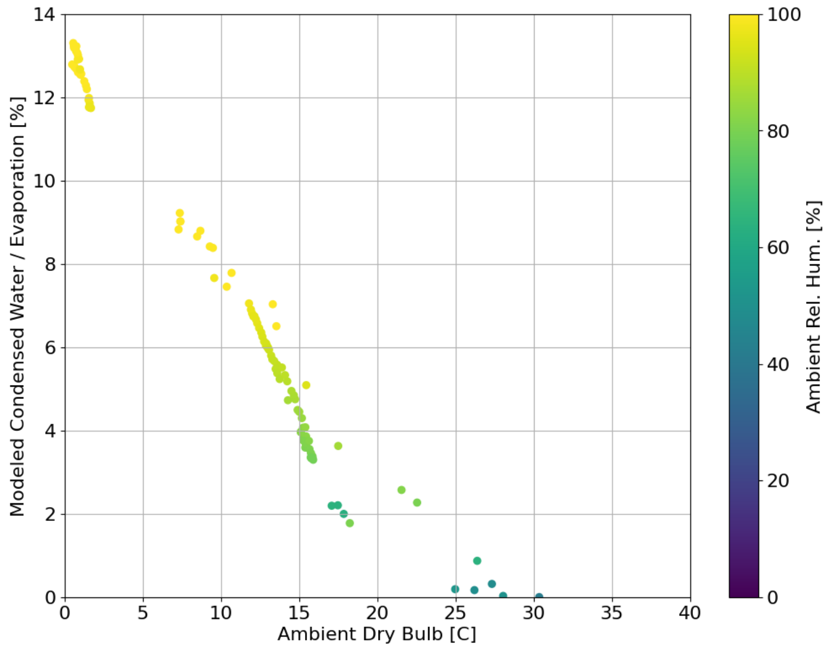


Figure 8 - Liquid plume formation versus Ambient Dry Bulb & RH – sample site

Collected Water Quality:

As has been validated in previous studies, the collected water from cooling tower plumes is extremely pure. This water is evaporated and recondensed water so it contains essentially no minerals or dissolved ions. Across all of our installations we have seen a dramatic reduction in the amount of dissolved ions and minerals in our collected water in comparison to the recirculating water in the cooling loop (a reduction in constituents & electrical conductivity anywhere from 30X-150X depending on the conditions). This enables the opportunity to up-cycle this captured water for high value applications such as boiler-feed where demineralized water is required. Additionally – since the amount of water required in the cooling loop is orders of magnitude larger than demineralized water needs, a small portion of the recovered water can have a meaningful impact on the demineralized water load of an industrial site, while the remainder of the captured water can continue to be recycled into the cooling loop, further reducing both makeup and blowdown water losses.

Plume Abatement and Drift Capture:

In addition to the value of the high-quality water capture, plume abatement and enhanced drift elimination are two other technical advantages of the WaterPanel™ technology.

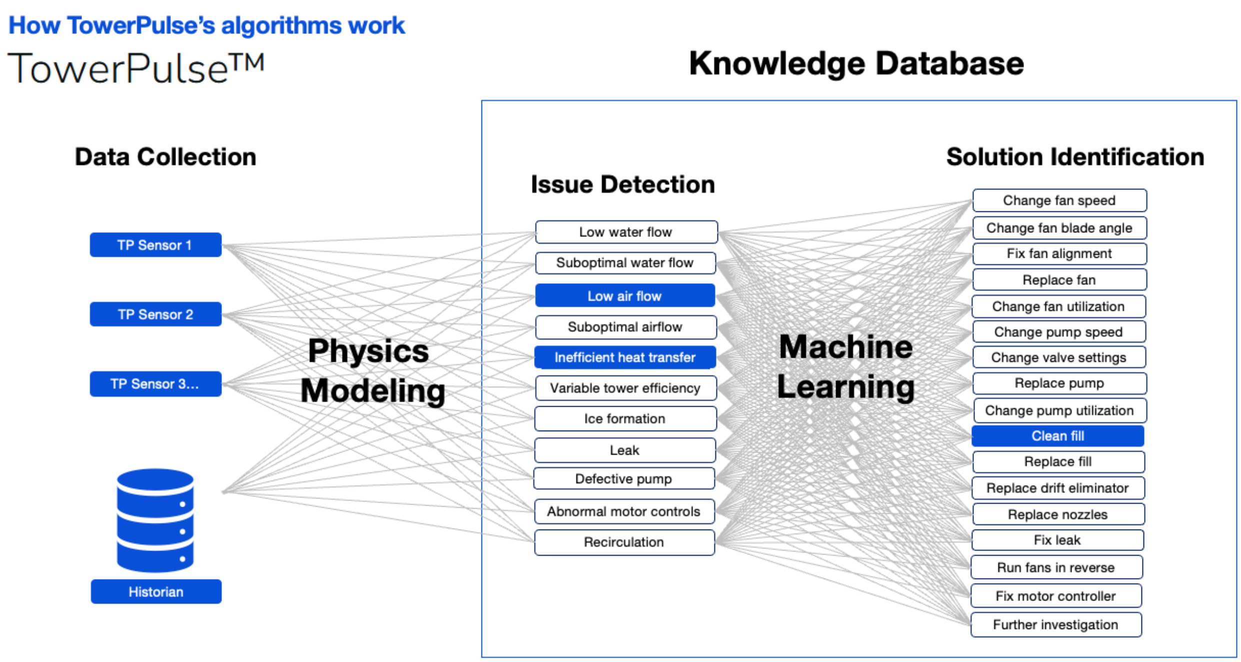
Cooling tower plumes and their formation are one of the largest emissions from industrial sites, particularly those with large heat loads. This phenomenon can cause substantial issues stemming from local regulations, safety, nearby equipment performance degradation and interference and even shut down entire facilities or require them to operate at substantially lower loads. Mitigating these issues with a commercially available plume abatement solution that simultaneously allows industrial facilities to re-use the water that is being lost due to evaporation is the key differentiator to our technology versus traditional alternatives – see Appendix B for more details.

In addition to Plume (condensation of super-saturated water vapor in certain ambient conditions), cooling tower “Drift” is the loss of small water droplets of the circulating cooling water loop that are carried out of a cooling tower with the exhaust air due to entrainment in the exhaust airflow. These microscopic droplets contain the same chemicals, salts, and bacteria as the circulating water and can cause environmental and health concerns, such as soil contamination, corrosion of nearby structures (piping, equipment etc.), and the spread of diseases like Legionnaires'. Drift droplets from cooling towers , carbon capture systems (DAC), and other industrial processes using sprays and mist are the main source of polluting emissions from cooling towers and they are often regulated by air permits. WaterPanel™ captures drift and keeps emissions below acceptable standards. WaterPanel™ captures and recycles the drift losses to reduce the need to acquire and treat new water and to buy more chemicals. It allows cost-effective and sustainable operations. Drift droplets typically have a wide range of droplet diameters, some that overlap with plume droplet diameters. Infinite Cooling now has the ability to provide advanced performance modeling of the WaterPanel™ capture system as a function of expected droplet spectra. This allows for the unique ability to provide advanced drift collection (85-90% additional reduction of drift that is not captured by traditional drift elimination systems in cooling towers) to meet site-specific goals such as PM 2.5 and PM 10 allowances on drift for cooling towers. With this unique technology, site operators can now optimize their water treatment programs to further reduce water consumption (often limited by air permits due to drift concentrations of chemicals).

Cooling Tower Performance Monitoring and Optimization – TowerPulse™:

In addition, to our advanced water capture technology, we have also developed a complementary software platform that improves overall cooling tower performance. The results of this technology development are relevant for the key metrics and goals associated with this award so these results were also highlighted. The system uses wireless sensors and physics-based machine learning algorithms to optimize key parameters of the cooling process. For power generation facilities, this increases the thermal efficiency of the cooling loop and condenser, resulting in measurable cycle efficiency gains. Improvements of one percent or more can deliver significant increases in electricity production for the same fuel input. The platform is applicable to a wide range of evaporative cooling systems including power plants, industrial facilities, chiller plants and data centers. Together, the plume capture technology and optimization platform provide operators with a comprehensive suite of tools to increase efficiency, reduce water use and improve operational performance.

For example – the cooling towers at our partner site were a 12-cell field erected mechanical draft cooling tower set servicing a 200+MW steam turbine on the back-end of a combined cycle natural gas facility. TowerPulse™ was deployed on the cooling tower in one week, and we measured a cooling tower efficiency score of 80%. TowerPulse™ enables the rectification of the cooling tower efficiency by identification of maintenance or operational interventions that drive up the efficiency of the cooling tower. The higher the efficiency of the cooling tower, the colder the return water it provides to the steam condenser in the summer months, thus driving efficiency of the overall steam-cycle. Additionally, during winter time, a more efficient cooling tower enables operators to utilize less of the cooling tower, saving on costly parasitic energy loads. For example the 80% efficiency identified, results in a reduction of 2 degrees C of cold water temperature return of the cooling tower water to the steam condenser, resulting in 0.8MW of reduced production. Additionally – TowerPulse™ is capable of tracking the effectiveness (NTU) of heat exchangers that are connected to the cooling tower, in this case a steam condenser. By connecting cooling tower operations to the direct measurement of condenser effectiveness, TowerPulse™ was able to detect a cyclic fouling opportunity in the steam condensers that are resulting in a 1MW loss in production that can be addressed by optimizing the water treatment program.



Acknowledgements:

This material is based upon work supported by the Department of Energy Technology Lab under Award Numbers **DE-FE0032057.** We would like to acknowledge the support and contributions of all individuals and organizations involved in the development of this report, including both the financial support from

DOE/NETL as well as the project site support from our partners at the Fox Energy Center. We thank our colleagues for their technical insights, feedback and collaboration throughout the project. Their collective efforts were essential to the successful completion of this work.

Disclaimer:

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Appendix A: Technology Maturation Plan

Prior to this award, we proposed a project plan that allowed us to take this technology from TRL 4 (lab-scale prototype) to TRL 6. We proposed to build a full-scale prototype of this new technology on the cooling tower of a large fossil plant. We designed and engineered a prototype, manufactured and installed it, and integrated it with power plant systems – this validated the technologies advancement to TRL 6. We demonstrated this prototype at the Fox Energy Center in Kaukauna, WI – a 600+MW power facility where we demonstrated our technology on one of the 12 cooling tower cells of the facility. Our technology can simply be retrofitted to the cooling tower allowing us to recover a portion of the water for re-use, abating plumes simultaneously. This means that any facility utilizing evaporative cooling (power or heavy industry etc.) would be applicable for our technology. The dominant styles of evaporative cooling towers in the industry are mechanical draft and natural draft cooling towers. Mechanical draft cooling towers can be factory assembled and shipped to site, or field-erected. Factory-assembled cooling towers are typically 12-18’ in characteristic size scale to allow for shipping. Field-erected mechanical draft cooling towers typically range from 30-60’ in size regardless of manufacturer and design. Natural draft cooling towers are the large hyperbolic structures that are typically utilized at large nuclear or coal plants and can range between 300-500’ in typical diameter and size.

Since the completion of the technical milestones and prototype demonstration of this award, we have advanced the TRL level of this technology **from 6 to 9**. As discussed in the final technical report main section, the technology is now made in a modular configuration allowing us to arbitrarily scale this technology regardless of the size scale of the cooling tower system. Since completion of this award, we have now demonstrated this technology on factory-assembled mechanical draft cooling towers, field-erected mechanical draft cooling towers, and are currently demonstrating the technology on natural draft cooling towers. These different types of cooling tower architectures and size-scales (ranging from 10’ to 50’ to 300’) represent the entire landscape of size for our technology and is all addressed with our existing modular technology. With our modular design we have been able to scale to all of these typical cooling tower systems and currently support all of the above with existing commercial deployments. With several installations now completing multi-year demonstrations this technology is fully commercially demonstrated. Modularization was the key engineering development that enabled us to scale down material costs, increase quality, hit our overall project cost targets, and dramatically decrease installation time since the technology comes pre-assembled in modular packages to site. Every project that Infinite Cooling takes on has a competitive ROI for our customers and profitable for Infinite Cooling.

The following is a description of the DOE Technology Readiness Levels.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	**TRL 9**	Actual system operated over the full range of expected mission conditions.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness

			Review (ORR) has been successfully completed prior to the start of hottesting.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning (1). Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants.(1) Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
Technology Development	**TRL 5**	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of

			simulants (1) and actual waste (2). Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Technology Development	**TRL 4**	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste (2). Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants.(1) Supporting information includes

			results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
Basic Technology Research	**TRL 2**	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
	TRL 1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.

Appendix B: Techno-Economic Analysis

Performance and Economic Benefits for a Typical Power Plant

For a 200MW steam turbine the benefits are as follows:

1. Generation Increase

TowerPulse™ enables an increase in cooling tower performance and a reduction in approach or cold water temperature. Reducing water temperature by 4F can lead to a reduction of condenser backpressure of 0.4 inHg which leads to an increase in steam cycle efficiency from 30% to 31%, which translates into up to 6MW in additional production. This can mean over $1.5M of additional production annually.

2. Energy Savings

Fan and pump optimization results in energy reductions between 20 and 50%. For a 200MW steam turbine, this can translate into up to 1MW of savings or $300,000 per year for a capacity factor of 70% and an average price of electricity of $50.

3. Maintenance Avoidance

Detection of control anomalies, pump failures, recirculation issues, and cyclic fouling avoids gearbox replacements, fan repairs, and condenser cleaning events. Based on pilot data the avoided maintenance cost is typically between $50K and $150K per year.

4. Water Savings and Water Reuse Value

WaterPanel™ demonstrations at large cooling towers recover 5 to 10% of evaporated water. For a plant that evaporates approximately a billion gallons per year this represents 50 to 100 million gallons of recovered water. At an effective long term industrial water cost of $15 per thousand gallons this corresponds to $750K - $1.5M per year in value. Additional value arises when recovered ultra pure water offsets demineralized water production.

Additional water savings arise from increasing cycles of concentration due to drift elimination and TowerPulse CoC optimization. Total water savings can represent 20-30% of evaporation.

5. Plume and Drift Mitigation Benefits

Elimination of visible plumes prevents weather related operational constraints and reduces compliance risk. Drift capture

6. Outage avoidance

Unavailability of water or freezing of plumes can lead to plants having to shut down temporarily at a cost that can be in the millions of dollars per day. Infinite Cooling prevents these outages and enables full operation in extreme weather when electricity prices are most expensive and when plants are most profitable.

ROI Summary

1. TowerPulse ROI

Across multiple power plant deployments the simple payback period is typically six months or less. Gains come from a combination of increased generation, lower parasitic load, and avoided maintenance.

2. WaterPanel ROI

WaterPanel ROI varies with local water cost and plume related constraints. The simple payback can be as short as one year in regions with high outage risk due to cooling towers and up to five years at sites where only water cost reduction drives ROI.

Comparison with Alternatives - Hybrid or Dry Cooling Systems

Hybrid cooling systems reduce plume formation but require significant capital investment. They typically increase cooling tower height, require added structural reinforcement, and introduce increased fan power. Dry cooling can reduce water consumption but causes a measurable efficiency penalty at warm temperatures and can increase plant heat rate.

Comparison Summary

1. Hybrid cooling systems commonly cost tens of millions of dollars and increase operational energy use.
2. Dry cooling introduces an output penalty of 5-10% or more in warm climates and remains capital intensive.
3. WaterPanel provides plume abatement and water savings at a third of the cost of hybrid cooling for new towers (for existing towers, WaterPanel is the only solution that can be retrofitted) and with negligible pressure drop.
4. TowerPulse provides savings at very low cost without altering mechanical equipment
5. Combined deployment achieves better functional outcomes than hybrid cooling while maintaining higher thermodynamic efficiency and costing 3X less.

Appendix C: Technology Gap Assessment

Technology Gap	**Description**	**Importance Level**	**Current State**
Robustness of WaterPanel™ technology in all cooling tower environments	Withstand all air velocities, water chemistries, environmental loads for lifetime of 10+ years	**High**	**Resolved** – modularization eliminated all stress-based robustness concerns. Material down selection to marine grade-aluminums (5000/6000 series) and 300 series stainless steel alloys has eliminated chemistry concerns.
Performance of WaterPanel™ technology at all cooling tower length scales (5'-500')	Electrostatic precipitation capture technique will remain unaffected by the length scale of different cooling tower designs – from 5' in size for factory assembled mechanical draft cooling towers, to 500' natural draft cooling towers.	**High**	**Resolved –** modularization allows for critical dimensions that maintain performance of our technology to be held at critical tolerances across an arbitrary length-scale of cooling tower. Since modules can be grouped together arbitrarily to support any cooling tower system size.
Cost-effective for standard cooling tower requirements	Acceptable ROI's for customers regardless of cooling tower size (# of modules)	**High**	**Resolved –** Modularization eliminated this technology gap. Engineering costs have been cut dramatically from our older custom-designed unit. Equipment costs can take advantage of economies of scale in sheet metal manufacturing since we are ordering large quantities of the same parts (regardless of the project). Installation costs have also been dramatically slashed since no site-assembly is required, only placement of the modules into the cooling tower and final commissioning. These effects have allowed us to provide extremely competitive ROI's for our products versus the alternatives to the value we offer.

Appendix D: Commercialization Plan

1. Commercial Readiness

The technologies developed and refined under this program are fully commercial today. Both offerings have been deployed in operating facilities across the United States and internationally. They have demonstrated reliable performance in real industrial environments, including continuous high load conditions.

Prospective customers can purchase the systems immediately, and installations can be completed without disrupting plant operations. The systems have already shown strong uptime, robust operation, and measurable financial and operational benefits in nuclear power, gas power, chemicals, food and beverage, and chiller plants.

2. Market Opportunity and Initial Focus

The global market for cooling tower performance technologies, water recovery systems, and plume mitigation solutions is over $25B per year. This value comes from the widespread use of evaporative cooling across power generation, industrial processes, commercial cooling, and the rapidly expanding data center sector.

The initial commercial focus is on:

- Power plants, especially nuclear and combined cycle gas units, which benefit immediately from higher cooling efficiency and lower water use
- Data centers, where improved cooling tower performance increases chiller efficiency and reduces total energy use and improves PUE
- Large industrial facilities with high water consumption or production constraints driven by cooling limitations

These segments offer the fastest adoption path because they have clear economic drivers and measurable operational constraints that the technology directly addresses.

3. Recommended Adoption Pathway

Organizations adopting these technologies typically follow a simple and effective sequence:

Step One: Optimize tower performance

Customers begin by deploying the monitoring and optimization solution to improve cooling efficiency, reduce parasitic load, increase capacity, and address underlying mechanical or operational issues in the tower. This generates immediate savings and improves the performance baseline for the entire plant or cooling system.

Step Two: Reduce water use and eliminate plume

After tower performance is optimized, customers can add the water recovery and plume mitigation system to reduce evaporation losses, eliminate visible plumes, and decrease reliance on external water sources. This is especially valuable in regions with high water prices or water scarcity, and in plants subject to plume or drift regulations.