Title

Field Validation of Electrochemical Water Filtration System on an Open Loop Cooling Tower at Toyota Motor Manufacturing Plant in Blue Springs, Mississippi

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Field Validation of Electrochemical Water Filtration System on an Open Loop Cooling Tower at Toyota Motor Manufacturing Plant in Blue Springs, MS

Operating and Performance Technical Report

Industrial Technology Validation

September 2024

Disclaimer

The work described in this report was funded by the U.S. Department of Energy's (DOE) Industrial Efficiency and Decarbonization Office (IEDO), formerly known as the Advanced Manufacturing Office (AMO).

The Industrial Technology Validation (ITV) program is designed to address the need to identify, validate, and showcase the capabilities of new, emerging, and underutilized technologies in the industrial sector. The primary objective of ITV is to conduct robust evaluation and document performance data on these technologies to help expedite their commercialization and widespread deployment. By performing thorough validations and demonstrating the efficacy of these industrial technologies, the ITV program plays a crucial role in providing the necessary information for industry stakeholders to make informed decisions about their adoption. Each report conveys the performance results from a specific installation at a specific industrial site, following a specific methodology. Performance may vary for other installations of the same technology or if other methodologies are used to assess performance.

Technologies selected for evaluation by the ITV program can vary in their stage of commercialization. Depending on its stage, there will be some notable variations in the evaluation, such as scale of installation or data availability, that will influence the depth of each analysis and the ability to extrapolate findings.

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List of Acronyms

AHU	Air handling units
ACU	Air compressor units
AHR	Ash house recovery
CF	Chemical flocculation
CHW	Chilled water
CHWR	Chilled water return temperature
CHWS	Chilled water supply temperature
CWET	Condenser water entering temperature
DC	Direct current
DWT	Dynamic Water Technologies
EC	Electrocoagulation
EVO	Efficiency Valuation Organization
gpm	Gallons per minute
hp	Horsepower
HOR	Heat of rejection
HVAC	Heating, ventilation, and air conditioning
EWT	Entering water temperature
IGV	Inlet guided vanes control
IPMVP	International Performance Measurement and Verification Protocol
ITV	Industrial Technology Validation
kWh	Kilowatt-hour
LWT	Leaving water temperature
MUTDS	Total dissolved solids in makeup water
mmhos	Millimhos
M&V	Measurement and verification
RMSE	Root mean square error
TMMMS	Toyota Motor Manufacturing Mississippi
TDS	Total dissolved solids
TSS	Total suspended solids

VFD	Variable frequency drives
WWTP	Wastewater treatment plant
yr	Year

Executive Summary

Project Background

The Industrial Technology Validation (ITV) program aims to identify and demonstrate the performance of new, emerging, and underutilized technologies in the industrial sector to help inform decisions towards accelerating commercialization and deployment.

One such ITV project is to demonstrate the performance of an electrochemical water treatment technology on a cooling tower at an automotive plant. Cooling towers are vital equipment for dissipating heat from industrial processes. However, they face challenges related to scaling, corrosion, and the growth of biological contaminants. Effective cooling tower water filtration and treatment is essential to reduce these contaminants, along with other total suspended solids (TSS) and total dissolved solids (TDS) in the system. Various treatment systems, such as sand-based filters, centrifugal separators, and disc filters, offer distinct advantages and limitations. ElectroCell Systems offers a skid-mounted, electrochemical based, side-stream filtration system.

Facility and Technology Description and Scope

This study evaluated the performance of an ElectroCell water treatment system at Toyota Motor Manufacturing Mississippi (TMMMS) compared to an existing centrifugal-based filtration system from Lakos. The incumbent technology uses centrifugal principles to eliminate TSS from cooling tower water. In contrast, the ElectroCell system employs a multi-stage electrochemical process using low-voltage and high-voltage ionizers to generate an electrostatic field to treat the water. The scope of the evaluation included six chillers, each rated at 2,000 tons, three cooling tower cells, three air compressors (one screw at 702 hp and two centrifugal at 1,860 hp), and the relevant water treatment systems.

Study Design and Objectives

The evaluation's goal was to assess the impact of the ElectroCell filtration system on energy, water, and chemical usage in the chilled water and compressed air systems with a cooling tower loop.

The following are some of ElectroCell Systems' claims and reasonings that were stated in their application and used as the basis for ITV evaluation:

- **Water usage reduction**: The electrochemical-based system removes particulate down to 1 micron, which is an improvement from most filtration systems. In theory, less particulate in the loop should reduce the need for blowdown and in turn makeup water.
- **Energy reduction**: The system minimizes scaling, resulting in less fouling and improved heat transfer within the system, leading to reduced energy consumption at

chillers, air compressors, and cooling towers. It also collapses laminar boundaries of the water, leading to better heat transfer.

- **Chemical usage reduction**: The system decreases the reliance on chemicals for water treatment by removing finer particulate compared to traditional filtration systems, thereby reducing the required chemical treatment to maintain water quality. Additionally, with less blowdown, and in turn less makeup water, less water needs to be chemically treated.

Methodology

The evaluation methodology followed a Measurement and Verification (M&V) strategy based on the International Performance Measurement and Verification Protocol (IPMVP) Option B – utilizing a retrofit isolation method with all parameter measurements – through comprehensive measurements and analyses of the affected systems. The objective was to compare energy, water, and chemical treatment use with the ElectroCell System compared to the incumbent centrifugal filtration system. Our analysis relied on field data to construct predictive models for energy, water, and chemical treatment use to assess the impact of the proposed technology. Data was collected from February 2022 to February 2023, when the centrifugal system operated, and from February 2021 to February 2022, when the ElectroCell System ran.[1] The methodology involved the development of mathematical models for various systems to study the impact from different aspects:

- **Energy Model:** This model predicted electricity consumption based on chilled water load and condenser water entering temperature for each of the chillers. It predicted cooling tower fan energy based on the cooling tower heat of rejection and approach temperature. The electricity consumed by the compressed air system was modeled based on compressed air flow and pressure. The electricity consumed by the respective filtration systems was also considered based on metered data throughout the entire evaluation period.
- **Water Model:** The water model predicted makeup water use based on cooling tower heat of rejection, ash house recovery volume, and makeup water total dissolved solids.
- **Chemical Treatment Model:** This model calculated the chemical treatment costs per kilogallon of blowdown rate for each of the inhibitors and biocides.

Each model's goodness of fit characteristics were evaluated to ensure they met IPMVP criteria. The energy, water, and chemical impacts were determined by comparing actual use with the centrifugal system to modeled use with the ElectroCell system.

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[1] The ElectroCell system was installed in August 2018. Data was collected about its operation from February 2021 to February 2022, at which point the incumbent centrifugal system was operated and data collected about its performance for a year, from February 2022 to February 2023. TMMMS then switched back to the ElectroCell system after the evaluation.

Project Results/Findings

Based on our analysis, the energy consumption associated with the chillers showed a reduction ranging from 1.1-1.4%, while the energy impact associated with the air compressors showed an improved efficiency of 2.9-3.3% compared to baseline. The water analysis showed 8-15% less makeup water usage and 45% less chemical treatment use. It should be noted that while the evaluation was normalized to all pertinent available factors using rigorous M&V approaches and sound statistical techniques, there may have been other unknown factors outside of the evaluation boundary that could have influenced the results.

These findings are based on the evaluation of this technology at the selected site and its specific configuration and set of operating conditions. The performance of filtration systems depends on site-specific factors like existing equipment conditions, ambient air quality, particulate matter presence, and seasonal variations. It is influenced by wet bulb temperature and the quality of makeup water, including hardness, pH, and TDS levels, all of which play a significant role in water and chemical usage and require careful consideration for implementation.

Table of Contents

List of Figures

List of Tables

SECTION 1

Introduction

1 Introduction

The U.S. Department of Energy's Industrial Efficiency and Decarbonization Office (IEDO) has introduced the Industrial Technology Validation (ITV) program. This initiative is designed to address the need to identify, validate, and showcase the capabilities of new, emerging, and underutilized technologies in the industrial sector. The primary objective of ITV is to conduct robust evaluation and document performance data on these technologies to help expedite their commercialization and widespread deployment. By performing thorough validations and demonstrating the efficacy of these industrial technologies, the ITV program plays a crucial role in providing the necessary information for industry stakeholders to make informed decisions about their adoption. In turn, this will contribute to accelerating the transition towards more sustainable and efficient industrial processes.

Cooling towers play a pivotal role in effectively dissipating the heat generated by industrial processes. However, their operation encounters substantial challenges related to scaling, corrosion, and the proliferation of biological contaminants, all of which significantly impact operational costs. To address these issues, it is essential to implement effective cooling tower water treatment measures aimed at reducing the concentration of total suspended solids (TSS) and total dissolved solids (TDS) within the system. Several water treatment systems are available in the market, each with its own set of advantages and drawbacks (Duan et al. 2012). These systems include sand-based filters, centrifugal separators, and disc filters, among others used in conjunction with chemical treatment solutions.

The technology evaluated herein, from ElectroCell Systems, offers a skid-mounted electrochemical-based pressurized water treatment system that can be configured as a side-stream water filtration system. According to ElectroCell Systems, the technology uses a three-stage process to remove TSS and control TDS. ElectroCell claims their technology saves energy, water, and chemical treatment use compared to conventional water treatment methods.

This evaluation was conducted at the Toyota Motor Manufacturing Mississippi (TMMMS) plant, comparing the ElectroCell system's performance to an existing centrifugal-based filtration system provided by Lakos. The incumbent technology utilizes centrifugal principles to eliminate TSS from cooling tower water. The primary objective of this evaluation was to gauge the impact of the ElectroCell filtration system on energy consumption, water usage, and chemical usage within the chilled water and compressed air systems that reject heat to an open loop cooling tower.

SECTION 2

Description: Facility, Technology, and Project

2 Description

2.1 Facility Description

TMMMS is located in Blue Springs, Mississippi, and has been manufacturing Toyota Corollas since 2011. The plant has 2,972 employees and produces approximately 165,000 cars per year. The facility operates 16 hours per day from Monday through Friday, with a week of shutdown in summer and a week of shutdown in winter. The chilled water (CHW) plant serves a variety of heating, ventilation, and air conditioning (HVAC) loads throughout the facility. The HVAC load consists of approximately 40 small-to-medium air handling units (AHUs) that provide sensible cooling only and three larger AHUs that provide sensible cooling and dehumidification to paint booths.

The CHW plant is served by six 2,000-ton chillers. Three of the chillers (labeled CH-501-1, -2, and -3) are constant speed and use constant primary flow, while the remaining three (labeled CH-501-4, -5, and -6) are variable speed and use variable primary flow. The secondary loop is served by four secondary pumps, equipped with variable frequency drives (VFDs). CHW is maintained at 44°F. Heat is rejected via an open condenser water loop. The loop is served by one large cooling tower with three cells. The cooling tower fans use VFDs, cycling on and off at 90% fixed speed, controlling to a minimum condenser entering water temperature setpoint of 60°F. In addition to serving the chillers, the condenser water loop cools three air compressors.

2.2 Project Description

The M&V demonstration intended to verify the change in energy, water, and chemical treatment use of a chilled water and compressed air system due to the ElectroCell filtration system serving an open loop cooling tower. The cooling tower initially used a centrifugal side stream filtration system, which is original to the facility. This technology uses a passive centrifugal system approach to remove suspended solids through a bleed every three to four minutes on average. The incumbent centrifugal system removes 98% of solids larger than 40 microns but is limited in removing smaller solids (Duan et al. 2012). Toyota replaced the side stream filtration system with the ElectroCell system in 2018.

2.3 Description of Incumbent System

TMMMS originally used a centrifugal filtration system. The simplicity of their design makes centrifugal filtration systems a more economical choice than other systems. They typically have long useful lives and relatively low maintenance costs. Separators are fed high-velocity water to develop a circular flow pattern (Figure 1).[2]. The centrifugal force causes heavier suspended solids to migrate toward the separator's sidewalls and downward into a holding

[2] For more information about centrifugal filtration technology, visit https://www.energy.gov/femp/articles/side-stream-filtration-cooling-towers.

chamber, which are then purged. The disadvantage of these systems is that they can only remove particulates down to 40 microns, compared to the ElectroCell system, which can remove particulates down to 1 micron. Any dissolved or smaller suspended solids are removed through blowdown and mitigated through chemical treatment. This could result in better-treated cooling tower water, leading to improved heat transfer by reducing deposition on heat transfer surfaces.

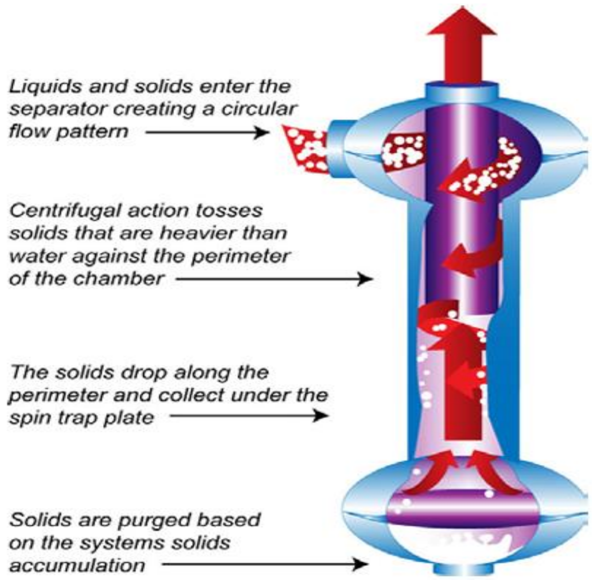

Figure 1. Centrifugal filtration technology

2.4 ElectroCell System Technology Description

TMMMS installed the ElectroCell System EC-6000 (Figure 2) in August of 2018 and ran it continuously for almost three years, at which point TMMMS switched back to the incumbent centrifugal system for this M&V effort.

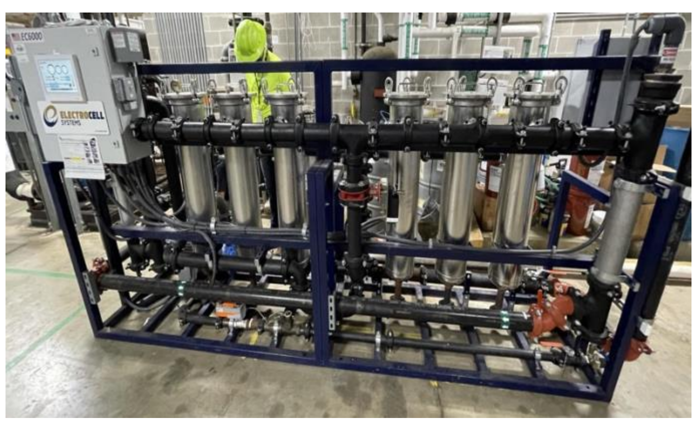

Figure 2. ElectroCell Systems Model EC-6000 installed at TMMMS

The following is an excerpt of ElectroCell Systems' description of their technology from their application:

In the first stage, water is sent through a series of low-voltage DC ionizers, which flocculate and coagulate suspended solids, creating larger particles from smaller particles. In the second stage, water is sent through static mixers, which collect particulate at the bottom of the mixer (Figure 3)*. The particulate is then removed through a bleed cycle, where water is sent through the mixers to empty the vessels for some time. The third stage uses a positively charged high-voltage DC ionizer cell, generating an electrostatic field. The electrostatic field collapses the laminar boundary of the water. Collapsing the laminar boundary should lead to better heat transfer.*

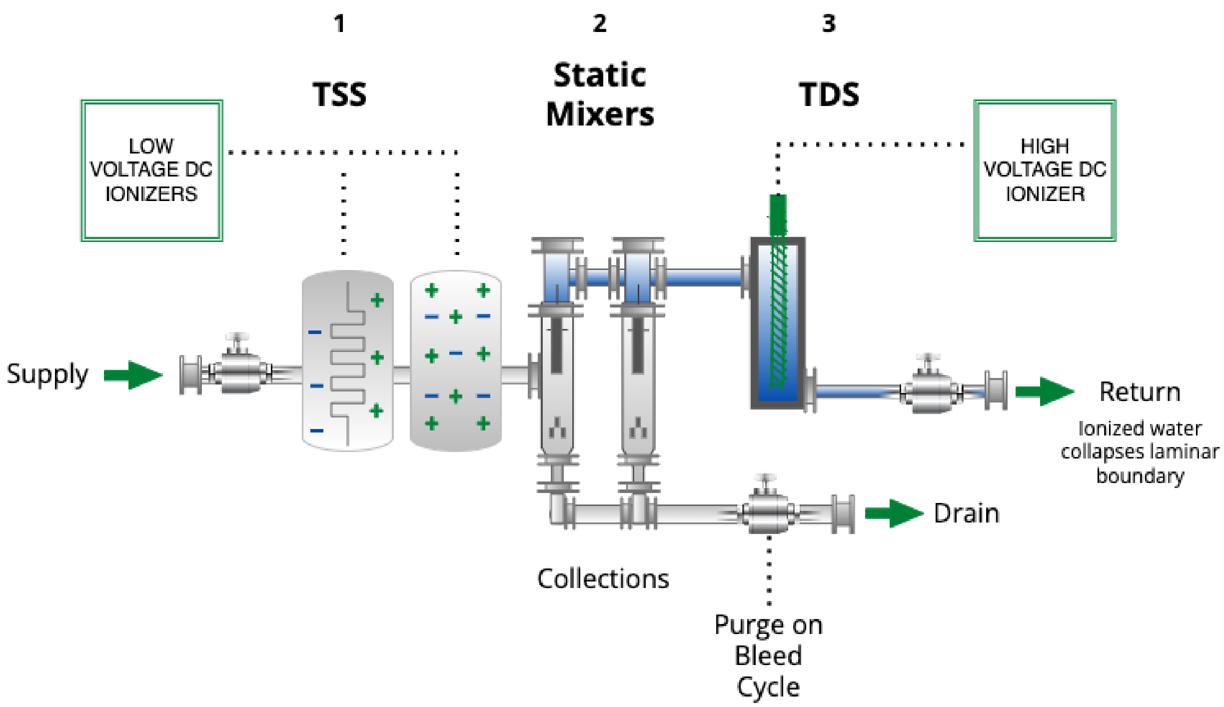

Figure 3. The three-stage ElectroCell system

SECTION 3

Technology Demonstration Intent

3 Technology Demonstration Intent

The primary objective of this study is to evaluate the energy, water, and chemical impact of implementing an ElectroCell system compared to a centrifugal filtration system within an open loop cooling tower. The evaluation focused on various performance metrics, comparing one year of operation with a centrifugal filtration system to one year with the ElectroCell System, normalized to pertinent variables as outlined in Section 5. The key performance indicators are listed below:

- Chilled water system performance (kWh/yr)
- Compressed air system performance (kWh/yr)
- Makeup water use (gallons/yr)
- Water treatment ($/yr)

By comparing these key performance indicators, the study aims to provide insights into the effectiveness of the ElectroCell system in terms of energy savings, water conservation, and reduced chemical treatment requirements for the chilled water and compressed air systems served by the open loop cooling tower.

The project scope includes chillers, cooling tower fans, air compressors, and filtration systems. There are six chillers (labeled CH-501-1, CH-501-2, CH-501-3, CH-501-4, CH-501-5, and CH-501-6), each having a rated capacity of 2,000 tons and operating within a specific temperature range. The evaporator's designed entering water temperature (EWT) is 68°F, while leaving water temperature (LWT) is 44°F, for the designed flow rate of 2,000 gallons per minute (GPM). On the condenser side, the EWT is 85°F, the LWT is 100°F, and the designed flow rate is 3,760 GPM. The maximum input power for each chiller is 1,249 kW.

There are three cooling tower cells, each having a design flow of 8,060 GPM and operating within an inlet temperature of 100°F and an outlet temperature of 85°F. These cooling tower cells have a drain-down capacity of 7,300 gallons and use a 200 horsepower (HP) motor with a variable frequency drive (VFD) set to a fixed speed of 90%. TMMMS utilizes three different air compressor units (ACUs) with varying specifications, made by Atlas Copco. Two centrifugal air compressors (referred to as C2 and C3 in the following sections) are rated at 1,860 HP with inlet guided vanes control (IGV), while the other air compressor (referred to as C1) is a screw rated at 702 HP and controlled by a VFD.

SECTION

4

Evaluation Scope and Boundary

4 Evaluation Scope and Boundary

4.1 IPMVP Option

The evaluation methodology followed the International Performance Measurement and Verification Protocol (IPMVP),[3] developed by the Efficiency Valuation Organization (EVO). The objective of the IPMVP is to develop a consensus approach to measuring and verifying efficiency investments to facilitate scaled-up global engagement on energy efficiency.

The IPMVP outlines four options depending on the purpose, scope, and objective of the project. These four options are categorized into two general types: retrofit isolation and whole facility. Retrofit-isolation methods consider only the affected equipment or system, independent of the rest of the facility. Whole-facility methods consider the total building or facility energy use and de-emphasize specific equipment performance. The primary difference in these approaches is where the measurement boundary is drawn. Options A and B are retrofit-isolation methods, Option C is a whole-facility method, and Option D can be used as either, but is usually applied as a whole-facility method.

The M&V approach selected for this demonstration follows IPMVP Option B, retrofit isolation with all parameter measurements (IPMVP 2022). Energy consumption, water usage, and chemical usage were monitored by field measurements, trended for one year with the incumbent centrifugal filtration technology and one year with the ElectroCell system. Savings were quantified by comparing actual consumption/usage data for one year with the incumbent centrifugal technology to predicted consumption/usage based on one year of actual operation with the ElectroCell system. The ElectroCell system was installed in August of 2018. The one-year evaluation period of the ElectroCell system was from February 10, 2021 through February 9, 2022 (Figure 4).

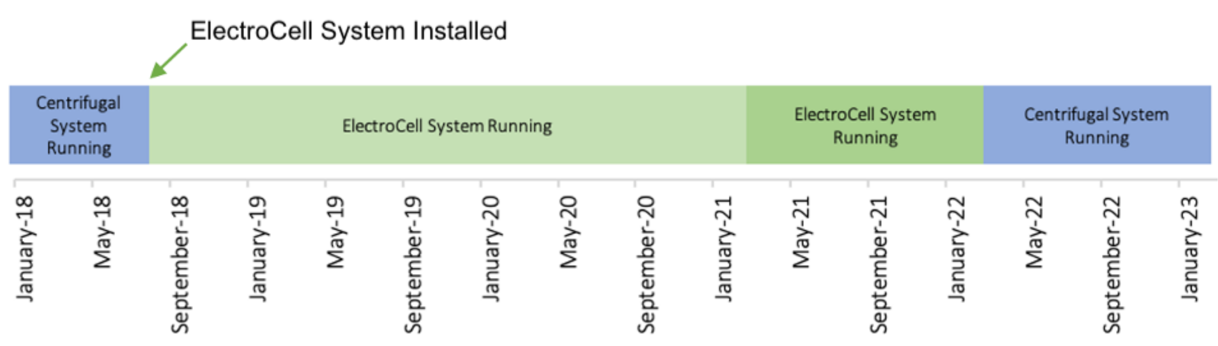

Figure 4. Timeline showing installation schedule and evaluation period

[3] For more information about IPMVP standards, visit https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp.

TMMMS switched to the incumbent centrifugal system on February 10, 2022. Thus, the period from February 10, 2022 through February 9, 2023 was used to assess the performance of the incumbent technology.

4.2 Measurement Boundary Descriptions

For the energy model, the system boundary includes the chillers, air compressors, filtration systems, and cooling tower fans (Figure 5). The load and energy consumption of the chillers, air compressors, filtration systems, and cooling tower fans are quantified using historical trend data (discussed in detail in Section 5). For water use, the measurement boundary includes both the cooling tower to quantify makeup water use and the ash house recovery water volume, an additional source for makeup water that is recovered condensation collected from dehumidifiers at the facility. (This source is called the "ash house recovery" makeup source, or AHR.) The AHR makeup source is weather-dependent, collected during dehumidification by air handlers, and consistently produces very clean water. Makeup water quality was also considered and factored into the performance assessment, as the water source changed during the evaluation period. For the chemical treatment, the measurement boundary includes the use of chemicals for the cooling tower water loop in gallons and blowdown volume in gallons. Toyota uses three chemicals to treat the cooling tower loop water: CL2250 and CL49 are biocides that control or inhibit biological growth, and CL5855 is an inhibitor that slows corrosion and scaling.

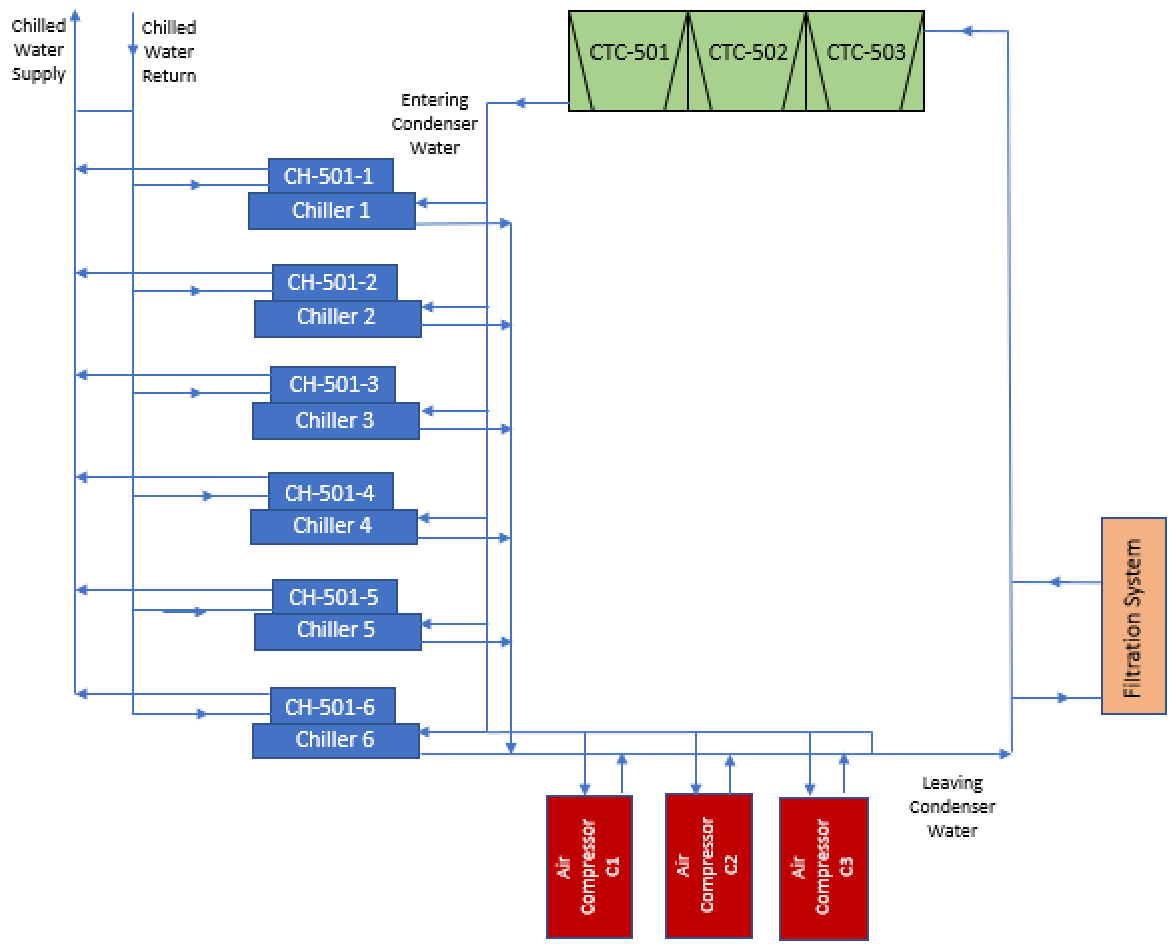

Figure 5. Scope of evaluation for the chilled water system

4.3 Interactive Effects Beyond the Measurement Boundary

The evaluation and the analysis solely focused on the systems or components within the boundary described above. The effects of the systems outside the boundary are assumed to have a minimal impact on the systems and variables within the boundary that are considered for this evaluation.

SECTION

5

Data Collection and Adjustments

5 Data Collection and Adjustments

5.1 Data Collection

Based on the scope and boundaries, a list of data points was developed (Table 1) to assess the impact of the ElectroCell system against the incumbent system. Some data for these points was obtained from TMMMS through their data acquisition and management system. Other data was obtained by installing additional loggers to supplement the data provided by TMMMS. The collected data spanned from February 2019 through February 2023. ElectroCell Systems provided data from their skid for one year. The evaluation team conducted two site visits to the facility, in October 2021 and October 2022.

Table 1. Summary of Data Points Collected for Each System

System	Data Point	Units	Sampling Rate
Chilled Water System (CHW)	Chilled water load	Tons	15 minutes
	Chiller power	kW	15 minutes
	Chilled water flow, primary loop	GPM	15 minutes
	Evaporator entering water temperature	°F	15 minutes
	Evaporator leaving water temperature	°F	15 minutes
	Condenser entering water temperature	°F	15 minutes
	Condenser leaving water temperature	°F	15 minutes
	Evaporator saturated temperature	°F	15 minutes
	Condenser saturated temperature	°F	15 minutes
	Cooling tower fan power	kW	15 minutes
Air Compressors	Compressed air flow	CFM[4]	5 seconds
	Compressed air pressure	PSI	5 seconds
	Compressor power	kW	5 seconds
Filtration Systems	Incumbent centrifugal filtration system	Amps	Hourly

[4] Cubic feet per minute.

System	Data Point	Units	Sampling Rate
	ElectroCell load	Amps	Hourly
	ElectroCell pump VFD speed	(%)	Hourly
	Filter flow	GPM	Hourly
	Bleed flow	GPM	Hourly
	Conductivity	GPM	Hourly
Outside Air Conditions	Dry bulb temperature	°F	Hourly
	Wet bulb temperature	°F	Hourly
	Outdoor air relative humidity	%RH	Hourly
Water	Makeup water usage	gallons	Hourly
	Blowdown water	gallons	Weekly
	Ash house recovery water	gallons	Weekly
	Makeup TDS	mmhos	Weekly
	Tower TDS	mmhos	Weekly
	Tower conductivity	mmhos	Weekly
Chemical Treatment	CL2250	gallons	Weekly
	CL5855	gallons	Weekly
	CL49	gallons	Weekly

5.2 Data Cleaning

Data cleaning is a crucial step in the data preparation process and the foundation for the subsequent data analysis. It involves identifying and rectifying errors or inconsistencies in datasets to ensure the data is accurate, reliable, and suitable for analysis. Cleaning was necessary when data sets were incomplete or included outlier data.

5.2.1 Energy

The data from the period when the ElectroCell system was operating, which was used to develop a predictive model, was scrubbed to only include data when the respective equipment was operational. All null data was removed to create an accurate model to predict energy use for each chiller. The chilled water load data for Chiller 4 was missing from August 20, 2022 through August 30, 2022. A separate model was created to predict the CHW load as a function of chiller power for the missing ten days and was used to calculate the power for this chiller during this period.

5.2.2 Compressed Air System

Compressed air data was retrieved from TMMMS' iZ controls system. The iZ controls system stages the air compressors on and off for efficient operation. This system also records and archives data points in five-second intervals. Two years of compressed air flow, compressed air pressure, and power data were collected and aggregated into an hourly level that was used for analysis. During one period, between August and November of 2022, compressed air flow data was missing for Compressors C2 and C3. To account for the missing data, other data from this period was removed to create predictive models, hence only using data when there is both flow and power data for the compressors. For example, the plot in Figure 6 below shows the period where flow data was missing for C3. C1 ran throughout the year and had no missing data.

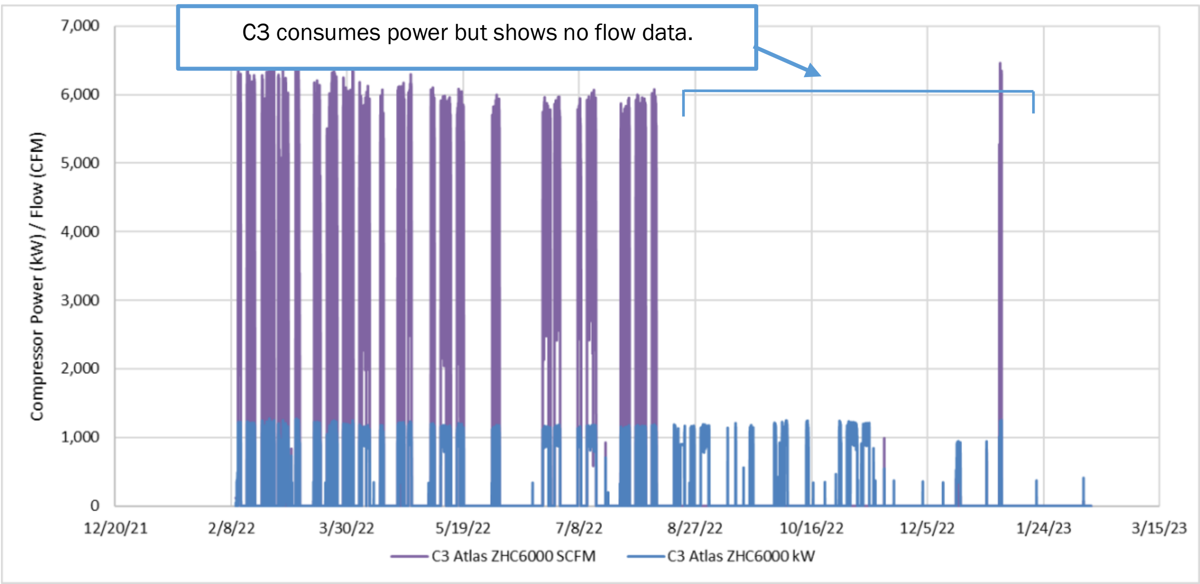

Figure 6. Plot showing missing data for Compressor C3 air flow

5.2.3 Makeup Water

Hourly makeup water data was available as part of the trend data; however, some data (e.g., blowdown) was only available at a daily interval from manual readings of totalized meters recorded on weekdays (i.e., five days per week). Additionally, the readings of a totalized meter on Mondays included usage from the weekend, so the data was aggregated to a weekly level to normalize for these daily anomalies.

The makeup water TDS and ash house recovery (AHR) volume were available on a weekly basis from TMMMS' chemical treatment contractor reports. The AHR gallon measurements were taken from manual readings of a totalized meter. There were some weeks when measurements were not taken and others when meter data was misread. For the weeks with missing data, the closest correct readings of the week before and after were used to calculate the total usage for the missing time period. Outliers, defined as values exceeding the mean by more than three standard deviations, were flagged and addressed appropriately. This usage was then divided by the number of days between correct readings to calculate a rate in gallons per day. Lastly, the rate was applied to the days between the missing week's read date and the period before and after the missing week.

The missing makeup TDS data from the chemical treatment reports was also estimated by taking an average of the readings before and after the missing week.

5.2.4 Chemical Treatment

Chemical treatment data was also recorded on weekdays based on changes in inventory tanks from the chemical treatment contractor. This data was aggregated to a weekly level, as the reading on Monday included usage over the weekend.

SECTION 6

Calculation Methodology

6 Calculation Methodology

The evaluation methodology, which followed IPMVP Option B (i.e., retrofit isolation approach with all parameter measurements), incorporates comprehensive measurements and analysis of the impacted systems. This approach relied on field data to construct predictive models for energy, water, and chemical treatment consumption. Specifically, it compares modeled energy, water, and chemical treatment use if the ElectroCell System was running, compared to actual use with the incumbent centrifugal filtration system (Figure 7).

To achieve this, actual data collected from February 2022 to February 2023, representing use of the incumbent centrifugal treatment system, was juxtaposed with predicted use with the ElectroCell system. This ElectroCell system model was developed based on data collected from February 2021 to February 2022. This approach allowed for the prediction of usage by the ElectroCell system if it were operating during the same period when the centrifugal treatment system was operating. The purpose was to account for any potential variations in operating conditions and assess the impact of the ElectroCell system by making appropriate adjustments.

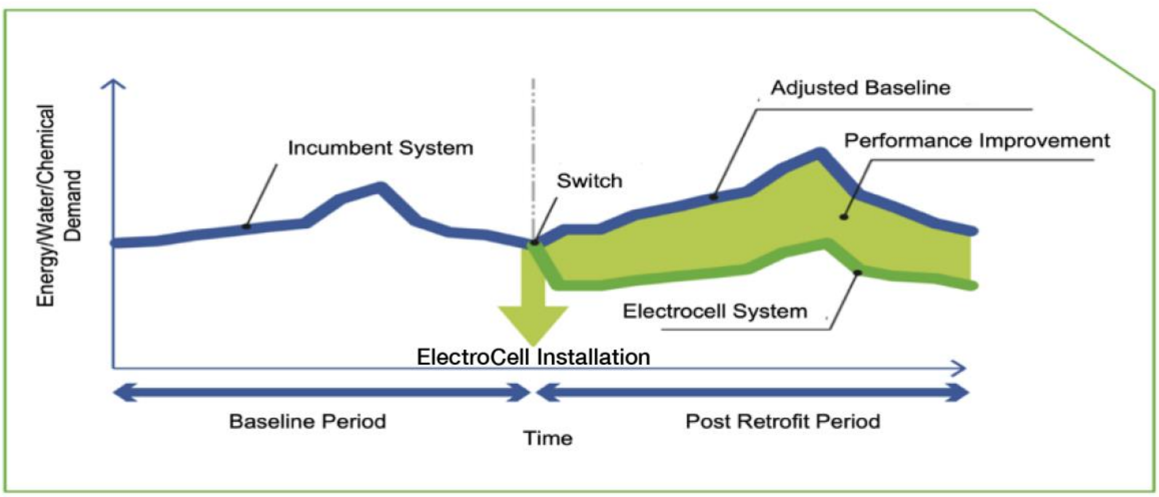

Figure 7. Evaluation methodology

These adjustments, whether routine or non-routine, are fundamental to IPMVP's methods for calculating energy and water savings. They allow an equitable comparison of energy and water used during two different periods. The savings or performance impact is calculated by comparing energy and water use with the incumbent centrifugal technology to energy and water use with the ElectroCell System after making the necessary adjustments to account for any changes between data collection periods, as shown in the equation below.

$$Savings\ Impact = Energy\ and\ Water\ Use_{Centrifugal} - Energy\ and\ Water\ Use_{Electrocell\ System} \pm Routine\ Adjustments\ \pm Non - Routine\ Adjustments$$

Routine adjustments are used to account for expected variations in independent variables that affect the performance variables. These may include, but are not limited to, outdoor temperatures, occupancy levels, day type, or production metrics. Routine adjustments involve developing a mathematical model to correlate energy or water use to the appropriate independent variables. The following section focuses on these routine adjustments and the model development effort for energy consumption associated with the chilled water and compressed air systems, as well as the water and chemical usage of the cooling tower system.

Non-routine adjustments (NRA) are made to account for non-routine events (NREs) that are unexpected changes in energy or water use and are not due to variations in independent variables. NRAs are corrections used to compensate for these unanticipated changes to ensure an equitable comparison of energy use between periods. There were no non-routine adjustments for this M&V effort.

6.1 Model Development

6.1.1 Chilled Water System Energy

The selected key performance variable for the chilled water (CHW) system energy model was electricity consumption. This includes all electricity consumed by the relevant components of the CHW system, including cooling tower fan and filtration pumps.

Each component of the CHW system was modeled separately to calculate the total system energy consumption. This involved identifying independent variables that affect energy consumption for each of the components. This also included understanding the underlying engineering principles, reviewing key performance variables, calculations/equations, factors such as weather, and exploratory data analysis to understand the relationships. A separate model was made for each of the six chillers and the cooling tower.

6.1.1.1 Chiller Energy

After considering many independent variables, it was found that the chilled water load of the chiller and the condenser water entering temperature (CWET) were the most significant variables in predicted chiller energy use. The chilled water load represents the amount of cooling the chiller provides, where the CWET is the temperature of the condenser water entering the chiller, which is affected by outdoor weather conditions and affects chiller performance.

Chilled water load (CHW Load) is the cooling load of the chiller in tons, which is calculated for each of the chillers using the following formula (Turner 2004):

$$CHW\ Load\ (Tons) = \frac{500 * Flow\ (gpm) * (CHWR - CHWS)°\mathrm{F}}{\frac{12{,}000\frac{Btu}{h}}{1\ Ton}}$$

Where Flow is the chilled water flow rate in gallons per minute, CHWR is the chilled water return temperature in °F, and CHWS is the chilled water supply temperature in °F.

Condenser water entering temperature (CWET) is the temperature of the water entering the chiller condenser from the cooling tower (Figure 5). The cooling tower at TMMMS cycles fans to maintain CWET setpoint. The CWET impacts the performance of the chiller as colder water entering condenser water reduces the required lift at the compressor. Separate models were created for each of the six chillers.

Based on the regression model, the *Chiller Power* (in kW) can be expressed as:

$$Chiller\ Power\ (kW) = CHW\ Load\ (Tons) * x_1 + CWET\ (°\text{F}) * x_2 + c$$

Where x_1 and x_2 are the regression coefficients for the independent variables CHW Load (tons) and CWET (°F), respectively, and *c* is the intercept term for the regression model. These coefficients and intercept terms for each of the chillers are summarized in Table 2 below. The regression coefficient (x_1 and x_2) represents the change in the dependent variable resulting from a one-unit change in the predictor variable, all other variables being held constant. In the regression model, for example, a one-ton increase in CHW Load for Chiller 1 increases the chiller power by 0.327 kW.

Table 2. Regression Model Characteristics for Each Chiller

Chiller	CHW Load Coefficient x_1	CWET Coefficient x_2	Intercept c
1	0.327448	7.334597	-221.546
2	0.469025	6.14441	-169.248
3	0.409682	5.277271	-150.4017
4	0.265995	9.300689	-298.1469
5	0.511618	3.210972	-89.1138
6	0.305587	6.567684	-145.5083

The goodness of fit (GOF) characteristics for all these models are shown in Table 3, which include R^2 (76-95%), zero bias, and CV_{RMSE} (5-16%) and meet the criteria established by IPMVP. For example, the regression analysis (Table 3) for Chiller 2 indicates that the coefficient of determination (R^2) is 95%, which means that 95% of the variation in chiller power draw can be explained by the model using chiller load and CWET as independent variables.

Root mean squared error (RMSE), or standard error of the estimate (SE), is an indicator of the scatter or random variability. It is the standard deviation of errors of prediction about the regression line. The coefficient of variation of the root mean squared error (CV_{RMSE}) is the RMSE normalized by the average y-value.

Normalizing the RMSE makes this a non-dimensional that describes how well the model fits the data. It is not affected by the degree of dependence between the independent and dependent variables, making it more informative than R^2 for situations where the dependency is relatively low. Net determination bias (bias) is the percentage error in the energy use predicted by the model compared to the actual energy use. The bias for all the models was calculated to be zero. All the GOF metrics were found to meet IPMVP criteria and to be adequate for calculating savings. Additional background and information about GOF can be found in Appendix A.

Table 3. Goodness of Fit Characteristics for All Six Chillers

Parameter	Description	IPMVP Recommendation	Chiller 1	Chiller 2	Chiller 3	Chiller 4	Chiller 5	Chiller 6
R^2	Coefficient of determination	>= 75%	92%	95%	90%	80%	76%	87%
Bias	Net determination bias	0	0	0	0	0	0	0
CV_{RMSE}	Coefficient of variation of the root mean squared error	<= 20%	12%	5%	9%	12%	16%	12%
Chiller Load t-stat	Chiller Load t-statistic, slope	>= 2	155.4	148.2	165.95	81.61	155.38	101.31
CWET t-stat	CWET t-statistic, slope	>= 2	64.94	37.46	40.73	52.98	22.88	42.07

To calculate total CHW system energy savings, actual chiller energy usage during operation of the centrifugal system was compared to the predicted usage of ElectroCell's technology, based on the regressions defined above. The actual chiller energy use used to create the predictive model is compared to the predicted use in Figure 8 below. This shows a strong correlation. Based on IPVMP requirements as outlined in Table 4, the models are considered to be valid.

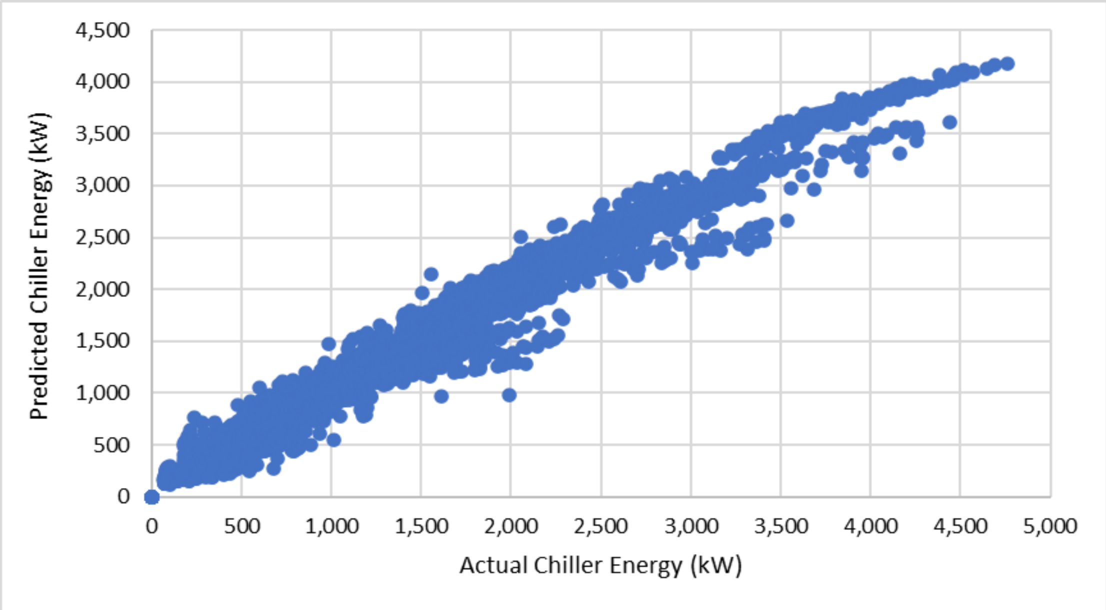

Figure 8. Actual vs. predicted CHW system energy with the ElectroCell system

6.1.1.2 Cooling Tower Energy

A model was developed to predict the cooling tower fan energy as a function of the independent variables. It was found that the heat of rejection (HOR) and cooling tower approach temperature were the most statistically significant independent variables. Cooling tower range, condenser water entering temperature, and wet bulb temperature were among the other independent variables considered; however, these variables were not statistically sound and contained inherent collinearity with the two selected independent variables.

Heat of rejection (HOR) is the heat introduced to the cooling tower by various sources. The cooling tower loop at TMMMS serves six chillers and three air compressors. HOR is one of the main drivers of cooling tower fan energy consumption. It is weather-dependent, as the CHW system serves HVAC loads. HOR in MBH was calculated using the following formula. It is assumed the cooling tower loop will absorb 85% of the power consumed by the air compressors as heat (Moskowitz 2010).

$$HOR\ (MBH) = \left(CHW\ Load\ (Tons) * \frac{12MBH}{1\ Ton}\right) + \left(Chiller\ Power\ (kW) * \frac{3.412\ MBH}{1\ kW}\right) + (Air\ Compressor\ Power(kW) * 85\% * \frac{3.412\ MBH}{1\ kW})$$

Where CHW Load is the total cooling load of Chillers 1–6, Chiller Power is the total power consumption of Chillers 1–6, and Air Compressor Power is the total power consumption of C1–C3. It is assumed that 85% of the power consumed by the air compressors will be rejected as heat to the cooling tower loop. *Cooling tower approach* is the temperature difference between the CWET and ambient wet bulb temperature (WBT).

$$Cooling\ Tower\ Approach\ (°F) = CWET\ (°F) - WBT\ (°F)$$

The CWET the cooling tower can achieve is constrained by ambient wet bulb temperature. The cooling tower fans must work harder as wet bulb temperature increases. While heat of rejection represents the load on the cooling tower, cooling tower approach represents the relationship between the CWET setpoint of the system compared to ambient conditions. This relationship between CWET, WBT, and cooling tower approach is illustrated in Figure 9.

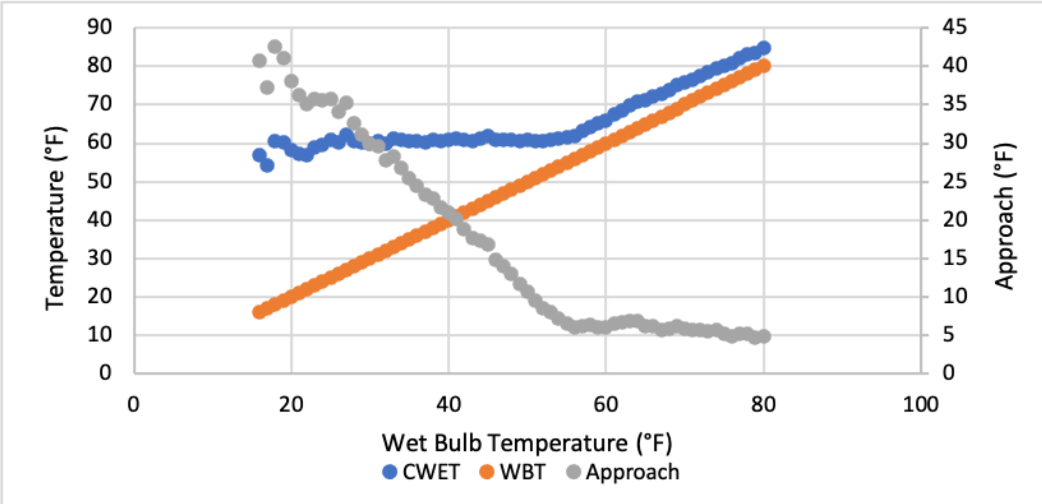

Figure 9. TMMMS cooling tower approach

Based on the regression analysis, the cooling tower power can be predicted in terms of the load on the cooling tower (heat of rejection) and weather conditions (cooling tower approach). The regression model using these independent variables can be described as:

$$Cooling\ Tower\ Power\ (kW) = 0.001749 * HOR\ (MBH) - 1.85 * CTAT(°F) + 64.68$$

Where HOR is the heat of rejection for the cooling tower and CTAT is the cooling tower approach temperature. The model details and goodness of fit (GOF) metrics for this model are shown in Table 4. Both independent variables, HOR and cooling tower approach temperature, were found to be the most statistically significant based on the regression analysis.

Table 4. Goodness of Fit Characteristics of the Cooling Tower Model

Parameter	Description	IPMVP Recommendation	Cooling Tower
R^2	Coefficient of determination	>= 75%	80%
Bias	Net determination bias	0	0
CV_{RMSE}	Coefficient of variation of the root mean squared error	<= 20%	32%
HOR t-stat	Heat of rejection t-statistic, slope	>= 2	130.57
CTAT t-stat	Cooling tower approach temperature t-statistic, slope	>= 2	66.10
Int t-stat	t-statistic, intercept	>= 2	90.85

While the R^2 value satisfies IPMVP requirements, the CV_{RMSE} exceeds the IPMVP recommended threshold of 20%. The cooling tower fans cycle on and off at constant speed setpoints of 90%. The stepped value nature of the data may indicate why the model statistics were poorer than the chiller models. This suggests that the uncertainty in the cooling tower model is higher than acceptable, which means that confidence in the accuracy of this model is low. The actual cooling tower energy usage is compared to the predicted use in Figure 10 below.

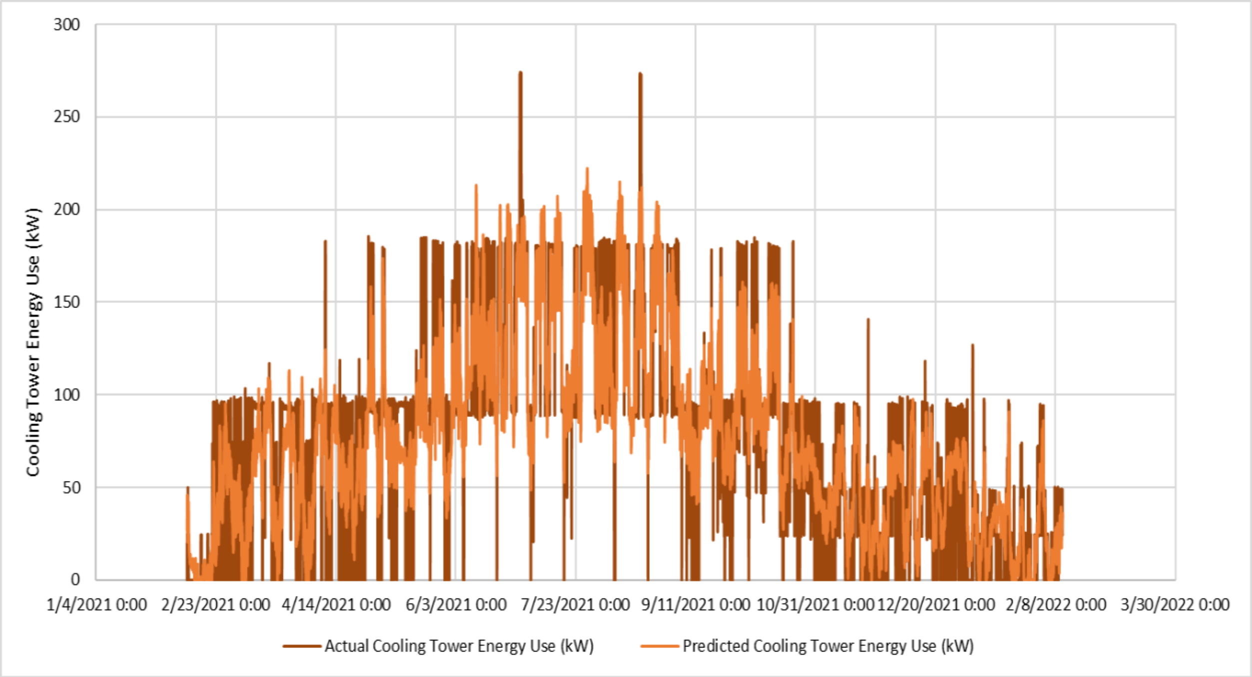

Figure 10. Actual vs. predicted cooling tower energy use with the ElectroCell system

Given these considerations, the evaluation model is unable to prove the ElectroCell system affects cooling tower energy use.

6.1.1.3 Filtration Energy

A current transducer was installed on the incumbent centrifugal system for six months to assess the power draw from this system. The average current draw of the system was 9.1 amps, which was constant with minimal variation. On the other hand, the average current draw for the ElectroCell system was 5.8 amps. Based on information provided by the vendor, the flow rate was adjusted on the ElectroCell system occasionally, usually before or after the cooling season, as more condenser flow is required during the cooling season when additional chillers are operating. It is assumed that if an adjustment is made every six months, then the average annual current draw of the system provides a reasonable estimate that can used to extrapolate over a year of operation. The filtration system energy model for both systems assumes 24x7 operation and averages measured current to calculate filtration system power using an average power factor of 85% and voltage of 480V. With these assumptions, the estimated power for the incumbent centrifugal system was 6.4 kW and 4.1 kW for the ElectroCell system.

6.1.2 Compressed Air Energy

The performance variable for the compressed air (CA) system is the energy consumed by the air compressor in kWh, which is the total sum of the electricity consumed by the three air compressors.

Predicted compressed air energy use was calculated as a function of compressed air flow and pressure for Compressor 1 (C1) and solely compressed air flow for Compressor 2 (C2) and Compressor 3 (C3).

6.1.2.1 Compressor 1 (C1)

Pressure and flow were considered as independent variables to predict compressor energy use. Data for compressor energy, compressed air pressure, and compressed air flow were analyzed to develop regression models with the ElectroCell system.

The predictive model used only data where both flow and pressure data were available and excluded other missing or anomalous data. The energy consumption model for C1 can be represented as:

$$C1\ Power\ (kW) = 0.14534 * Flow\ (SCFM) + 0.45 * Pressure\ (PSI) - 49.33$$

Where Flow is the flow rate of the compressed air generated in SCFM, and Pressure is the compressed air pressure that's being delivered to the facility in PSI. The GOF characteristics for this model for C1 are shown in Table 5 below and highlighted in light gray. Note that for C2 and C3, GOF statistics are calculated for the regression portion of the changepoint model.

Table 5. Goodness of Fit Characteristics of the Compressed Air Model

Parameter	Description	IPMVP Recommendation	C1	C2	C3
R^2	Coefficient of determination	>= 75%	98%	93%	93%
CV_{RMSE}	Coefficient of variation of the root mean squared error	<= 20%	5.5%	18%	2%
Flow t-stat	Flow t-statistic, slope	>= 2	1,120.95	175.58	230.17
Pressure t-stat	Pressure t-statistic, slope	>= 2	8.93	N/A	N/A
Int t-stat	t-statistic, intercept	>= 2	8.38	32.79	36.92
Bias	Net determination bias	0	0	0	0

Figure 11 shows the predicted power for C1 based on the regression model shown above, compared to actual C1 power.

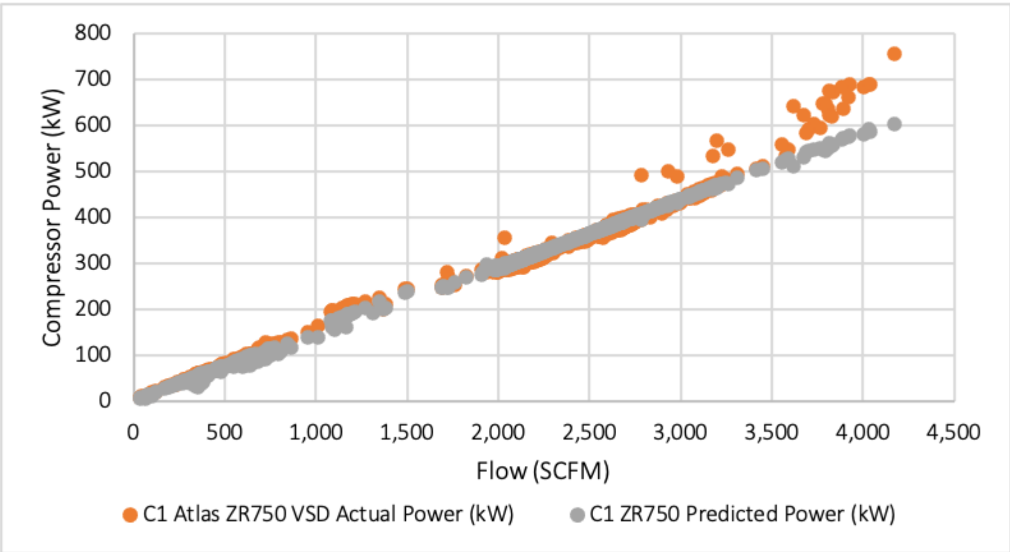

Figure 11. Actual vs. predicted C1 power

6.1.2.2 Compressors 2 and 3 (C2 and C3)

C1 is a screw compressor that operates as a trim unit, modulating to maintain system pressure and operating during nights and weekends during off-production. C2 and C3 are centrifugal compressors that use inlet guide vanes and have much poorer turn down than C1.

Electricity consumption, compressed air pressure, and compressed airflow data was analyzed for C2 and C3 using the same regression techniques. This analysis did not yield meaningful regression models, unlike for C1, as these compressors exhibited non-linearity in their operation when the compressors were unloading. This operation is shown in Figure 12 and Figure 13, where C2 and C3 power is plotted as a function of compressed air flow. This was confirmed later, through exploratory analysis of the electricity consumption as function of compressed air pressure and compressed air flow which did not show any relationship, unlike for C1.

Hence, the energy models for C2 and C3 were developed using a changepoint model to capture non-linearities exhibited by the operation of these compressors with the incumbent centrifugal system. This model assumes that the average power draw is constant below the changepoint for the compressed air flow of 4,000 SCFM and 4,380 SCFM for C2 and C3, respectively which is a function of how these compressors are operating and the amount of compressed air storage that might be available for these units. The second part of the model is a linear regression for power draw as a function of compressed air flow at higher compressed airflows.

- For C2 Compressed Airflow:
    - If the airflow < 4,000 SCFM:

C2 Power = 748 kW.

- If the airflow ≥ 4,000 SCFM:

C2 Power = 0.162633×Flow (SCFM) +166.67 kW

- For C3 Compressed Airflow:
    - If the airflow < 4,380 SCFM:

C3 Power = 848 kW.

- If the airflow ≥ 4,380 SCFM:

C3 Power = 0.168769×Flow (SCFM) +146.56 kW

Where Flow is the volume of the compressed air generated in SCFM.

The goodness of fit characteristics for the C2 and C3 models are shown in Table 5 above. The model’s GOF metrics, including R^2 (93-98%), zero bias, and CV_{RMSE} (2-18%), all meet IPMVP criteria. Figure 12 and Figure 13 show the predicted C2 and C3 power, based on the non-linear model shown above, compared to actual power data.

Figure 12. Actual vs. predicted C2 power

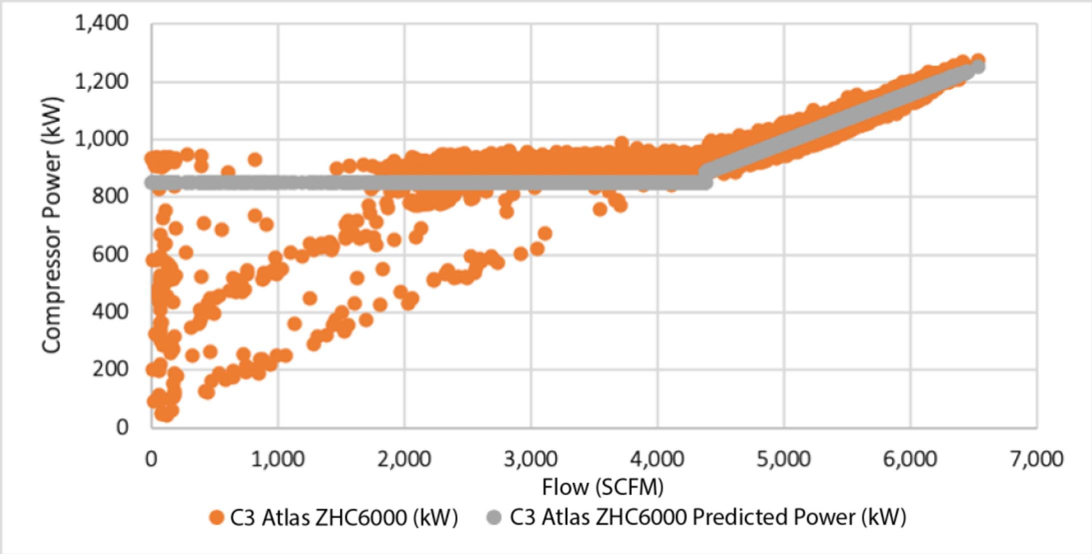

Figure 13. Actual vs. predicted C3 power

Figure 14 shows a plot of the actual total air compressor energy use compared to the total modeled compressor energy use from February 2022 through June 2022.

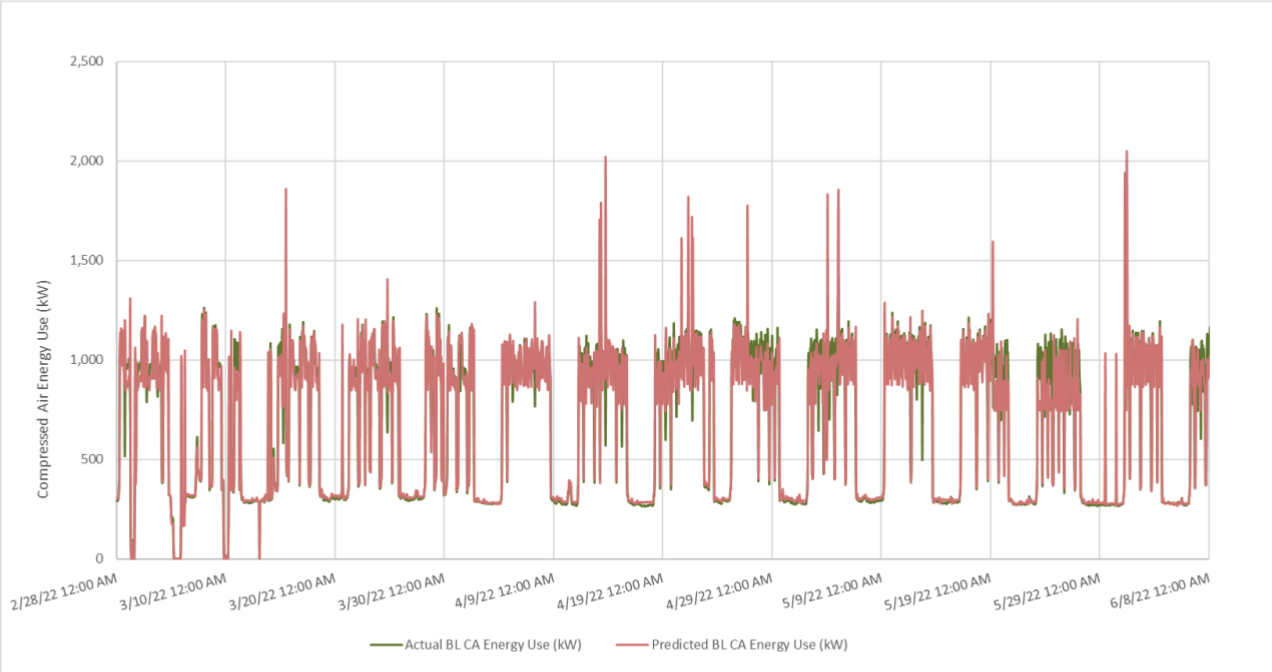

Figure 14. Actual vs. predicted compressor energy use

6.1.3 Water Use

A model was developed to predict makeup water use as a function of independent variables. Regression analysis identified three significant in predicting makeup water use: HOR, which is a function of the load on the cooling tower; makeup water TDS (MUTDS); and ash house recovery (AHR), which is an additional source of makeup water collected from the dehumidifiers at the facility. The quality of the AHR water is consistently clean and therefore volume alone was considered to be a valid independent variable.

Heat of rejection (HOR) is the total amount of heat introduced to the cooling tower. The cooling tower loop at TMMMS serves six chillers and three air compressors. HOR is the primary driver of the makeup water use. It is weather-dependent, as the CHW system serves HVAC loads. HOR was calculated using the following formula.

$$HOR\ (MBH) = CHW\ Load\ (Tons) * \frac{12MBH}{1\ Ton} + Chiller\ Power\ (kW) * \frac{3.412\ MBH}{1\ kW}$$
$$+ Air\ Compressor\ Power\ (kW) * 85\% * \frac{3.412\ MBH}{1\ kW}$$

Where CHW Load is the total cooling load of Chillers 1–6, Chiller Power is the total power consumption of Chillers 1–6 and Air Compressor Power is the total power consumption of C1–C3. It is assumed that 85% of the power consumed by the air compressors will be rejected as heat to the cooling tower loop.

TMMMS purchases water through their utility. The quality of the makeup water TDS (MUTDS) changed significantly when the utility changed water treatment plants and switched to a new river source in August 2021 (Figure 15). This change in quality is accounted for by adding it as an independent variable to model the makeup water usage.

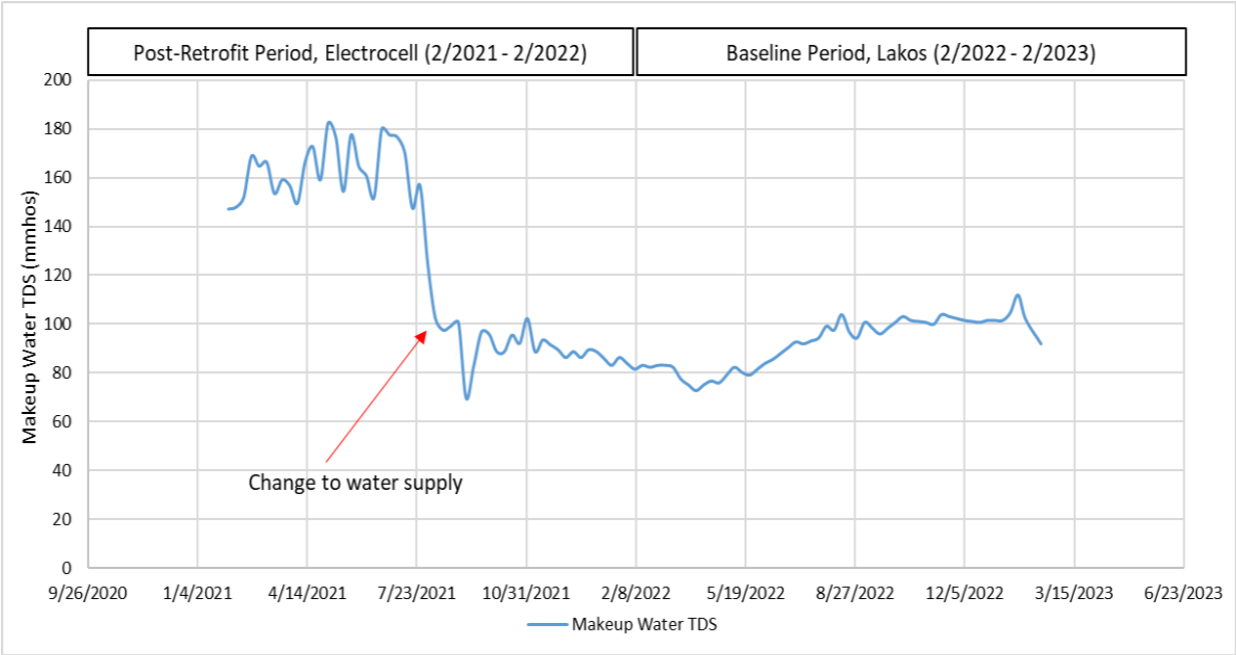

Figure 15. Makeup water total dissolved solids

Ash house recovery makeup water (AHR) is the recovered condensate collected from dehumidifiers at the facility, which is an additional source of clean makeup water. AHR volume affects the amount of additional makeup water that's needed for cooling tower operation.

The model to predict makeup water use with the ElectroCell system to account for any changes in the operating conditions can be defined as:

$$MU_{PR} = 0.095 * HOR - 0.4586 * AHR + 724.55 * MUTDS - 46{,}393.92$$

Where HOR is the heat of rejection expressed in MBH, AHR is the ash house recovery volume in gallons, and MUTDS is the total dissolved solids in makeup water (mmhos).

The significance of the independent variables and goodness of fit characteristics for the makeup water regression model are shown in Table 6. HOR is the main driver for makeup water usage, reflecting the amount of process heat rejected by the cooling tower. However, it is important to include the AHR gallons, as the more of this water is recovered, the less makeup water is required. Additionally, makeup water quality also significantly affects makeup water usage. As the makeup TDS for the incoming water increases, the system must blowdown more and use more makeup water.

Table 6. Goodness of Fit Characteristics for Makeup Water Usage Models

Parameter	Description	IPMVP Recommendation	Value
R^2	Coefficient of determination	>= 75%	98%
CV_{RMSE}	Coefficient of variation of the root mean squared error	<= 20%	11%
HOR t-stat	HOR t-statistic, slope	>= 2	23.43
AHR t-stat	AHR t-statistic, slope	>= 2	3.07
MUTDS t-stat	MUTDS t-statistic, slope	>= 2	3.93
t-stat	t-statistic, intercept	>= 2	2.25
Bias	Net determination bias	0	0

Based on the calculated R^2, the water model can explain 98% of the variation in makeup water usage. CV_{RMSE} was calculated to be 11%. The bias for this model was calculated to be zero. All the GOF metrics meet IPMVP criteria, validating the model to be adequate for calculating water use savings. To illustrate the validity of the model, the actual water use data used to make the predictive model was compared to the modeled water use in Figures 16 and 17.

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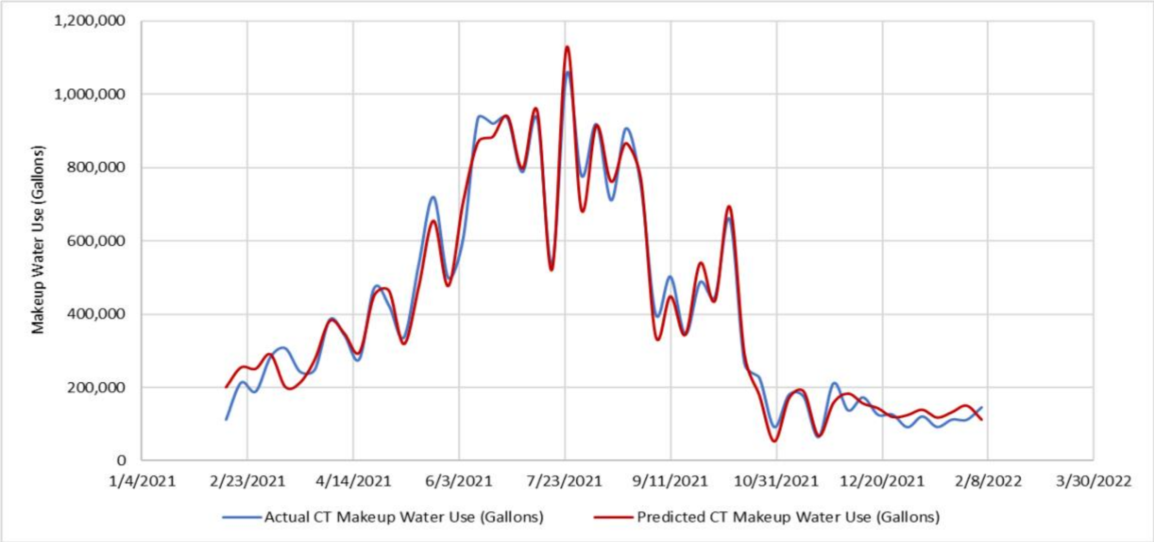

Figure 16. Actual vs. predicted makeup water use

As shown in Figure 16 above, the predicted makeup water use tightly aligns with actual makeup water use, demonstrating the model's validity. Figure 17 below further demonstrates the model's validity, showing a strong linear relationship when plotting predicted makeup water use against actual makeup water use for the same period when the ElectroCell system operated.

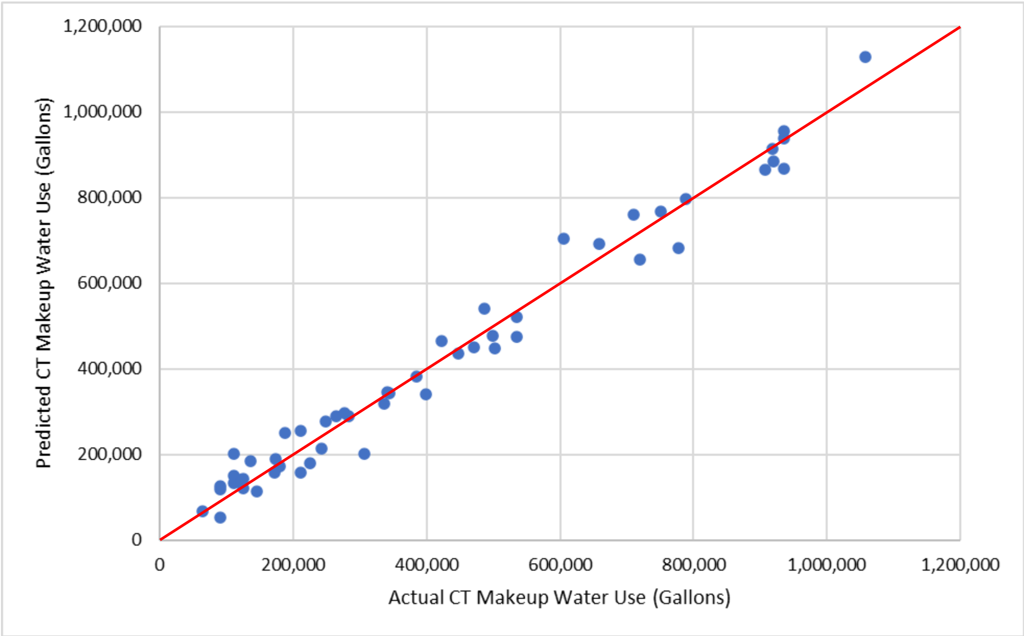

Figure 17. Actual vs. predicted makeup water use

6.1.4 Chemical Treatment Use

Another major impact of the proposed technology is on the chemicals used for water treatment. TMMMS uses an inhibitor, CL5855, and two biocides, CL2250 and CL49. Inhibitors help prevent unwanted chemical reactions such as corrosion and scale, while biocides prevent biological growth.

Chemical treatment costs were normalized to weekly blowdown. Blowdown is the water in the cooling tower loop that is removed when the loop conductivity reaches its threshold. As water evaporates from the cooling tower, dissolved solids become highly concentrated in the loop, which causes the conductivity of the cooling tower loop to rise. Cooling tower water is removed through blowdown and made up with clean makeup water to maintain the conductivity setpoint. With this understanding, blowdown was selected as the independent variable. Blowdown is solely impacted by the water quality in the loop. While the water model uses makeup water as an independent variable, makeup water was not selected for the chemical treatment model, as it is also directly affected by the evaporative loss and drift loss of the cooling tower.

A chemical treatment use per kilogallon of blowdown rate was calculated for each chemical for the one-year period when the ElectroCell system operated and applied to the blowdown use in the one-year period when the incumbent centrifugal system operated to calculate chemical treatment savings (Table 7).

Table 7: Chemical Treatment Use Per Blowdown Routine Adjustment

	Centrifugal Treatment System			ElectroCell Treatment System			
Chemical	Usage (gal)	Blowdown (kgal)	Usage / Blowdown (gal/kgal)	Usage (gal)	Blowdown (kgal)	Usage / Blowdown (gal/kgal)	Predicted Usage (gal)
CL2250	1,143	1,645	0.695	631	2,350,400	0.268	442
CL5855	317		0.193	383		0.163	268
CL49	1,055		0.641	944		0.402	661
Total	**2,515**			**1958**			**1371**

6.2 Summary of Important Assumptions

This analysis is mostly based on actual measured data from the field using a combination of existing data acquisition and management systems, along with additional data loggers that were installed to augment and supplement existing data. However, the following are some of the assumptions that were made to account for missing variables and data:

- There was insufficient temperature data for the air or water entering and leaving the air compressors. The heat of rejection of the air compressors could not be calculated using temperature data. Instead, it is assumed that 85% of the power consumed by the air compressors is rejected as heat to the cooling tower loop (Moskowitz 2010). This assumption is based on engineering judgment and is considered to be an industry standard assumption. Furthermore, the heat rejected by the air compressors is very consistent with the power consumed by the air compressors.
- Filtration system power was calculated with an assumed voltage of 480V and an average power factor of 85% for both filtration systems.
- Any missing weekly AHR water data or makeup TDS data was estimated by using the values from weeks before and after the missing week. This is assumed to be valid, as the week-to-week variation of this data was minimal.

SECTION

7

M&V Results

7 M&V Results

Based on the models for adjustments, developed using the methodology described in the previous section, the predicted energy consumption and water use were calculated for the ElectroCell technology for the baseline period when the incumbent centrifugal water treatment system was operating. This predicted energy consumption and water usage were compared with the actual energy and water usage to calculate the performance improvement that can be attributable to the ElectroCell technology.

7.1 Energy

This evaluation concluded that the ElectroCell system had a small impact on energy use of the chillers and air compressors and no impact on cooling tower energy. This improvement may be attributed to reduced deposition on the heat transfer surfaces, resulting from better-treated water from the cooling tower. The ElectroCell filtration system itself did consume less energy than the incumbent centrifugal system. The itemized impact on the chillers, cooling tower, incumbent centrifugal and the ElectroCell system are shown in Table 8 and elaborated in more detail in Appendix B.

- The energy consumption associated with the chillers showed small impacts ranging from 1.1-1.4% of savings compared to baseline.
- The energy consumption associated with the cooling tower showed no significant impact from the ElectroCell system.
- The energy impact associated with the air compressors showed an improved efficiency of 2.9-3.3% compared to baseline.
- The ElectroCell system used 37% less energy than the incumbent centrifugal system, based off measured data for both systems.

Table 8. Summary of Energy Savings from Evaluated Systems

Electricity	Actual Energy Consumption with Centrifugal System (kWh/yr)	Predicted Energy Consumption with ElectroCell System (kWh/yr)	Impact (kWh/yr)	Impact (%)
Chiller Energy	9,720,823	9,604,764	116,060	1.1–1.4%
Cooling Tower Fan Energy	756,754	764,440	-7,686	~0%
Filtration System Energy	56,188	35,500	20,687	37%
Compressed Air System Energy[a]	6,328,087	6,132,543	195,544	2.9–3.3%
Total Energy	16,861,852	16,537,247	324,605	1-3%

[a] Includes all three air compressors.

7.2 Water Use

The analysis of makeup water usage by the cooling tower showed that the total annual predicted makeup water consumption for the ElectroCell system during the centrifugal system operating period was 20,538,119 gallons. This predicted usage was 8-15% less than the actual water usage with the incumbent centrifugal filtration system (Table 9) and was found to be statistically significant.

Table 9. Annual Makeup Water Use, Centrifugal vs. ElectroCell System

	Centrifugal System (gal/yr)	ElectroCell System (gal/yr)	Impact (gal/yr)	Impact (%)
Makeup Water	23,219,390	20,538,119	2,681,271	8–15%

7.3 Chemical Treatment

Based on our analysis, comparing the volume of chemicals and associated costs obtained from the site, after adjusting for blowdown, the ElectroCell System reduced chemical treatment cost for all three chemicals combined by 45% (Table 10).

Table 10. Chemical Treatment Usage, Centrifugal vs. ElectroCell System

Chemical	Centrifugal Actual Chem Treat (gal)	Centrifugal Actual Chem Treat Costs	ElectroCell Modeled Chem Treat (gal)	ElectroCell Modeled Chem Treat Costs	Annual Impact (gal)	Annual Cost Impact ($)	Annual Percentage Impact (%)
CL2250	1,143	$40,845	442	$15,778	701	$25,067	61%
CL5855	317	$7,950	268	$6,722	49	$1,228	15%
CL49	1,055	$59,428	661	$37,214	394	$22,214	37%
Total	2,515	$108,224	1,371	$59,715	1,145	$48,509	45%

SECTION 8

Summary and Conclusions

8 Summary and Conclusions

8.1 Overall Technology Assessment at the Demonstration Site & Final Results

This evaluation followed an M&V strategy based on IPMVP Option B, retrofit isolation with all parameter measurements, to analyze the impact of the ElectroCell system on an open-loop cooling tower, contrasting it with the existing centrifugal system on energy, water, and chemical usage. The evaluation showed an 8-15% reduction in makeup water consumption and a 45% decrease in chemical treatment requirements. The energy consumption associated with the chillers showed small impacts ranging from 1.1-1.4%, while the air compressors showed an improved efficiency of 2.9-3.3% compared to the baseline.

The evaluation methodically normalized data for all relevant factors using rigorous M&V approaches and sound statistical techniques. However, it is important to acknowledge the potential influence of unidentified factors beyond the evaluation boundary that might have affected the results. Table 11 provides a summary of evaluation results, comparing them to ElectroCell's claims from their ITV application. More detail about the modeling and results can be found in Appendix B.

GSA Proving Ground evaluated six alternative water treatment technologies based on their field performance. The in-field validation studies found that all systems maintained water quality while significantly reducing cooling tower water consumption, yielding water savings of 23-32% (Dean, Tomberlin, and Silvestri 2020). However, no measurable energy savings or increase in chiller performance was seen because the condenser tubes were clean at the beginning of the demonstration. If the chiller tubes and heat exchangers are clean and included as part of regular preventative maintenance program, very little savings potential exists. Conversely, if the baseline chiller condenser tubes and heat exchangers are not in good condition, significant opportunities for energy savings exist.

Table 11. Summary of Evaluation Results

	ElectroCell Claimed Savings (%)	Measured Savings (%)
Energy Consumption	10–12%	1.1–3.3%
Water Use	15–20%	8–15%
Chemical Treatment Use	Less chemical treatment required	45%

8.2 Lessons Learned and Considerations for Future Evaluations

The condition of the condenser tubes was not assessed during this evaluation. Future evaluations should measure the condition of the tubes before and after the study through non-destructive testing techniques. The ability of the ElectroCell system to clean any existing fouling was not tested during this evaluation, as the testing configuration was not suitable. A different testing configuration and more controlled O&M practices of condenser tube cleaning might make evaluation for this aspect possible.

ElectroCell Systems' claim that the system breaks down laminar boundaries to provide better heat exchange was not tested. Incorporating additional instrumentation to calculate the Reynolds number could test this ability. Also, the ability of the ElectroCell system to remove TDS was not directly evaluated. Targeted measurements of TDS at the inlet and the outlet of the ElectroCell system could have provided better insight.

In summary, this evaluation focused on the effect of the ElectroCell system at a plant-wide CHW system level. More targeted measurements as described above could produce more statistically significant independent variables and reduced model uncertainty.

8.3 Deployment Considerations

This evaluation focused on an open-loop cooling tower system situated within an automobile plant. The cooling tower loop rejects heat from chillers and air compressors. The condenser water undergoes heat dissipation through evaporation in the cooling tower, through the flow of fluid over the fill structure for heat exchange. The cooled water gathers in a basin before being cycled back to the facility's cooling loop. This technology's relevance extends to closed-loop cooling towers that dissipate heat and adopt different water treatment systems that demand significant makeup water use.

The effectiveness of this technology depends on several site-specific factors, encompassing variables like ambient air quality, the presence of airborne particulate matter, and seasonal fluctuations. Such conditions can lead to issues such as biological growth or mineral buildup, necessitating additional chemical treatments. Cooling tower performance correlates closely with wet bulb temperature, resulting in differing efficiency and output levels across diverse locations. Evaporative cooling systems tend to excel in arid climates with low wet bulb design temperatures.

8.4 National Impact

The water usage for cooling, condensing, and steam in the U.S. manufacturing sector is estimated to be between 9,098 and 10,255 million gallons per day (MGD). Out of this total, the overall open cooling tower water withdrawal rates are calculated to be approximately 5,710 and 6,436 MGD, while the evaporative cooling tower water withdrawal rates are estimated to between 2,447 and 2,758 MGD (Karki and Rao 2023). The water reductions observed through electrochemical treatment from the evaluations were used to estimate the overall impact of this technology. The reductions ranged from 5% to 18%, with a weighted average of 11%.

The total potential reductions in water withdrawal for the listed manufacturing subsectors under 100% adoption of electrochemical treatment range from 278 to 313 MGD, and from 3 to 4 MGD under a 10% adoption scenario (Table A.10 in the Appendix). In the top five manufacturing subsectors, the adoption of electrochemical treatment could lead to reductions in water withdrawal. Specifically, the estimates suggest that with 100% adoption, water withdrawal could decrease by up to 108 MGD in the primary metals sector, 77 MGD in chemicals and petrochemicals, 63 MGD in paper manufacturing, 29 MGD in petroleum refining and coal, 21 MGD in food manufacturing, and 2 MGD in transportation equipment.

Delivering treated water to an industrial facility requires the water to be extracted from the water source, treated, conveyed to the facility, and returned back to the source. Each of these steps requires the consumption of energy, referred to as the "embedded energy" of the water supply and wastewater network. An estimated weighted average energy intensity for the embedded energy of water supply is 2,069 kWh/MG (Rao, McKane, and de Fontaine 2015). Based on this estimate and an emissions factor of 0.000699 metric tons CO_2/kWh,[5] the carbon impact of various adoption scenarios can be calculated. For instance, with 10% adoption, the corresponding figure is estimated to be around 1,029 metric tons of CO_2 per year.

[5] Per EPA estimate. To learn more, visit https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references.

SECTION 9

Appendix

9 Appendix

9.1 Background: Goodness of Fit Statistics

Coefficient of Determination (R^2)

One of the metrics to assess the fitness of the model is coefficient of determination, R^2, which measures the extent to which variations in the dependent variable y can be explained by the regression model. The possible ranges for R^2 are between 0 and 1, with a value of 0 indicating that none of the variation can be explained by the model, and therefore the model provides no guidance in understanding the variations in y using the selected independent variables. On the other hand, an R^2 of 1 means that the model explains 100% of the variations in y. Typically this value falls somewhere in between for most models, but generally the greater the coefficient of determination, the better the model describes the relationship of the independent variables and the dependent variable. IPMVP states that a minimum acceptable R^2 value is 0.75.

Root Mean Squared Error (Standard Error of the Estimate)

Root mean squared error (RMSE) or standard error of the estimate (SE) is an indicator of the scatter, or random variability, in the data, and hence is an average of how much an actual y-value differs from the predicted y-value. It is the standard deviation of errors of prediction about the regression line.

Coefficient of Variation of the Root Mean Squared Error (CV_{RMSE})

CV_{RMSE} is the RMSE normalized by the average y-value. Normalizing the RMSE makes this a non-dimensional value that describes how well the model fits the data. It is not affected by the degree of dependence between the independent and dependent variables, making it more informative than R-squared for situations where the dependence is relatively low.

Bias

Bias (or net determination bias) is simply the percentage error in the energy use predicted by the model compared to the actual energy use. The sum of the differences between actual and predicted energy use should be zero. If the net determination bias = 0, then there is no bias. ASHRAE Guideline 14-2002 accepts an energy model if the net determination bias error is less than 0.005%. Often bias may be minor, but it will still affect savings estimates. If the savings are large relative to the bias, bias may not be important, but in many cases, bias may be influential.

t-Statistic

The t-statistic is a measure of the significance for each coefficient (βi) and hence the related independent variable's contribution to the overall model. The larger the t-statistic, the more significant the coefficient is to estimate the dependent variable. The coefficient's t-statistic is compared with the critical t-statistic associated with the required confidence level and degrees of freedom. For a 95% confidence level and a large number for degrees of freedom (associated with a lot of data), the comparison t-statistic is 1.96. Measure the t-statistic for every independent variable used, and if the t-statistic is lower than the critical value (such as 1.96) for any variable, reconsider your model. IPMVP[6] specifies that the t-statistic must be greater than 2.0 in order for the independent variable to be significant.

Fractional Savings Uncertainty

Model predictions come with inherent uncertainties from various sources that includes measurement and modeling. While the uncertainties associated with measurements are assumed to be negligible, uncertainties for the model need to be assessed to understand the confidence associated with the savings and performance improvement from the proposed technology. These uncertainties can be quantified by determining the savings uncertainty at a specific confidence level. This confidence level is chosen to be 95% that indicates that there is a 5% chance of being wrong. This uncertainty, when presented as a percentage of the average metered savings, is known as fractional savings uncertainty (FSU). A lower FSU signifies greater confidence in the accuracy of the savings estimates. In essence, smaller FSUs indicate more reliable and trustworthy predictions of savings. FSU for the models were calculated following ASHRAE Guidelines 14,[7] BPA M&V guidelines,[8] and the IPMVP measurement and uncertainty guide.[9] FSU for a normalized regression, considering auto correlation, can be calculated as:

$$FSU = \frac{\Delta E_{save}}{E_{save}} = \frac{1.26 * t}{m * \bar{E}_{EC,n} * F}\sqrt{MSE'^{\left(1+\frac{2}{n'}\right)}m}$$

$\frac{\Delta E_{save}}{E_{save}}$	FSU for a regression in percentage
t	t-statistic, 95% confidence interval, infinite degrees of freedom (1.96)
m	Number of periods in post retrofit period
$\bar{E}_{EC,n}$	Mean energy use per period with the ElectroCell system
F	Savings in percentage
MSE	Mean squared error of the regression model
n'	Number of independent observations w/ autocorrelation

[6] EVO's IPMVP 10000-1.2012.
[7] ASHRAE Guidelines 14 – Measurement of Energy and Demand Savings.
[8] BPA Verification by Energy Modeling Protocol, October 2018.
[9] Uncertainty Assessment for IPMVP, International Performance Measurement and Verification Protocol, July 2019, EVO 101000-1:2019.

9.2 Model Statistical Summary

The model results here show the model outputs for the energy and water models. They are not considered to be the final evaluation result. Table A.1 contains a summary of the evaluation results.

Table A.1. Energy, Water, and Chemical Treatment Use Summary

	Centrifugal System	ElectroCell System	Impact	Impact (%)	Impact (% Range)
CHW System Energy (kWh/yr)	10,533,765	10,404,704	129,061	1.2%[a]	1.1–1.4%[a]
CA System Energy (kWh/yr)	6,328,087	6,132,543	195,544	3.1%[a]	2.9–3.3%[a]
Makeup Water Use (gal/yr)	23,219,390	20,538,119	2,681,271	12%	8–15%
Chemical Treatment Use ($/yr)	$108,224	$59,715	48,509	45%	45%

[a] Assumed to be negligible

Energy Model

This evaluation concluded that the ElectroCell system had no statistical impact on energy use of the chillers, cooling tower, or air compressors. The ElectroCell system did consume less energy than the incumbent centrifugal system.

- The separate chiller models showed slightly mixed results, all which was considered noise from the model and not true savings.
- The cooling tower model's fractional savings uncertainty (FSU) was 85%, which fails IPMVP requirements of not to exceed 50%. The model is not valid, and the results are considered to be in the noise.
- The ElectroCell system used 37% less energy than the incumbent centrifugal system, which was based off measured data for both systems and considered to be valid.
- The total modeled annual predicted energy consumption for the three air compressors during the period when the ElectroCell system operated was slightly lower than the period when the incumbent centrifugal system was active by around 3%. The FSU for this analysis was close to 6.8%, which is less than the allowable threshold established by M&V guidelines of 50%. Taking FSU into account, with 95% confidence the annual energy impact lies between 182,273 and 208,815 kWh, however the impact is also small and considered negligible (Table A.2).

Table A.2. Summary of Energy Impact from Chilled Water and Compressed Air Systems

	Actual Energy Consumption with Centrifugal System (kWh/yr)	Predicted Energy Consumption with ElectroCell System (kWh/yr)	Impact (kWh/yr)	Impact (%)	FSU (%)	Lower CL (kWh)[a]	Upper CL (kWh)
Chiller Energy	9,720,823	9,604,764	116,060	1.2%	11%	103,323	128,796
Cooling Tower Fan Energy	756,754	764,440	-7,686	-1.0%	85.2%	-6,843	-1,134
Filtration System Energy	56,188	35,500	20,687	36.8%	N/A	N/A	N/A
Compressed Air System Energy[b]	6,328,087	6,132,543	195,544	3.1%	6.8%	182,273	208,815

[a] At 95% confidence level, i.e., is the percentage of times you expect to reproduce an estimate between the upper and lower bounds of the confidence interval.
[b] Includes all the three air compressors.

Water Use

The analysis of makeup water usage by the cooling tower showed that the total modeled annual predicted makeup water consumption during the period when the ElectroCell system was active was 20,538,119 gallons. The predicted water usage with the ElectroCell system was about 12% less than the actual water usage with the incumbent centrifugal filtration system (Table A.3). The calculated FSU is 31.6%, which is less than 50% of the annual reported impact and passes ASHRAE guidelines for assessing uncertainty in the model. Taking FSU into account, with 95% confidence, the makeup water impact lies between 1,833,882 and 3,528,660 gallons (Table A.3).

Table A.3. Annual Makeup Water Use, Centrifugal vs. ElectroCell System

	Centrifugal Makeup Water (gal/yr)	ElectroCell Makeup Water (gal/yr)	Impact (gal/yr)	Impact (%)	FSU	Lower CL[a] (gals)	Upper CL[b] (gals)
Makeup Water	23,219,390	20,538,119	2,681,271	11.5%	31.6%	1,833,882	3,528,660

[a] At 95% confidence level.
[b] At 95% confidence level.

Chemical Treatment

ElectroCell Systems claims their system functions with reduced need for chemical additives for treating the system. Based on our analysis, comparing the volume of chemicals and associated costs after adjusting for blowdown, the ElectroCell system reduced chemical treatment use for all three chemicals by 45% (Table A.4).

Table A.4. Chemical Treatment Usage, Centrifugal vs. ElectroCell System

Chemical	Centrifugal (Actual) Chem Treat (gallons)	Centrifugal (Actual) Chem Treat Cost ($)	ElectroCell (Modeled) Chem Treat (gallons)	ElectroCell (Modeled) Chem Treat Cost ($)	Annual Impact (gallons)	Annual Cost Impact ($)	Annual Percent Impact (%)
CL2250	1,143	$40,845	442	$15,778	701	$25,067	61%
CL5855	317	$7,950	268	$6,722	49	$1,228	15%
CL49	1,055	$59,428	661	$37,214	394	$22,214	37%
Total	2,515	$108,224	1,370	$59,715	1,145	$48,509	45%

9.3 Savings and Impact Details

The itemized results here show the model outputs for each component of the energy and water models. They are not considered to be the final evaluation result. Some models showed an increase in use, while some components showed a decrease. In these cases, the outputs are considered to be noise. The results are shown in Tables A.5 and A.6 below.

Table A.5. CHW System Energy Consumption Per Component

	Actual Energy Consumption with Centrifugal System (kWh/yr)	Predicted Energy Consumption with ElectroCell System (kWh/yr)	Impact (kWh/yr)
Chiller 1	3,324,662	3,476,136	-151,474
Chiller 2	2,848,453	2,855,316	-6,863
Chiller 3	1,223,262	1,126,769	96,493
Chiller 4	1,758,032	1,542,877	215,155
Chiller 5	444,441	465,503	-21,063
Chiller 6	121,973	138,162	-16,189
Cooling Tower	756,754	764,440	-7,686
Filtration System	56,188	35,500	20,687
Total	10,533,765	10,404,704	129,061
Savings Percentage			1.2%
$FSU_{(heterogeneous)}$			13.2%
Savings Uncertainty (kWh/yr)			17,057

Table A.6. Compressed Air System Energy Consumption Per Component

Air Compressor	Predicted Energy Consumption with Centrifugal System (kWh/yr)	Actual Energy Consumption with ElectroCell System (kWh/yr)	Impact (kWh/yr)
C1	1,759,799	1,754,083	5,716
C2	1,834,955	1,694,952	140,003
C3	2,733,333	2,683,508	49,825
Total	6,328,087	6,132,543	195,544
Savings			3.1%
$FSU_{(heterogeneous)}$			6.8%
Savings Uncertainty (kWh/yr)			13,271

9.4 Fractional Savings Uncertainty

As discussed, model predictions often come with inherent uncertainties from various sources. These uncertainties can be quantified by determining the savings uncertainty at a specific confidence level. This uncertainty, when presented as a percentage of the average metered savings, is known as fractional savings uncertainty (FSU). The calculated FSU for each of the chillers and the cooling tower that are all part of the chilled water system are shown in Table A.7. The combined FSU for the entire chilled water system is shown using the following expression:

$$CHW\ System\ Energy\ Model\ Heterogeneous\ FSU = \frac{\sqrt{\begin{matrix} FSU_{CHi} * S_{CHi} \\ +FSU_{CT} * S_{CT} \end{matrix}}}{S_{total}}$$

FSU_{CHi}	FSU for each of the chiller (1-6) models	%
S_{CHi}	Energy Savings for each of the chiller (1-6) models	kWh/yr
FSU_{CT}	FSU for cooling tower	%
S_{CT}	Energy Savings per cooling tower	kWh/yr
S_{total}	CHW System Energy Model Savings	kWh/yr

Table A.7. Summary of FSU Analysis for Each CHW System Component

	Chiller 1	Chiller 2	Chiller 3	Chiller 4	Chiller 5	Chiller 6	Cooling Tower	Aggregate
FSU	**5.3%**	**71.5%**	**2.8%**	**3.7%**	**7.3%**	**3.1%**	**85.2%**	**13.2%**
MSE	4,986	2,289	4,537	3,792	10,735	4,195	674	
t-stat	1.96	1.96	1.96	1.96	1.96	1.96	1.96	
m BL	16,353	5,666	10,899	4,111	12,999	5,360	8,514	
F (Savings)	-5%	0%	8%	12%	-5%	-13%	-1%	
p	0.89	0.70	0.29	0.33	0.75	0.65	0.49	
n	8,725	8,725	8,725	8,725	8,725	8,725	8,725	
n'	492	1,510	4,850	4,396	1,269	1,869	3,021	
$E_{EC,n}$	570	912	719	519	651	537	80	

Similarly, the FSU is calculated for the compressed air system. Details of the individual compressors and aggregate are summarized in Table A.8. Table A.9 summarizes the FSU associated with the makeup water savings.

Table A.8. Summary of FSU Analysis for Air Compressors

	C1	C2	C3	Aggregate
FSU	**27.9%**	**7.5%**	**15.9%**	**6.8%**
MSE	223	16,104	8,585	
t-stat	1.96	1.96	1.96	
F	0.3%	7.6%	1.8%	
n	8,601	8,601	8,601	
m	22,309	3,295	6,406	
p	0.75	0.40	0.86	
n'	1,236	3,692	667	
Ebase,n	272	952	988	

Table A.9. Summary of FSU Analysis for Makeup Water Use

Water Use FSU	
t-stat	1.96
MSE	1,892,362,401
n	52
m	52
F	11.5%
$E_{EC,n}$	415,997
FSU	**31.60%**

The following section presents a national market impact analysis for different manufacturing subsectors under various assumed adoption levels.

9.5 Market Impact Analysis

Table A.10. National Impact Summary of Electrochemical Treatment on Evaporative Cooling Tower Water Usage in Manufacturing Sub-sectors

NAICS Code	Manufacturing Subsector	Evaporative Cooling Tower Water Withdrawal (MGD)		Electrochemical Treatment Impact on Evaporative Cooling Tower Water Withdrawal (MGD)			
				100% Adoption		10% Adoption	
	Manufacturing Subsector	Low Estimate	High Estimate	Low Estimate	High Estimate	Low Estimate	High Estimate
331	Primary Metals	841	948	96	108	1	1
325	Chemicals and Petrochemicals	604	681	69	77	1	1
322	Paper Manufacturing	493	555	56	63	1	1
324	Petroleum Refining and Coal Product Manufacturing	226	255	26	29	0	0
311	Food Manufacturing	161	182	18	21	0	0
336	Transportation Equipment Manufacturing	20	22	2	2	0	0
Grand Total		**2,448**	**2,757**	**278**	**313**	**3**	**4**

References

Dean, Jesse, Gregg Tomberlin, and Andrea Silvestri. 2020. *GSA Guidance—Alternative Water Treatment Systems for Cooling Towers.* Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/73940.pdf.

Duan, X., J.L. Williamson, K.L McMordie, Stoughton, and B.K. Boy. 2012. *Side Stream Filtration for Cooling Towers.* Richland, WA: Pacific Northwest National Laboratory. U.S. Department of Energy Federal Energy Management Program. https://www.energy.gov/sites/default/files/2013/10/f3/ssf_cooling_towers.pdf.

Efficiency Valuation Organization (EVO). 2022. International Performance Measurement & Verification Protocol (IPMVP) Core Concepts 2022. https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp.

Karki, Unique and Prakash Rao. 2023. "Techno-economic analysis of the water, energy, and greenhouse gas emissions impacts from the adoption of water efficiency practices in the U.S. manufacturing sector." *Resources Conservation and Recycling.* https://doi.org/10.1016/j.resconrec.2023.107054.

Moskowitz, Frank. 2010. "Heat recovery and compressed air systems." *The Compressed Air Challenge.* https://www.compressedairchallenge.org/data/sites/1/media/library/articles/2010-09-CABP.pdf.

Rao, Prakash, Aimee McKane, and Andre de Fontaine. 2015. "Energy Savings from Industrial Water Reductions." Presented at: 2015 ACEEE Summer Study on Energy Efficiency in Industry, Buffalo, NY

Turner, W.C., 2004. Energy Management Handbook, Fairmont Press, 2004.

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DOE/EE- 2894 • September 2024

FIELD VALIDATION OF

Electrochemical Water Filtration System on an Open Loop Cooling Tower at Automotive Plants

Photo from Energy 350

MAKEUP WATER

↓ **11%**

CHEMICAL TREATMENT

↓ **36%**

CARBON

↓ **15 tons CO_2/year**

Based on reduction in embedded energy from less water being supplied and treated at both plants.

The U.S. Department of Energy's Industrial Efficiency and Decarbonization Office Industrial Technology Validation program is open to all industrial sites that want to team with technology providers to evaluate innovative technologies in their plants, reduce greenhouse gas emissions, and meet decarbonization goals.

Open loop cooling towers play a pivotal role in rejecting heat for chilled water systems serving industrial processes, heating, ventilation, and air conditioning loads. Exposure to outside conditions can present certain operating challenges to system performance including scaling, corrosion, and biological growth. These issues are mitigated through the use of effective cooling tower water filtration and treatment systems to reduce contaminants—along with other total suspended solids (TSS) and total dissolved solids (TDS)—in the system.

The U.S. Department of Energy's Industrial Efficiency and Decarbonization Office is interested in an electrochemical-based filtration system with the ability to remove TSS particulate down to 1 micron. The removal of finer particulates reduces the need for blowdown and, in turn, makeup water use and chemical treatment in the cooling tower. Additionally, the removal process can reduce fouling at the condensers, resulting in better heat exchange and energy savings.

Two Industrial Technology Validation program projects validated the electrochemical water filtration system at the Toyota Motor Manufacturing, Mississippi plant in Blue Springs, Mississippi, and the Nissan Canton Vehicle Assembly Plant in Canton, Mississippi. Researchers found that installation of both systems resulted in water and chemical treatment savings with minimal impact on energy use.

Technology Performance Assessment

Electrochemical-Based Water Filtration System Removes Suspended Solids From Open Loop Cooling Tower

THE PROCESS

Open loop cooling towers cool water through direct contact with ambient air. Water is evenly distributed over the cooling tower film as air passes over it. Most of the heat is rejected as latent heat when the water evaporates. Saturated air is exhausted through the upper section of the cooling tower while the remaining cooler water is collected at the cooling tower basin and sent back to the chillers to capture heat again. As water continues to circulate, TSS and TDS begin to concentrate. Too high of a concentration of solids leads to scaling, corrosion, and biological growth (see Figure 1).

The system must discharge cooling-loop water through blowdown once the concentration becomes too high. Any water that is removed via blowdown must be replaced by adding clean makeup water. A key parameter to evaluate cooling tower performance is the amount of blowdown and makeup water that is used by the cooling tower. Facilities aim to minimize the blowdown and makeup water by recirculating and reusing the water. Traditionally, water filtration systems include chemical treatment to mitigate TDS and TSS, ensuring that water can be recirculated efficiently without sacrificing equipment integrity.

THE TECHNOLOGY

The proposed technology uses a custom electrochemical process to remove TSS down to 1 micron. In the first stage, water is sent through a series of low-voltage direct current (DC) ionizers, which flocculate and coagulate suspended solids, creating larger particles from smaller particles. In the second stage, water is sent through static mixers, where particulate is collected at the bottom of each mixer. The particulate is then removed through a bleed cycle, where water is sent through the mixers to empty the vessels in a timed cycle. In the third stage, a positively charged high-voltage DC ionizer cell is used to generate an electrostatic field. The electrostatic field disrupts the laminar flow of the water at the condensers to help reduce fouling and improve heat transfer (see Figure 2).

Researchers compared the emerging electrochemical technology to the centrifugal system at the Toyota plant and an existing filtration system at the Nissan plant to quantify potential impact on energy, water, and chemical treatment.

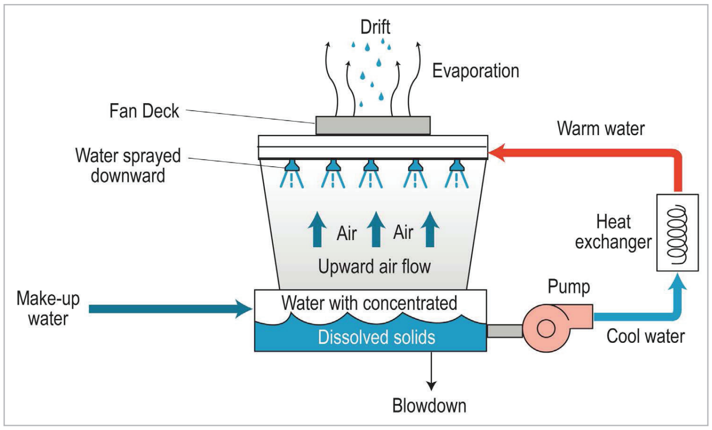

Figure 1. Illustration of water flow across a cooling tower. *Graphic from U.S. Department of Energy's Federal Energy Management Program*

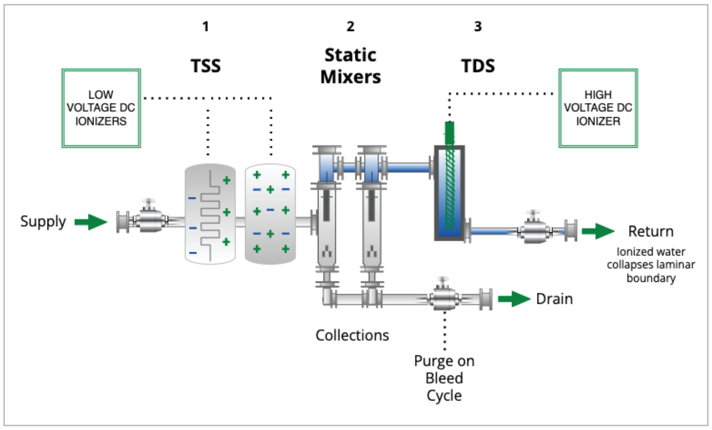

Figure 2. Schematics showing the three stage ElectroCell system. *Graphic from Lawrence Berkeley National Laboratory*

THE DEMONSTRATION SITE

Two host sites were selected: Toyota Motor Manufacturing, Mississippi and Nissan Canton Vehicle Assembly Plant. The former, constructed in 2011, manufactures 165,000 cars per year, while the Nissan plant has produced over 5 million vehicles since opening in 2003 and currently operates at a little more than half its annual capacity of 410,000 cars.[1] Both locations operate 16 hours per weekday with a summer and winter week-long shutdown. The analysis evaluated the performance of the ElectroCell EC-6000 installed as a side stream system on the open loop cooling tower serving each site's chilled water system. The incumbent system at the Toyota plant uses centrifugal force where high-velocity water is fed through separators to develop a circular flow pattern that causes the heavier suspended solids to migrate toward the separator's sidewalls and downward into a holding chamber and get purged. At the Nissan plant, the incumbent system uses a sand filter that separates particulates from the water by sending water through a pressurized vessel where the particulates are captured, and the treated water is sent back to the cooling tower loop.

The study objectives were to quantify the impact on energy, water, and chemical treatment associated with this electrochemical-based water treatment system. The evaluation boundary included the chillers, cooling towers, air compressors, and filtration systems. This measurement and verification effort followed International Performance Measurement and Verification Protocol Option B—Retrofit Isolation (All Parameter Measurement) (see Figure 3)—through comprehensive measurements and analyses of the affected systems. The analysis relied on field data to construct predictive models for energy, water, and chemical treatment use to assess the impact of the proposed technology. The evaluation measured and analyzed the energy, water, and chemical treatment use of the chilled water system for one year with the incumbent systems and for one year with the ElectroCell system. Researchers created predictive models from the first year of operation with the electrochemical system to predict what the energy, water, and chemical treatment use would be during the second year of operation using the incumbent systems. The predicted use with the new technology was compared to actual use with the incumbent systems during the second-year performance period to quantify the impact of the electrochemical system, as illustrated in the figure below.

The chilled water energy model predicted the energy use of the chillers and cooling tower using statistically relevant independent variables—chiller cooling load, temperature of the water as it enters the condenser, the cooling tower's heat rejection, and the cooling tower approach temperature. Air compressor energy was predicted based on the compressed airflow and pressure. Makeup water use was predicted based on the cooling tower's heat rejection, makeup water TDSs, and recovery water volume from dehumidifiers. Chemical treatment use was normalized based on the water blowdown volume.

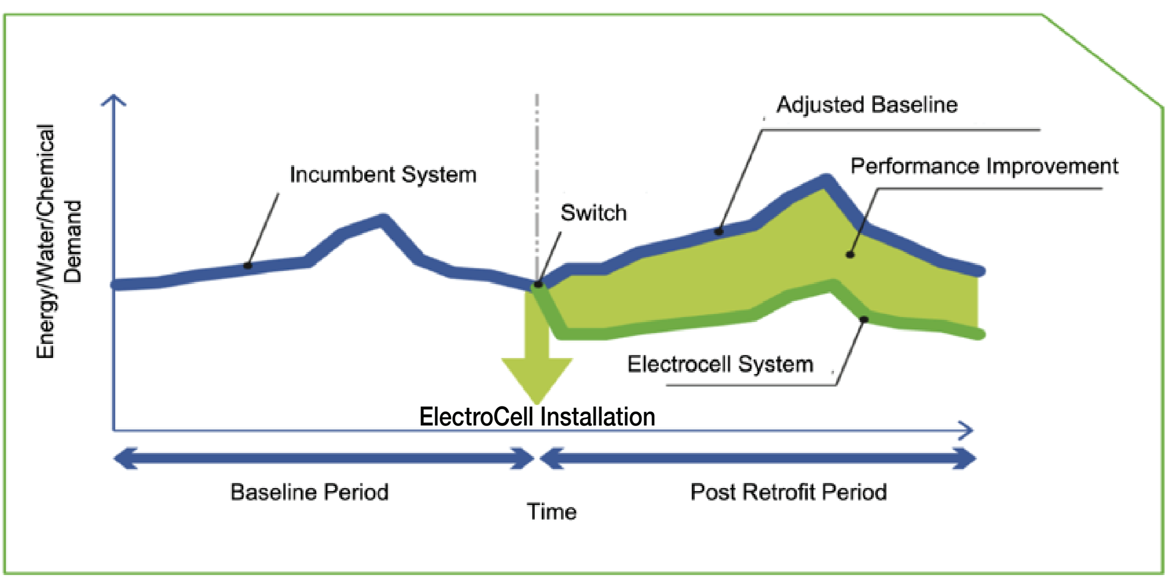

Figure 3. Plot showing the evaluation methodology. *Graphic from Lawrence Berkeley National Laboratory*

1 Mihalascu, Dan. 2023. "Nissan To Build Two Electric Sedans At Mississippi Plant From 2026." InsideEVs. https://insideevs.com/news/675789/nissan-build-two-electric-sedans-mississippi-plant-2026/

Findings

Based on the analysis, the ElectroCell system showed makeup water savings of 11.5% at Toyota and 11.3% at Nissan and chemical treatment savings of 45% at Toyota and 27% at Nissan. However, at both locations, there was a very minimal impact on the energy consumed by the chillers, cooling towers, or air compressors. It should be noted that although the evaluation was normalized by accounting for pertinent available factors using rigorous measurement and verification approaches and robust statistical techniques, there could have been other unknown factors beyond the scope of the evaluation that influenced the results. This finding of water usage and associated chemical reduction with no energy impact is consistent with another evaluation study that looked at the performance of different electrochemical-based treatment systems against more traditional water treatments.[2]

Conclusions

This evaluation focused on an open loop cooling tower system evaluated at an automobile plant. This technology could have a meaningful impact to any industrial or commercial facility with an open loop cooling tower. It could also apply to closed loops that require filtration, although the effect of the ElectroCell system is likely to be less impactful in that case, as closed loops typically operate where blowdown water is already optimized through other water treatment means. This evaluation studied the effects of the ElectroCell system on the energy, water, and chemical treatment impacts of the cooling tower, chilled water, and compressed air systems. Future evaluations could consider looking at non-energy benefits associated with the equipment, such as fouling and, thereby, fewer operating and maintenance requirements.

Based on these evaluations showing water reduction ranging from 5% to 18%, a weighted average of 11% was used to project the market impact of electrochemical based water treatment systems assuming the same baseline conditions. Under a 10% adoption of electrochemical treatment scenario, potential reductions in water withdrawal for listed manufacturing subsectors range from 3 to 4 million gallons per day. Delivering treated water to industrial facilities consumes embedded energy for the equipment in the supply and process network. With an estimated weighted average energy intensity for this embedded energy of 2,069 kilowatt-hours per million gallons and an emissions factor of 0.699 metric tons CO_2 per megawatt-hours, the carbon impact, with a 10% adoption, is around 1,029 metric tons of CO_2 per year.

ElectroCell system installed at Toyota Motor Manufacturing, Mississippi plant. *Photo from Energy 350*

2 Tomberlin, Gregg, Jesse Dean, and Michael Deru. 2018. *Electrochemical Water Treatment for Cooling Towers.* Golden, CO: National Renewable Energy Laboratory (Prepared for General Services Administration). https://www.gsa.gov/system/files/DWT%20Final%20Report%206-28-19.pdf.

These findings are based on two reports: Field Validation of Electrochemical Water Filtration System on an Open Loop Cooling Tower at Toyota Motor Manufacturing Plant in Blue Springs, Mississippi and Field Validation of Electrochemical Water Filtration System on an Open Loop Cooling Tower at Nissan Manufacturing Plant in Canton, Mississippi. Both reports can be found on the program website: https://bit.ly/4ejtfHS

For more information contact U.S. Department of Energy's Industrial Technology Validation program at ITV-Support@lbl.gov.

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