Field Evaluation of Ultra-Efficient Dedicated Outdoor Air System with Integral Energy Storage

Final Report

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Executive Summary

This report provides the results of a field demonstration of an ultra-efficient, dedicated outdoor air system with integral energy storage. The project evaluates the humidity, temperature, cooling performance, efficiency, and peak load-shifting capability of a novel emerging technology described as a liquid desiccant-enhanced dedicated outdoor air system with integral energy storage. At its core, the technology combines liquid desiccant with indirect evaporative cooling and thermochemical energy storage. This air conditioning technology fundamentally reimagines how buildings are cooled, dehumidified, and interact with the grid.

The host site for this project is a grocery store located in Southern California, in California Climate Zone 8. The unit operates 7 days a week for 18 hours per day, delivering 2,500 cubic feet per minute of conditioned 100 percent outdoor air into the main sales area at a 55°F dew point. The unit is comparable to a conventional 15-ton direct expansion dedicated outdoor air system.

An energy storage, liquid desiccant, dedicated outdoor air system achieves energy efficiency beyond the theoretical limit of a conventional direct expansion dedicated outdoor air system. However, energy efficiency alone is not the complete solution for achieving California's deep decarbonization goals, because not all kilowatt-hours are valued equally, and therefore an important integral feature is dispatchable load shifting. The idea is to utilize excess renewable energy—for example, from 9 a.m. to 4 p.m.—and draw the energy from storage from 4 to 9 p.m., saving and shifting energy use.

An energy storage, liquid desiccant, dedicated outdoor air system helps futureproof buildings and electric utility distribution systems against weather-driven electricity consumption and associated peak demand from compressor-based air conditioners as the frequency and duration of heat waves with rising dew points increase. The efficiency of an energy storage, liquid desiccant, dedicated outdoor air system improves with rising ambient temperatures, while its supply air dew point remains consistent. The coincident peak demand of an energy storage, liquid desiccant, dedicated outdoor air system is not correlated with peak temperature, a key attribute for providing load flexibility and enhancing the resilience of California's summer grid. The field data from this project were used to train a regression model for estimating the energy and peak-demand savings of the energy storage, liquid desiccant, dedicated outdoor air system compared to a baseline direct expansion dedicated outdoor air system. The regression models were applied to multiple locations in California (climate zones 8, 12, and 15) to evaluate the energy savings of the technology under different climate conditions. Those results are presented in Table 1 along with the energy saved during the peak period of 4 to 9 p.m.

Table 1: Annual energy savings of emerging technology to baseline technology for a 2,500 cubic feet per minute dedicated outdoor air system.

Annual Energy Use Comparison Direct Expansion Dedicated Outdoor Air System vs. Energy Storage, Liquid Desiccant, Dedicated Outdoor Air System				
California Climate Zone	Direct Expansion Dedicated Outdoor Air System Annual Electricity Usage (kWh)	Energy Storage, Liquid Desiccant, Dedicated Outdoor Air System Annual Electricity Usage (kWh)	Energy Storage, Liquid Desiccant, Dedicated Outdoor Air System Annual Electricity Savings (kWh)	% Savings
8	42,577	22,057	20,500	48
12	28,250	9,829	18,421	65
15	60,718	18,782	41,936	69

Table 2: Annual energy savings during peak period from 4-9 p.m. of emerging technology to baseline technology for a 2,500 cubic feet per minute dedicated outdoor air system.

Annual Peak Energy Use (4-9 p.m.) Comparison Direct Expansion Dedicated Outdoor Air System vs. Energy Storage, Liquid Desiccant, Dedicated Outdoor Air System				
California Climate Zone	Direct Expansion Dedicated Outdoor Air System Peak Demand (kW)	Energy Storage, Liquid Desiccant, Dedicated Outdoor Air System Average Peak Demand With Load Shifting (kW)	Load Shifting Peak Demand Savings (kW)	Load Shifting Peak Demand Savings (%)
8	8,725	1,676	7,049	81%
12	7,938	1,605	6,333	80%
15	15,038	2,038	12,465	83%

The field test results showed that an ultra-efficient dedicated outdoor air system with integral energy storage has the potential to substantially increase distribution grid resilience during periods of extreme heat, futureproof buildings against the increased frequency and duration of heat waves with rising dew points, advance building decarbonization by storing and shifting excess renewable electricity, and reduce costs for ratepayers by lowering electricity use and peak demand, while shifting consumption to take advantage of time-of-use rates and utility-sponsored load management tariffs and incentives.

Recommendations

Study findings show that energy storage, liquid desiccant, dedicated outdoor air systems' energy savings, peak-demand reduction, and load-shifting capabilities are substantial when compared to a baseline direct expansion dedicated outdoor air system. In the field study, only 8-16 percent of the total energy used by the emerging dedicated outdoor air system evaluated occurred during the peak hours of 4 to 9 p.m. It is recommended that additional field evaluation of the final commercial product be conducted to validate the energy savings determined in this project and provide additional data for measure development. Future efforts should both inform the development of new code requirements and identify potential barriers to broader adoption and codification of these advanced systems.

Feedback from diverse stakeholders—including building owners, tenants, architects, electric utilities, regulators, and the sustainability and engineering community—has been universally positive. Beyond its efficiency benefits, energy storage, liquid desiccant, dedicated outdoor air systems address the critical need for flexible building loads that can integrate as dynamic and predictable grid resources. Despite this widespread recognition of energy savings and load shifting potential, adoption rates remain low, primarily due to risk aversion associated with emerging building-integrated products. This CalNEXT project aims to reduce that risk and accelerate adoption for the benefit of ratepayers and society at large.

Abbreviations and Acronyms

Acronym	Meaning
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
CFM	Cubic feet per minute
COP	Coefficient of Performance
DOAS	Dedicated outdoor air system
DX	Direct expansion
DX-DOAS	Direct expansion dedicated outdoor air system
EM&V	Evaluation, measurement, and verification
EER	Energy Efficiency Ratio
ES-LD-DOAS	Energy storage, liquid desiccant, dedicated outdoor air system
GHG	Greenhouse gas
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
ISMRE2	Integrated Seasonal Moisture Rate Efficiency
kWh	Kilowatt-hour
LD-DOAS	Liquid desiccant dedicated outdoor air system
M&V	Measurement and verification
MRC	Moisture removal capacity
MRE	Moisture removal efficiency

Acronym	Meaning
NREL	National Renewable Energy Laboratory
UC Davis WCEC	University of California at Davis Western Cooling Efficiency Center

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Introduction

Commercial building energy performance has improved significantly over the past two decades through evolving codes, technology innovations, and green building standards. Heating, ventilation, and air-conditioning (HVAC) systems remain the largest energy consumer and represent the greatest opportunity for energy and carbon emission reductions. Traditional mixed-air HVAC systems integrate ventilation with space conditioning through a unified air distribution network, combining outdoor ventilation air with recirculated indoor air. This approach constrains temperature and humidity control, as the system must simultaneously satisfy ventilation, heating, and cooling requirements. Mixed-air systems require continuous operation during occupied hours to maintain minimum ventilation, leading to inefficient energy use during low-occupancy or minimal-load periods. As Title 24 standards evolve to include dedicated outdoor air systems (DOAS), it is important to evaluate how the operational efficiency of DOAS contributes to energy and carbon emission savings. This project demonstrates and validates a novel emerging technology that has the potential to achieve high cooling efficiency using a desiccant-enhanced, indirect evaporative cooling approach with integrated storage for providing load flexibility. The technology can be compressorless, depending on the source of heat to regenerate the liquid desiccant. However, in the case of the demonstrated product, a compressor-based heat pump (HP) cycle was used to achieve high efficiency during regeneration. The project evaluates the humidity, temperature, cooling performance, efficiency, and peak load-shifting capability of the emerging technology operating as a DOAS for a grocery store in Southern California. At its core, the technology combines liquid desiccant with indirect evaporative cooling and thermochemical energy storage (ES-LD-DOAS) to achieve high-performance cooling, dehumidification, and load flexibility.

This project demonstrates ES-LD-DOAS' ability to achieve energy efficiency beyond the theoretical limit of conventional direct expansion dedicated outdoor air systems (DX-DOAS). However, energy efficiency alone is not the complete solution for achieving California's deep decarbonization goals, because not all kilowatt hours (kWh) are valued equally, and therefore an important integral feature is dispatchable load shifting. The idea is to utilize excess renewable energy for storage, for example from 9 a.m. to 4 p.m., and draw the energy from storage from 4 to 9 p.m., saving and shifting kWh.

Further, the project demonstrates why an ES-LD-DOAS will help futureproof buildings and electric utility distribution systems against weather-driven increases in electricity consumption and associated peak demand of compressor-based air conditioners as the frequency and duration of heat waves and high dew points increase. The efficiency of ES-LD-DOAS improves with rising ambient temperatures, and its cooling capacity remains consistent. The coincidence peak electricity demand of an ES-LD-DOAS is not correlated with peak temperature, a unique attribute for the resilience of California's summer grid. This stands in stark contrast to conventional air conditioning, whose energy intensity and demand profiles rise as a function of outdoor ambient temperature, and whose cooling capacity decreases, leading to oversizing to meet infrequent peak-day cooling requirements.

Background

Dehumidification is a critical function of HVAC systems in buildings where excess moisture poses an increased risk to occupants and facilities. Numerous studies have demonstrated the interaction between occupant health and moisture content or relative humidity. According to a 2023 literature review, the viability of the influenza virus appears to increase in dry air with a relative humidity of less than 50 percent and in high humidity with a relative humidity of greater than 70 percent. Additionally, high relative humidity is associated with increased allergen loads, such as pollen, mites, and mold (Guarnieri, et al. 2023). A 2019 study on relative humidity and workplace wellbeing also showed a correlation between higher stress and exposure to relative humidity outside the 30 to 60 percent relative humidity range established by ASHRAE 55-1989 (Razjouyan, et al. 2020).

Several dehumidification technologies have been introduced over the years. For example, a mechanical dehumidifier with a passive desiccant wheel uses a moisture-absorbing material that cools and dries the incoming air. The passive desiccant can be more affordable to operate than other technologies. However, it requires an exhaust air stream, and its performance depends on the exhaust air being drier than the outdoor air. Another example is a mechanical dehumidifier with a sensible heat exchanger, which does not need exhaust air but instead has an air-to-air heat exchanger to precool and reheat the outdoor air.

ES-LD-DOAS is a novel, liquid desiccant-enhanced, indirect evaporative cooling technology, historically referred to as desiccant enhanced evaporative air-conditioning, and was invented in 2009 by the National Renewable Energy Laboratory (NREL). NREL has issued licenses for the commercialization of its numerous patents. NREL's invention won the prestigious Research and Development (R&D) 100 award for its unparalleled energy efficiency and ability to independently control humidity and temperature. The game-changing energy savings exceed the maximum theoretical efficiency of direct expansion (DX), compressor-based cooling equipment and unlock the potential for deep decarbonization of building cooling and the reduction of gigatons of greenhouse gas (GHG) emissions. The first products being commercialized are a packaged 15- and 20-ton ES-LD-DOAS with planned releases for return air rooftop units (RTUs) and higher supply-airflow rates for use in indoor grow operations, hospitals, sports arenas, and other facilities.

ES-LD-DOAS commercialization has been supported by numerous grants laying the groundwork for this field evaluation, including from:

- San Diego Gas and Electric (SDG&E) for use in a combined cycle with a fuel cell waste heat
- The Caltech Rocket Fund for prototype development
- Two Wells Fargo Innovation Incubator grants to fund testing at NREL
- A California Energy Commission CalTestBed grant for early-stage testing at the University of California, Davis Western Cooling Efficiency Center (UC Davis WCEC)
- Lab testing performed by the Oak Ridge National Laboratory under a Small Business Voucher
- Two grants from the New York State Energy Research and Development Authority (NYSERDA) for market analysis and product development
- A grant from Utilization Technology Development (UTD) to test and develop guidelines to use waste heat for desiccant regeneration at the Gas Technology Institute

- Two grants from the Defense Innovation Unit for field testing at a US Army base and an Air National Guard base
- A grant from the Department of Defense through its Environmental Security Technology Certification Program for grid resiliency to test ES-LD-DOAS equipment and energy storage in a microgrid-managed environment

This project is a field evaluation to independently validate the energy efficiency, cooling performance, and load-shifting capability of a 15-ton ES-LD-DOAS unit installed on a grocery store delivering 100 percent outdoor air.

Product Description

The 15-ton ES-LD-DOAS is a packaged product, comprised of a novel air conditioning core, a liquid desiccant regeneration system, an energy storage tank, sensing and control equipment, air filters, air supply fans, cloud-connected digital twin fault detection, and performance optimization services. The ES-LD-DOAS unit itself was fabricated to high-quality standards and installed as a single packaged unit, simplifying the mechanical design, installation, and control integration. Figure 1 shows the general architecture of the unit tested and Figure 2 provides an exploded view of components.

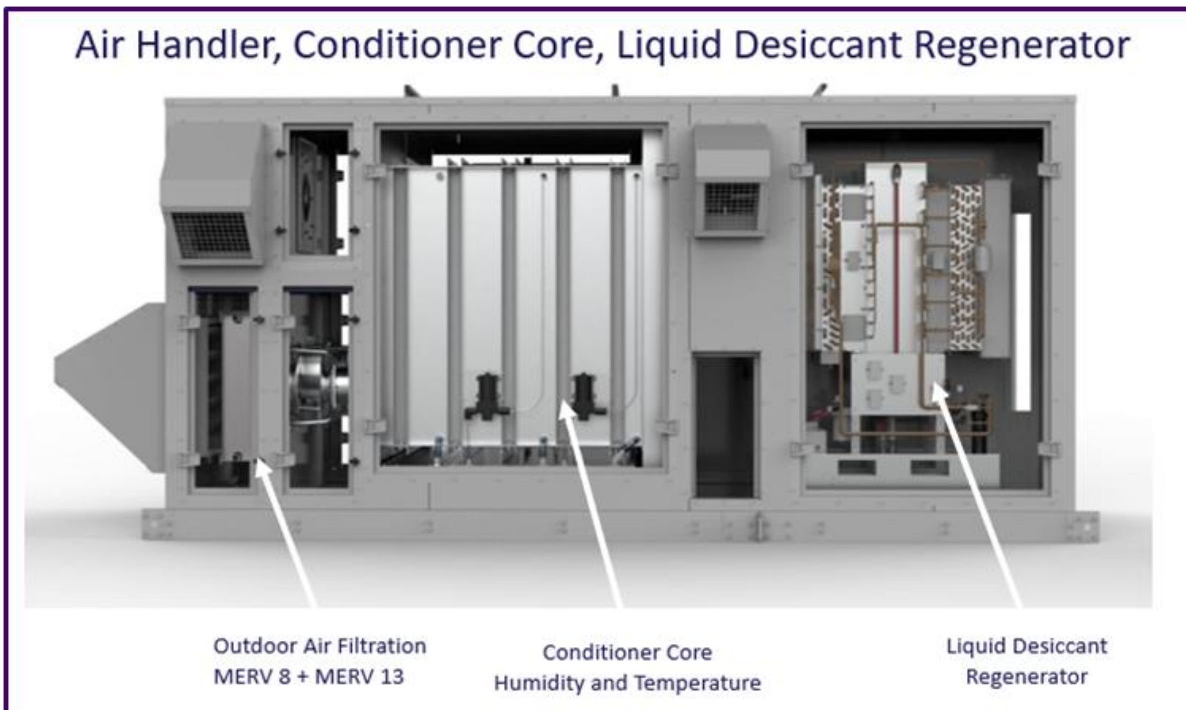

Figure 1: ES-LD-DOAS general arrangement used in the field testing for this project.

Compressorless Air-Conditioning Core

The novel, compressorless, air-conditioning core uses a proprietary, non-corrosive, nontoxic, and non-flammable liquid desiccant to dehumidify the outdoor air stream (latent cooling) and a dew point-style indirect evaporative cooler to control temperature (sensible cooling). The air-conditioning core is designed to operate in all global climatic conditions, ranging from hot and humid to hot and dry. The air-conditioning core does not consume electricity, and its cooling capacity does not degrade with ambient temperature. This feature eliminates weather-related design-day equipment oversizing and partial-load inefficiencies associated with compressor-based DX cooling equipment selection. The conditioning core adapts to changing outdoor ambient conditions by varying a low flow rate of liquid desiccant and water to achieve independent control of dew point and dry-bulb temperature. The ES-LD-DOAS eliminates the impact of heat waves on electrical distribution equipment and the need for increased generation resources.

Liquid Desiccant Regeneration

The liquid desiccant must be regenerated for continued use, meaning the water absorbed from the air into the desiccant must be removed. Water is easily removed from the desiccant by heating the desiccant/water mixture to approximately 170°F. The liquid desiccant regenerator includes a novel, variable-capacity, high-efficiency, electrically-driven heat pump (HP) to produce the necessary heat for regeneration. This feature transforms cooling efficiency, meaning regeneration energy efficiency increases as ambient temperatures soar. The regenerator uses the HP to provide heat, not cooling, so the Coefficient of Performance (COP) increases with temperature. This feature eliminates peak-temperature, design-day equipment oversizing and partial-load inefficiencies associated with compressor-based DX cooling. It also eliminates the impact of heat waves on electrical distribution equipment and the need for increased generation resources. The LD-DOAS moisture removal efficiency exceeds the theoretical limits of compressor-based DX systems.

Thermochemical Energy Storage

The liquid desiccant is stored in an uninsulated, sealed tank and serves as a means of energy storage to provide peak-load shifting. The duration of peak-load shifting is typically 4 to 6 hours and can be extended to 12 hours using an optional add-on tank. The liquid desiccant regenerator is designed for remote dispatch or local control by a building management system. The electrically-driven HP can, for example, be controlled to operate from 10 a.m. to 4 p.m., utilizing excess renewable electricity. The HP is locked out during the peak-demand period, for example, between 4 and 9 p.m. The ES-LD-DOAS continues to deliver cooling, pulling preconditioned liquid desiccant from the energy storage tank. For reference, the 15-ton ES-LD-DOAS, when running on storage, consumes less than 3 kW of electricity for supply fans, pumps, and control power. For comparison, a 15-ton DX-DOAS consumes about 15 kW. The ES-LD-DOAS is a new electrically-driven energy efficiency measure with load flexibility enabled by integral, dispatchable energy storage. The ES-LD-DOAS is designed for aggregation to megawatt-scale capacity as a distributed, behind-the-meter energy resource and to manage load on distribution networks.

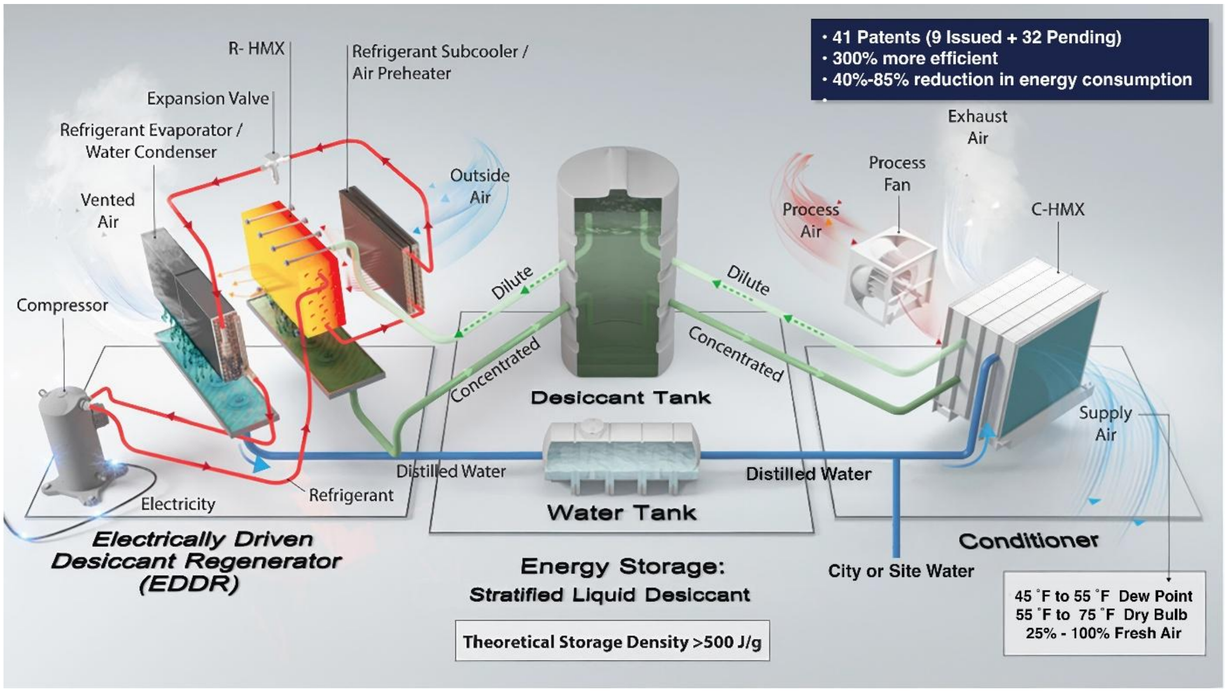

Figure 2: ES-LD-DOAS diagram.

Objectives

The project includes the design and installation of one ES-LD-DOAS unit on an existing commercial grocery store located in Southern California. The unit was continuously monitored from August-October 2025, including parts of both the summer and shoulder cooling seasons. This project increases stakeholder awareness, technical understanding, and accelerates the advancement of ES-LD-DOAS into the marketplace, as well as the development of energy efficiency programs for use within the State of California and beyond. Independent monitoring was provided by AESC, and data analysis and supporting services were provided by the UC Davis WCEC.

The ES-LD-DOAS demonstrated for this project delivers 2,500 cubic feet per minute (CFM) of conditioned, 100 percent outdoor air, 18 hours per day, 7 days per week, conditioned to 70 to 80°F dry-bulb temperature and 55°F dew point temperature, without the need for or use of reheat. The goals for this project are as follows:

1. Verify the ES-LD-DOAS equipment's cooling performance, efficiency, and capacity, as well as desiccant regeneration efficiency and capacity, and thermochemical energy storage for flexible load shifting
2. Provide field-verified estimates of energy savings, demand savings, and GHG emissions savings compared to code-compliant DX-DOAS equipment
3. Develop recommendations for next steps toward the development of a deemed efficiency measure, as well as recommendations for product enhancements, operations, and maintenance

4. Increase stakeholder awareness to advance the adoption of ES-LD-DOAS

Methodology and Approach

Test Site

The research team selected a medium-sized (55,000 square foot) retail grocery store as the test site due to the relatively high cooling load factor. The store was located in Southern California, in California Climate Zone 8 and has a primary air handling system with a cooling capacity of 400 kBtu/h. The site operates 7 days per week, 18 hours per day, and requires a large amount of outdoor air for ventilation which must be conditioned to control for humidity and temperature. Dehumidification plays a critical role in ensuring product quality, optimizing equipment performance, and enhancing the overall customer experience. Figure 3 and Figure 4 show an overhead view of the demonstration site and a blueprint of the installation location, respectively.

Latent cooling to manage the dew point is essential for the operation of a grocery store and is a major source of electricity consumption and operational costs. The ES-LD-DOAS is designed to efficiently remove excess moisture and deliver dry, cool air into the building. However, energy efficiency alone is not the complete solution for deep decarbonization because not all kWh are valued equally. Therefore, an important feature is the load-shifting thermochemical energy storage that can transform grocery stores into grid-interactive flexible loads.

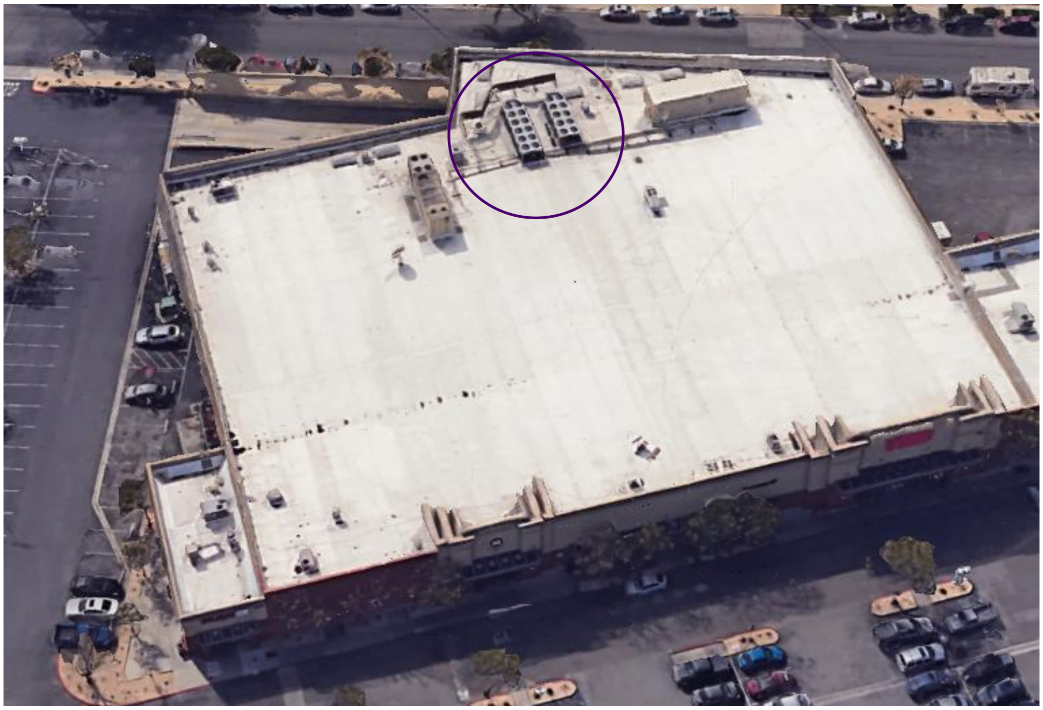

Figure 3: Test site overhead view.

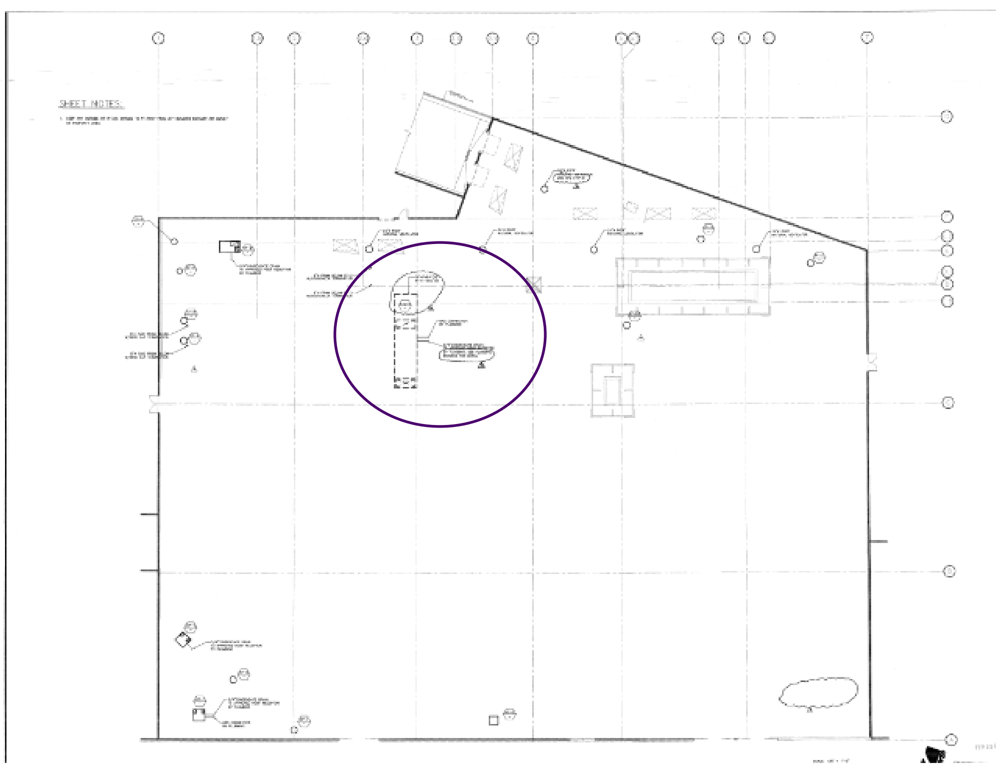

Figure 4: Test site overhead view blueprint.

The ES-LD-DOAS preconditioned up to 2,500 CFM of outdoor air, which was delivered through an insulated ducting system into an existing unit rooftop unit serving the main sales floor (Figure 5). The integration with existing equipment mitigated host-site risk associated with testing ETs and minimizes disruption to store operations during implementation.

Figure 5: ES-LD-DOAS piping to existing rooftop air handler.

Test Plan

The research team continually monitored and analyzed the energy consumption and cooling performance of the ES-LD-DOAS on a weekly basis throughout the project. The findings are reported, and the results are compared against the AHRI 920 Standard design guidelines for testing DX-DOAS equipment. The evaluation, measurement, and verification (EM&V) plan provides a method for contrasting the efficiency and capacity of ES-LD-DOAS technology against DX-DOAS equipment based on integrating the measured performance into a building energy model. This allows the technology to be compared across different application scenarios.

AESC, in consultation with UC Davis WCEC, created the M&V plan in accordance with the International Performance Measurement and Verification Protocol (IPMVP). Relevant codes and standards, including ASHRAE, California Title 24, and the Alternative Calculation Method (ACM) Manual, were also referenced to determine energy (kWh), demand (kW), load- shifting and flexibility savings, as well as latent and sensible cooling performance.

AESC implemented the M&V plan by installing the data gathering equipment listed in Table 3. All data were collected at one-minute intervals, except for indoor air temperature and humidity, which was taken at five-minute intervals. Data were collected on the existing primary air handler (AC3), as well as the ES-LD-DOAS. Ambient temperature data were collected on-site at the unit's outside air intake. The ambient temperature data are critical for normalizing and calibrating energy patterns to actual meteorological weather observations.

Table 3: List of installed M&V sensors.

Measured Variable	Equipment	Accuracy	Frequency
Indoor air temperature (°F) and relative humidity (%)	Monnit MNS2-9-IN-HU-RH industrial humidity sensor	± 2% relative humidity, 0.54°F	5 min average
AC3 unit power (kW)	DENT	+/- 1% of full scale	1 min average
AC3 return air temperature (°F) and relative humidity (%)	Monnit MNS2-9-IN-HU-RH industrial humidity Sensor	± 2% relative humidity, 0.54°F	1 min average
AC3 mixed air temperature (°F)	ACI duct averaging sensor	±0.36°F	1 min average
AC3 supply air temperature (°F) and relative humidity (%)	Monnit MNS2-9-IN-HU-RH industrial humidity sensor	± 2% relative humidity, 0.54°F	1 min average

Additionally, the data points listed in Table 4 were collected from the ES-LD-DOAS's onboard sensors including the reported accuracy of measurement. The outdoor airflow and supply airflow measurements were calculated from the airflow measured at the process fans and one exhaust fan. Due to the sensitivity of airflow measurement accuracy to the sensor installation, the UC Davis WCEC conducted a tracer-gas airflow measurement on August 14 to confirm accuracy. The field validation found that the onboard airflow measurement was in agreement with the third-party test method.

Table 4: List of onboard M&V sensors.

Measured Variable	Equipment	Accuracy	Frequency
ES-LD-DOAS unit power (kW)	WattsOn – Mark II	+/- 1% of full scale	1 min average
Outdoor airflow (CFM)	Calculated from piezometer rings on 2 process fans and 1 exhaust fan	Field calibrated	1 min average
Exhaust airflow (CFM)	Piezometer ring	Field calibrated	1 min average
Supply air to AC3 flow (CFM)	Calculated from piezometer rings on 2 process fans and 1 exhaust fan	Field calibrated	1 min average
Outside air temperature (°F) and relative humidity (%)	Distech HS-D22XTX	± 2% relative humidity, 0.36°F	1 min average
ES-LD-DOAS regenerator exit air temperature (°F) and relative humidity (%)	Distech HS-D22XTX	± 2% relative humidity, 0.36°F	1 min average
ES-LD-DOAS conditioner exhaust air temperature (°F) and relative humidity (%)	Distech HS-D22XTX	± 2% relative humidity, 0.36°F	1 min average
ES-LD-DOAS supply air to AC3 temperature (°F) and relative humidity (%)	Distech HS-D22XTX	± 2% relative humidity, 0.36°F	1 min average
Regenerator Power	Wattnode Pulse Powermeter WNB-3D-480-P	± 0.45% reading + 0.05% full scale	1 min average

All instrumentation was connected to the internet through a cellular gateway. AESC site visits determined the placement of the gateway based on cellular service levels. Data were stored in the device's native cloud and downloaded and validated on a weekly basis. There were no connectivity or other requirements for the site host other than access and power to the equipment. AESC, WCEC, and the ES-LD-DOAS supplier verified, diagnosed, repaired, and improved data collection and control methods as required.

Data Analysis

The UC Davis WCEC supported the development of unit control parameters, operational modes, schemes, and analytical and modeling approaches in support of the goals and requirements of the EM&V plan while considering the needs and constraints of the host customer, indoor latent and sensible load profiles, and anticipated outdoor, weather-driven humidity and temperature. Due to the poor condition of the baseline equipment, performance modeling was used to compare the performance of the ES-LD-DOAS to a US Department of Energy (DOE) minimum-efficiency DX-DOAS.

Data analysis for this project included:

- Latent and sensible cooling performance (outdoor air: dry-bulb temperature and relative humidity; conditioned supply air: dry-bulb temperature and dew point)
- Moisture removal efficiency (MRE)
- Moisture removal capacity (MRC)
- Comparison against model-based, code-compliant DX-DOAS equipment performance
- Thermochemical energy storage load shifting

DOAS Equipment Standards

The AHRI 920 Standard is specifically designed for DX-DOAS. The standard was created to establish consistent definitions and testing requirements for DX-DOAS units. These systems are designed to provide ventilation and dehumidification using 100 percent outdoor air. The standard was introduced to address the need for a reliable method of comparing the performance of these systems, ensuring manufacturers adhere to consistent testing protocols.

Moisture Removal Capacity (MRC)

MRC measures the amount of moisture the DOAS unit can remove from the air, expressed in pounds of moisture per hour (lb/h). This metric is crucial for evaluating the dehumidification performance of the unit.

Moisture Removal Efficiency (MRE)

MRE measures how effectively DOAS equipment removes moisture from the air relative to the amount of energy consumed, and is reported in pounds of moisture removed per kWh (lb/kWh) of energy consumed. MRE is akin to the widely understood Energy Efficiency Ratio (EER) rating used for packaged RTUs. A higher MRE indicates greater efficiency, meaning the system removes more moisture per unit of energy consumed.

Integrated Seasonal Moisture Removal Efficiency 2 (ISMRE2)

The ISMRE2 standard is akin to the widely understood Integrated Energy Efficiency Ratio (IEER) rating used for packaged RTUs. ISMRE2 is a seasonally weighted calculation that reports the dehumidification efficiency of DOAS units without the use of supplemental heat. It is a metric used to evaluate the efficiency of DX-DOAS units in removing moisture from the air over an entire dehumidification season. This metric helps assess how well these systems perform in real-world conditions throughout the dehumidification season.

Table 5 outlines the ES-LD-DOAS ISMRE2 performance at the AHRI Standard 920-rated conditions. For reference, the minimum code-compliant DX-DOAS ISMRE2 value in Title 24 for air-cooled and air-source HPs without ventilation energy recovery systems is 4.0 lb/kWh.

Table 5: ES-LD-DOAS ISMRE2 calculation per AHRI Standard 920.

AHRI 920 Rating Conditions	ISMRE Weighting	Entering Air Dry-Bulb/Wet-Bulb Temperature (°F)	Discharge Air Dry-Bulb/Dew Point Temperature (°F)	MRC (lb/h)	ES-LD-DOAS MRE (lb/kWh)
Rating A	14%	95/78	70/55	131	9.8
Rating B	34%	80/73	70/55	123	10.6
Rating C	39%	70/66	70/55	98	10
Rating D	13%	63/59	70/55	76	9.7
ES-LD-DOAS ISMRE2 (lb/kWh)				10.1	
Minimum code compliance				**4.0**	

Preliminary ES-LD-DOAS Energy Savings Compared to DX-DOAS

A preliminary estimate of energy savings was calculated by comparing the performance of an ES-LD-DOAS against a standard ASHRAE 90.1-compliant DX-DOAS, both achieving the same space conditions. Table 6 provides the moisture removal required for the ventilation air provided by the DOAS at the test site, using typical year weather data (TMY3) representative of the site location (Fullerton, California). Title 24 uses the same minimum ISMRE2 efficiencies as ASHRAE 90.1. Table 7 provides the preliminary performance estimates for the baseline and ES-LD-DOAS electric energy usage, as well as the energy savings based on an 8760 model of both systems. This model maintains a 4.0 ISMRE2 efficiency for the baseline DX-DOAS and a 10.1 ISMRE2 efficiency for the ES-LD-DOAS, as summarized in Table 5 above.

Table 6: ES-LD-DOAS average host site monthly moisture removal, based on Fullerton Climate Zone 8 weather.

Month	ES-LD-DOAS Host Site Monthly Moisture Removal (lb/month)
Jan	-
Feb	25
Mar	6
Apr	140
May	2,265
Jun	8,380
Jul	19,987
Aug	25,680
Sep	11,834
Oct	6,770
Nov	245
Dec	53

Table 7: Preliminary estimates of energy savings for ES-LD-DOAS compared to DX-DOAS.

Month	DX-DOAS Electricity Usage Per Month (kWh)	ES-LD-DOAS Electricity Usage Per Month (kWh)	ES-LD-DOAS Electricity Savings Per Month (kWh)	Electricity Savings (%)
1	784	376	408	52
2	14	353	61	51
3	718	355	363	51
4	966	445	521	54
5	2,517	909	1,608	64
6	3,961	1,580	2,381	60
7	7,194	2,855	4,339	60
8	7,998	3,463	4,535	57
9	5,557	1,980	3,577	64
10	3,006	1,341	1,665	55
11	975	457	519	53
12	911	436	475	52
Total	35,301	14,551	20,750	59

Findings

The findings from the field demonstration and performance modeling of the ES-LD-DOAS are presented below.

Overview

The demonstration results were evaluated using a combination of field data analysis and performance modeling. The ES-LD-DOAS was installed at a grocery store in Southern California, which had an existing primary air handler for managing comfort, including heating, cooling, ventilation, and dehumidification. The ES-LD-DOAS was used to supplement the existing air handler by pre-conditioning a portion—approximately 50 percent—of the store's ventilation air, thus offsetting that conditioning load from the existing unit. The monitoring effort focused on evaluating the specific service provided by the DOAS unit compared to a relevant baseline, rather than the impact on this site. This provides the data necessary to compare the performance to a traditional DX-DOAS unit.

Performance Regression Modeling

Field testing was used to develop performance regressions of the ES-LD-DOAS for simulation modeling. The performance of the ES-LD-DOAS is dependent on outdoor air conditions, the exhaust air ratio (EAR) of the indirect evaporative cooler, airflow rate, and desiccant concentration. These curves included supply air temperature and humidity, and power consumption as a function of environmental variables. The independent variables used for the performance curves included environmental factors such as outdoor temperature and humidity.

The project team investigated the integration of these curves into EnergyPlus building simulation software, but there were some unique challenges presented by this approach. One variable that could not be easily incorporated was the regenerator power and desiccant concentration. The regenerator can use different methods for removing moisture from the liquid desiccant, including waste heat, solar thermal heaters, HPs, or electric resistance heaters. The unit in this demonstration used an integrated HP for concentrating the desiccant solution, and the dehumidification delivered by the ES-LD-DOAS was observed to be dependent on the desiccant concentration. Due to the challenge of integrating the performance model in EnergyPlus, a full-year hourly simulation was performed, comparing the performance of the ES-LD-DOAS to a DX-DOAS model using a custom analysis tool that was decoupled from a building energy simulation. The analysis tool evaluated the capacity, energy use, and carbon impacts of a DOAS unit conditioning 2,500 CFM of outdoor air for building ventilation. Since DOAS units operate with 100 percent outdoor air, the analysis would not be directly tied to the loads of a particular building, allowing this analysis to provide a good comparison to the impact of a baseline DX-DOAS and the ES-LD DOAS technology.

Results

The ES-LD-DOAS was installed and commissioned on August 14, 2025. The unit provides about half of the 5,000 CFM ventilation required by the grocery store, with the other half coming from an outdoor air intake with a damper on the ductwork between the ES-LD-DOAS and the existing rooftop air handling unit (Figure 6).

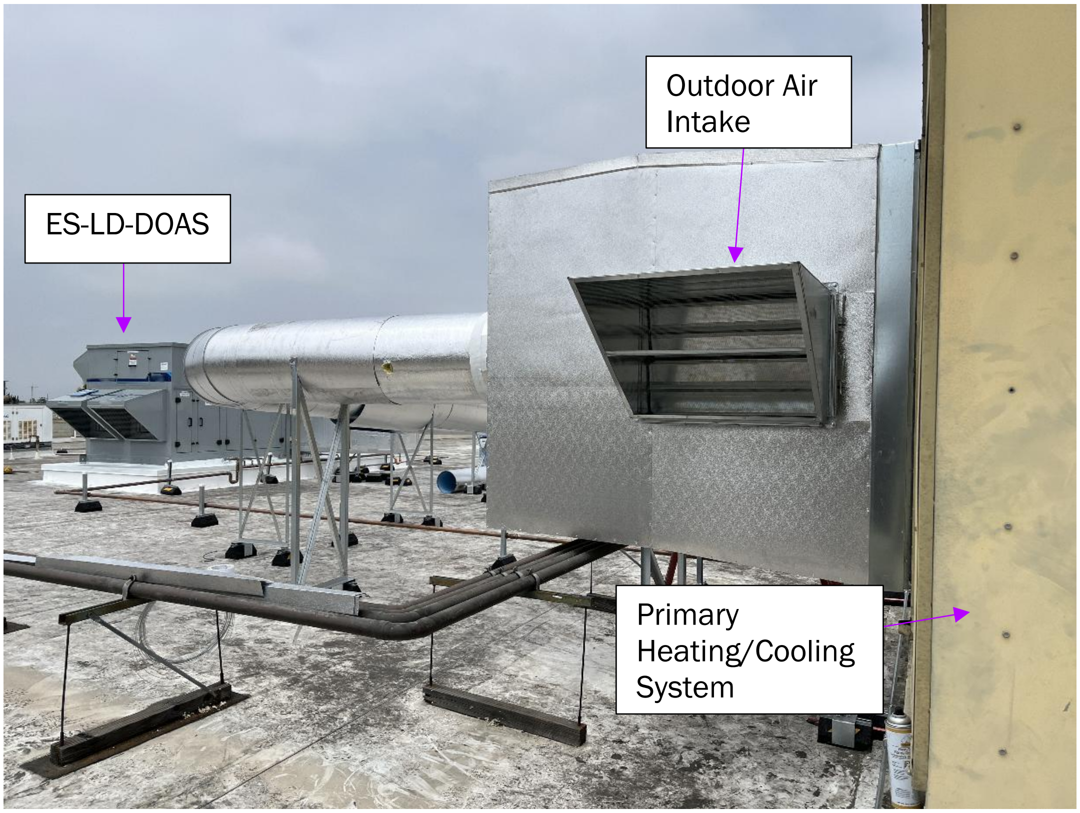

Figure 6: Photo of retrofit installation showing ES-LD-DOAS supply ducting, outdoor intake, and primary heating and cooling system for the grocery store.

Initial data collected on the performance of the ES-LD-DOAS showed that the system required updates to the control system to avoid overuse of the regenerator. The manufacturer implemented a new control scheme that reduced the exhaust airflow rate to better manage the liquid desiccant use and reduce fan power. These control updates were implemented on September 9, 2025, and were shown to significantly reduce regenerator usage.

Table 7 shows the regenerator use as illustrated by the compressor RPM, indicating only one brief period of downtime throughout the day. After the controls were changed, the regenerator operation was reduced by nearly half (Figure 8) with usage eliminated during the critical peak hours of 4 to 9 p.m.

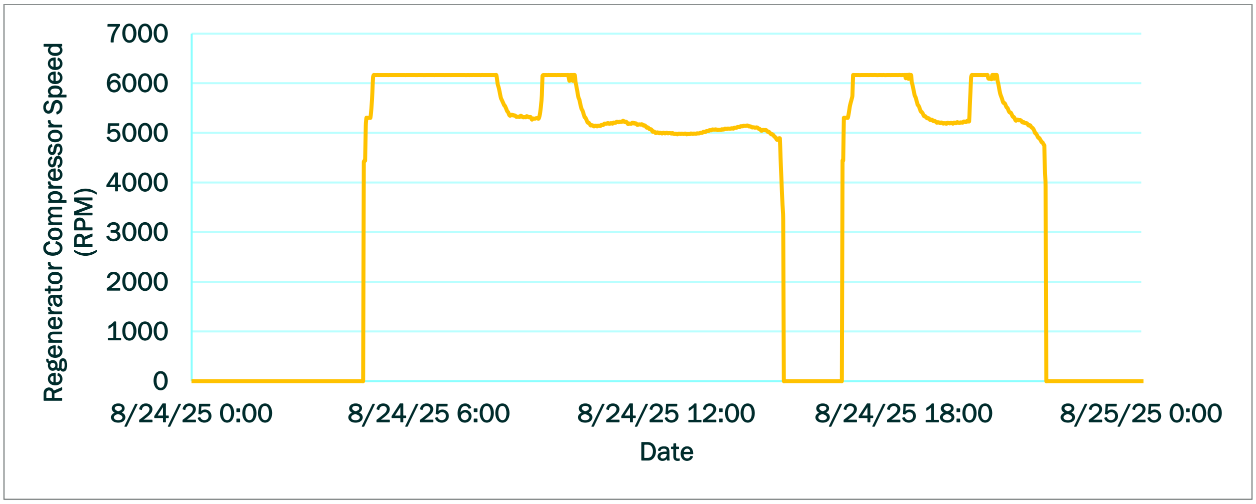

Figure 7: Regenerator compressor use shortly after installation and before the controls change.

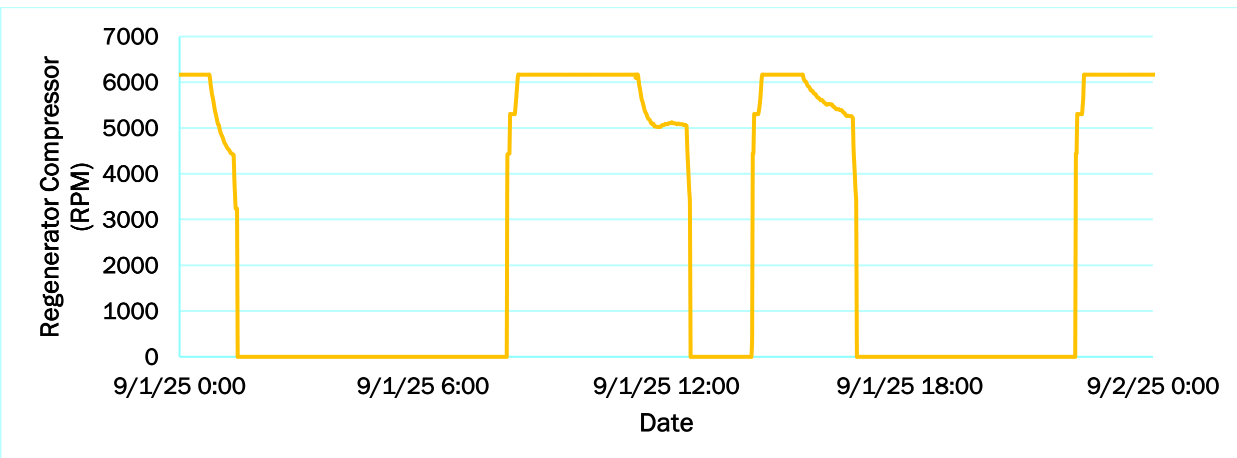

Figure 8: Regenerator compressor use after the controls change.

Monitoring of the primary heating and cooling system at the store showed lower supply air temperatures after the ES-LD-DOAS installation. The store was experiencing significant moisture issues near cold storage items, with condensation forming on the refrigerated doors and eventually dripping onto the floor. Monitoring conducted for this study discovered that the primary cooling system was not operating its second-stage cooling appropriately, as can be seen in Figure 9. The store was able to resolve that issue, which improved the problem with water forming on the ground. It can still be observed in Figure 6 that dew point temperatures in the store improved with the addition of the ES-LD-DOAS. When the primary cooling system was using its second stage compressor, return air dew point temperatures reached about 55°F, whereas after the retrofit, the return dew point temperature dropped to 51°F during second-stage cooling.

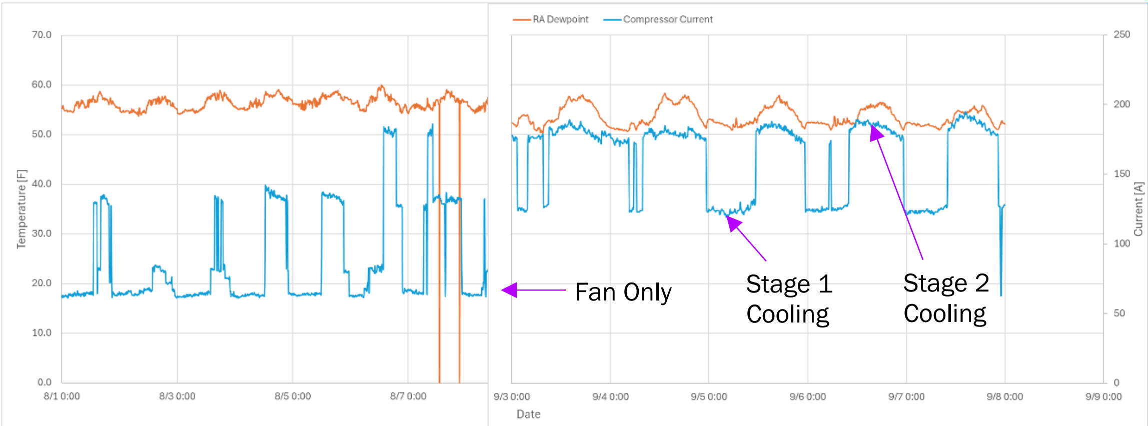

Figure 9: Return air dew point before and after the retrofit with compressor current indicating the status of the primary cooling system.

Figure 10 shows an example of the performance data collected over two days in September, plotted with the total electric power. Regenerator use was apparent from the periods of larger power consumption above 10 kW. The COP when the regenerator was not operating was very high, with an average value of 6.8 (23.1 EER) across 16 days of operation since the controls update (September 10 to October 7). However, the desiccant regeneration process was more energy intensive than the cooling operation and resulted in an average COP of 0.94 (3.2 EER) when the regenerator ran while performing cooling and dehumidification. The regenerator could also operate when the unit was not providing conditioned air to the building, resulting in a COP of 0. When evaluating the performance of the unit over full monitoring period, the combined COP, including maintenance power used to regenerate desiccant when the unit was not providing cooling, was 1.3 (4.5 EER). This result cannot be compared to traditional cooling efficiency, since the unit processed 100 percent outside air, and the performance of DOAS units is typically related to their moisture removal efficiency.

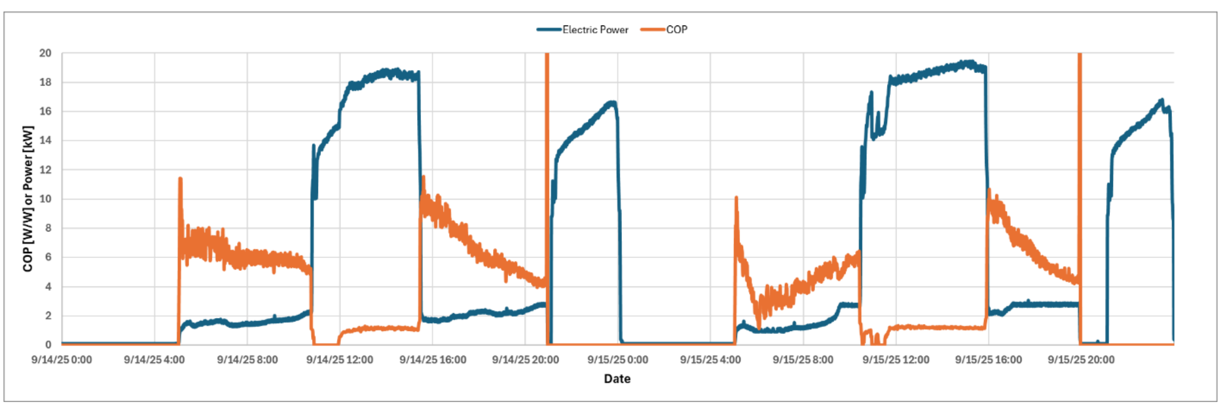

Figure 10: Example data from unit showing the cooling efficiency (COP) and power over two days in September.

Moisture removal efficiency (MRE) was calculated and shown over an example two-day period in Figure 11. The MRE is shown to greatly exceed the seasonal performance (ISMRE2) requirement of 4.0 lbs/kWh during periods of operation, reaching values of 10 to 35 depending on ambient conditions. Similar to COP, the MRE dropped significantly to below 3.0 lbs/kWh when the regenerator was operating. The overall MRE over full monitoring period was calculated by accounting for all moisture removed and all power used over the period of observation, including when the regenerator was running and no building conditioning was occurring. The overall MRE was found to be 3.94 for the measurement period. This was based on the observed conditions in the field rather than at the AHRI 920 rated conditions, so it cannot be directly compared to ISMRE2.

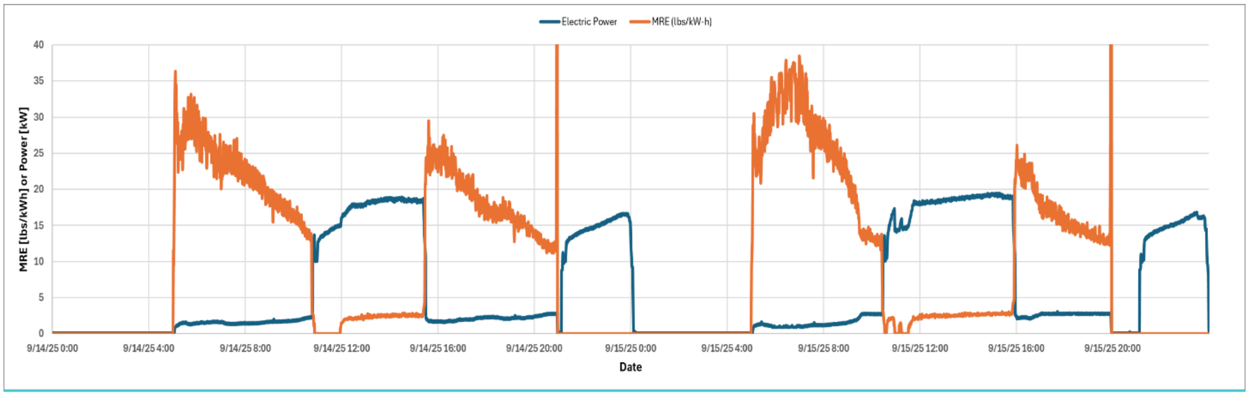

Figure 11: Example data from unit showing the moisture removal efficiency (MRE) and power over two days in September.

It is clear from Figure 10 and Figure 11 that the regenerator process was a key variable in the energy efficiency of the ES-LD-DOAS operation. It is also apparent that the unit could provide cooling and dehumidification for four to five hours without using the regenerator, providing significant load-shifting benefits. The regenerator was observed to operate at night to re-concentrate the liquid desiccant and again during the day after several hours of operation. The controls implemented allowed regenerator cycles to avoid peak electricity periods from 4 to 9 p.m., reducing the cost to operate the DOAS and demonstrating grid flexibility. During the first six days of operation, it was observed that only 6 percent of the total energy consumed by the unit occurred during the peak electricity period.

Data Analysis

The data from field demonstration were used to train a regression model, allowing estimates of energy performance to be made compared to a standard minimum-compliant DX-DOAS. The field data collected over 16 days was used to calibrate the regression models and includes observations near the highest dew points expected in many California Climate zones. The maximum dew point observed during the field test was 71°F, whereas the maximum expected dew point based on typical meteorological data was 75°F. There was less data collected at low ambient dew point temperatures with the lowest dew point observed being 57°F. The energy modeling performed in this report used a supply dew point setpoint of 55°F, meaning the equipment would only perform dehumidification when the outside air when dew point conditions were above 55°F. Although the field data collection did not span the full range of annual weather conditions, it did capture the conditions under which a DOAS system performs the majority of its conditioning work. As a result, only minimal extrapolation was needed to estimate annual performance, enabling accurate full-year energy modeling.

A simple model of the ES-LD-DOAS, to be used in any building energy modeling software, must at least approximate all parameters which have a strong influence over the efficiency and capacity of the system. Critical values include:

1. Ambient air dry-bulb temperature
2. Ambient air dew point temperature
3. Exhaust air ratio (EAR) of the system, defined as how much air must be flown through the process plates that is subsequently bled off into the exhaust channels, instead of delivered to the building
4. Desiccant concentration entering or exiting the conditioner
5. Desiccant concentration entering or exiting the regenerator

Of these, the only one that was not monitored was number 4, the desiccant concentration entering the conditioner. Thus, the first step in this effort was to develop a surrogate model for desiccant concentration.

Desiccant Concentration Modeling

For this model, we used moisture accounting. The first step was to start from an initial condition of known concentration in the tank. In a simulation, this can simply be an input for the first timestep of the simulation. When validating the model against field data, we chose a known exit concentration from the regenerator during a time when the conditioner was off.

The next step was to track the moisture that was absorbed by the desiccant as the conditioner ran. This was determined not by the traditional moisture removal rate (MRR) of the supply airflow, but rather by something termed the water absorption rate (WAR). The difference is that more air flowed over the desiccant, and was dehumidified to set point, than the air that flowed into the building. We termed the prior process air and the latter supply air. The difference was due to the fact that some cool, dry air needed to flow in the exhaust channels of the indirect evaporative cooler. The EAR is the ratio of airflow in the exhaust channels to that in the process channels.

$$EAR = \frac{CFM_{process} - CFM_{suppy}}{CFM_{process}}$$

$$MRR = \dot{m}_{supply\ air}(\omega_{in} - \omega_{out})$$

$$WAR = \dot{m}_{process\ air}(\omega_{in} - \omega_{out}) = \frac{\dot{m}_{supply\ air}(\omega_{in} - \omega_{out})}{1 - EAR}$$

The WAR above describes how much water is entering the desiccant, thus diluting it. However, the system wants to know the desiccant concentration, or mass fraction, so this rate of water addition must be taken in the context of the mass of water and mass of desiccant solute that is already in the tank. For the mass of solute, if at any point we know the volume, density, and mass fraction of the desiccant in the tank, we can calculate the mass of solute in the tank. A good value to use is the initialization during commissioning, when a 150-gallon tank is filled 70 percent full with 70 percent desiccant.

$$kg_{solute} = (tank\ volume) \cdot (desiccant\ density) \cdot (desiccant\ concentration)$$

This mass of solute in the tank will remain fixed. Thus, the evolution of the concentration is determined by the rise and fall of the mass of water in the tank. The initial condition of water in the tank during commissioning is given by:

$$kg_{H2O} = (tank\ volume) \cdot (desiccant\ density) - kg_{solute}$$

Thus, as we march forward in time, we now add the weight of water absorbed by the conditioner—or subtract the amount removed by the regenerator, if on—to the weight of the water that was in the tank immediately prior. From the new weight of water, a new concentration can be calculated:

$$Concentration_{new} = \frac{kg_{solute}}{kg_{solute} + kg_{H2O,previous} + kg_{H2O,added\ or\ removed}}$$

The desiccant tank in the ES-LD-DOAS stratifies well, meaning that the desiccant concentration can be different at different parts of the tank. If the tank is full at 70 percent concentrated desiccant, as the conditioner operates and returns dilute desiccant back to the tank, the dilute desiccant stays on top while the conditioner can continue taking 70 percent desiccant until it is depleted. A truly thorough tank model will account for this turnover and stratification. Initially, the surrogate model developed here did account for turnover as well. However, to calculate desiccant turnover, one must keep track of the flow rates of desiccant. Because the subsequent regressions in this work did not depend strongly on desiccant flow rate, due primarily to the method of control the system currently uses, a “bulk average” (non-turnover) desiccant model was assessed. It was determined that this approach did not add significant error to the results, while simplifying the analysis greatly. However, it is worth noting that due to this approximation, the model’s predicted conditioner inlet concentration is always an underestimate, making the performance predictions more conservative.

DESICCANT CONCENTRATION MODEL COMPARED TO DATA

The test unit was equipped with a single mass flowmeter that determined the desiccant concentration in the system. The flow meter was located at the exit of the regenerator, so the data collected is only valid when the regenerator pump is running. Figure 12 shows the agreement between the surrogate concentration model and the measured concentration value at the regenerator exit. When the regenerator turns off, the measured value flatlines (blue), because the regenerator is no longer measuring any flowing desiccant. When the conditioner turns on, the model begins predicting concentration (orange and green). When the regenerator turns back on, the minimum value agrees well with the predicted value from the surrogate model.

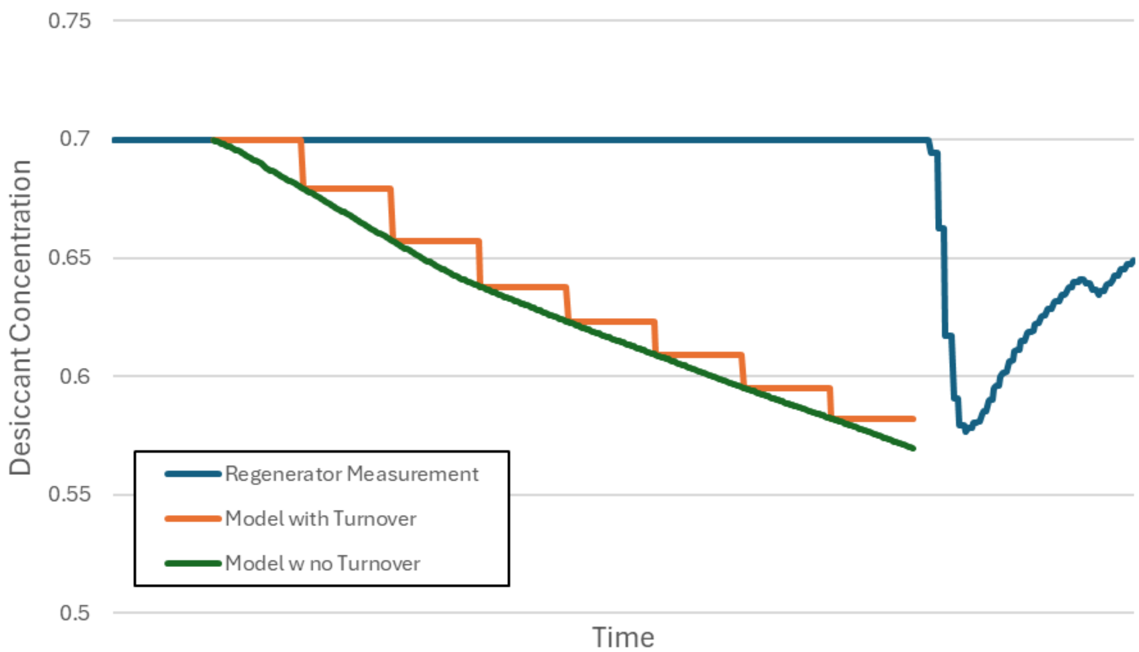

Figure 12: Comparison of the surrogate desiccant concentration model with measured concentration.

Regression System Performance

The system was predominantly controlled to modulate the EAR in order to achieve a steady supply air dew point. EAR is a key factor for predicting overall performance, because it impacts the WAR, i.e., the amount of moisture the regenerator must reject, as well as the conditioner fan power. Thus, the first task of a system model is to predict EAR.

EXHAUST AIR RATIO REGRESSION

Parameters expected to impact the system's required EAR include ambient absolute humidity, ambient dry-bulb temperature, desired supply air absolute humidity, and desiccant inlet concentration. The resulting regression is shown below. The **average absolute error is 8.0 percent.** Note that data with EAR less than 19 percent were truncated from the fitting. This is because for this unit, an EAR of 18 percent was deemed the minimum, and below that value the desiccant flow was modulated in order to hit humidity set points. This means a regression seeking to predict EAR from that data will be inherently flawed.

A multivariable linear regression was implemented to predict the EAR based on the synthetic tank desiccant concentration ($mf_{LD\ in}$), ambient humidity ratio ($\omega_{air\ in}$), ambient dry-bulb temperature ($T_{air\ in}$), and supply air dew point ($T_{dew\ point\ air\ out}$). The regression is:

$$EAR\ \left[\frac{cfm}{cfm}\right] = -1.328 \cdot mf_{LD\ in}\ \left[\frac{kg}{kg}\right] + 75.21 \cdot \omega_{air\ in}\ \left[\frac{kg}{kg}\right] + 0.00818 \cdot T_{air\ in}\ [°C] - 0.01567 \cdot T_{dew\ point\ air\ out}\ [°C] + 0.1862$$

The regression was performed and checked on a dataset that was collected from September 10 through 16 to see how well it would perform. The actual EAR was compared to the predicted EAR when the conditioner was running, and the regenerator was off. Figure 13 presents the comparison of the two values, which shows good agreement between the predicted and measured values, with an average absolute error of 10 percent.

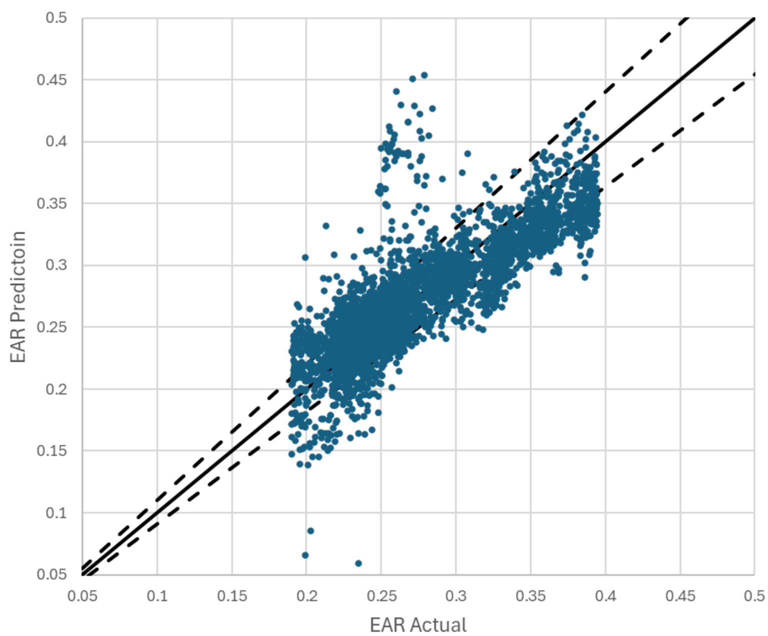

Figure 13: Linear regression of exhaust air ratio using inlet concentration, inlet air absolute humidity, inlet air dry-bulb temperature, and exit air absolute humidity as regressors.

FAN POWER VIA EXHAUST AIR RATIO

As mentioned previously, the EAR can be used to predict the fan power usage of the conditioner. Inspection of the data showed that an exponential relationship could be used to predict the power as a function of the EAR. Figure 14 shows the relationship, with a strong R^2 value of 0.96. The equation is:

$$Fan\ Power\ [kW] = 0.615 \cdot exp\ (3.6979 \cdot EAR \left[\frac{kg}{kg}\right])$$

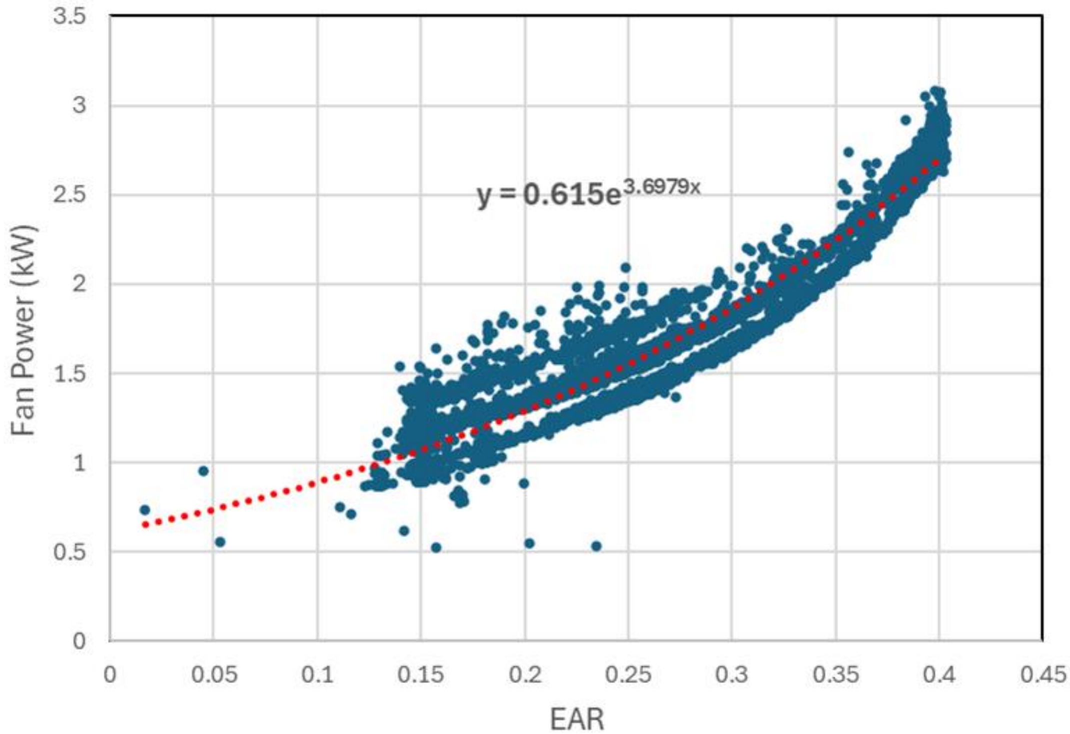

Figure 14: **Chart showing the exponential relationship between the EAR and the power usage in kW.**

SUPPLY AIR DRY BULB REGRESSION

While supply air dew point is considered an input to the model in order to calculate EAR, supply air dry-bulb temperature is considered an output of the model—one that depends on EAR. Besides EAR, other parameters that the prediction of dry-bulb temperature depends on include: supply air dew point, since lower supply air dew points improve evaporative cooling effectiveness; outdoor air dew point, since higher outdoor air dew points mean that the heat exchanger will have to overcome more heat of condensation while dehumidifying to the set point; and ambient dry-bulb temperatures. The resulting regression is shown below, and Figure 15 shows the comparison of predicted to measured values. The **average absolute error is 1.9 percent.** Note that if the EAR, which is sufficient to meet dehumidification set points, results in a dry-bulb temperature that is too high, or if no dehumidification is required but sensible cooling is, this regression can be inverted and used to predict an EAR that yields a desired dry-bulb temperature.

$$T_{supply,DB}\ [°C] = 0.1946 \cdot T_{dew\ point\ air\ out}\ [°C] + 0.9649 \cdot \omega_{air\ in}\ \left[\frac{kg}{kg}\right]$$

$$+ 0.308 \cdot T_{air\ in,DB}\ [°C] - 17.10 \cdot EAR\ [\frac{CFM}{CFM}] + 17.23$$

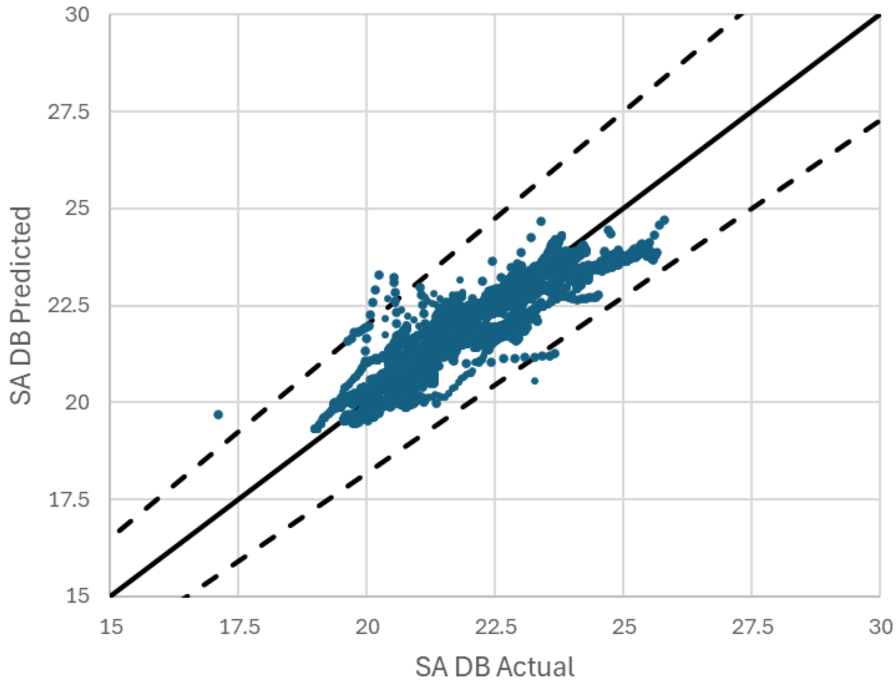

Figure 15: Linear regression of supply dry-bulb temperature using inlet air absolute humidity, inlet air dry-bulb temperature, exhaust air ratio, and exit air absolute humidity as regressors.

REGENERATOR POWER CONSUMPTION

Moving on to the regenerator, the key parameters of interest are:

1. The rate of removal of water from the desiccant; we term this water removal rate (WRR), to prevent confusion with the more common supply air term, moisture removal rate (MRR)
2. The efficiency of removal of water from the desiccant; we term this water removal efficiency (WRE), to prevent confusion with the more common air handler term, moisture removal efficiency (MRE)
3. Power consumption, equal to simply WRR/WRE

After analyzing the data, the power consumption was found to be the cleanest regression against our available inputs. This was due to the large dependence on inlet desiccant concentration. Inlet desiccant concentration plays a significant role in refrigeration system performance. Because of how the compressor is controlled, i.e., variable speed is modulated to seek a constant condensing temperature, power is regressed very well when inlet concentration is an input parameter (see regression below). Other inputs that affect the power consumption are ambient absolute humidity, and ambient dry-bulb temperature. **The average absolute error is 2.8 percent**, and Figure 16 shows the comparison between the measured and predicted values. It is worth noting that other things will affect the saturation temperature strongly too, such as regenerator airflow rate and regenerator desiccant flow rate. However, those were held constant during the M&V period. This is by no means an optimal control strategy for these conditions, and one of the reasons that longer testing will continue to provide valuable insight. The regression is:

$$Pwr_{regenerator}\ [kW] = 141.67 \cdot \omega_{air\ in}\ \left[\frac{kg}{kg}\right]$$

$$- 0.00737 \cdot T_{air\ in,DB}\ [°C] + 24.30 \cdot mf_{LD,in}\ \left[\frac{kg}{kg}\right] - 2.12$$

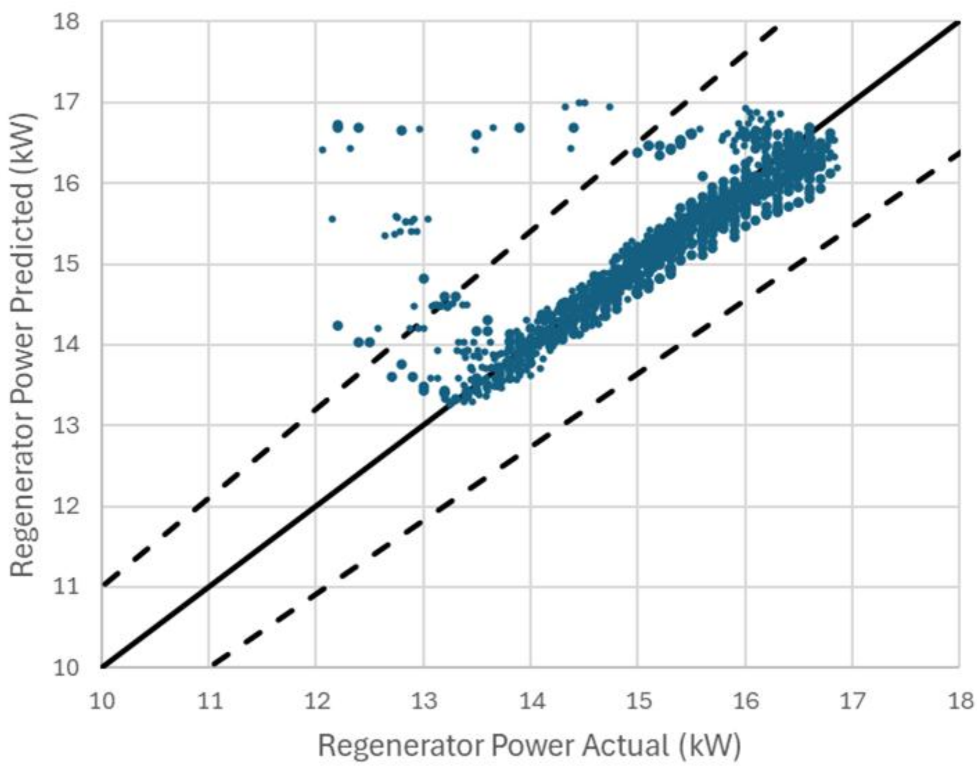

Figure 16: Linear regression of regenerator power consumption, using inlet concentration, inlet air absolute humidity, and inlet air dry-bulb temperature as regressors.

REGENERATOR WATER REMOVAL RATE

Since regenerator power consumption has already been regressed into a prediction, WRR is the needed supplemental prediction, allowing WRE to be predicted as well. For this regression, inputs include the same parameters as for regenerator power consumption (inlet desiccant concentration, ambient absolute humidity, and ambient dry-bulb temperatures), as well as regenerator power consumption (an output of the prior regression). The regression is shown in Figure 17, with an **average absolute error of 5.3 percent.** It is clear that there is a bias to the fit, and that either a useful inlet parameter is omitted, or one of them should be non-linear in relationship. Additional training data and data analysis would help improve this regression.

The regression is:

$$WRR_{regenerator}\left[\frac{kg}{hr}\right] = 11.07 \cdot \omega_{air\ in}\left[\frac{kg}{kg}\right]$$

$$+\ 0.1852 \cdot T_{air\ in,DB}\,[°C] - 45.29 \cdot mf_{LD,in}\left[\frac{kg}{kg}\right] + 3.121 \cdot Pwr_{regen}\,[kW] + 26.25$$

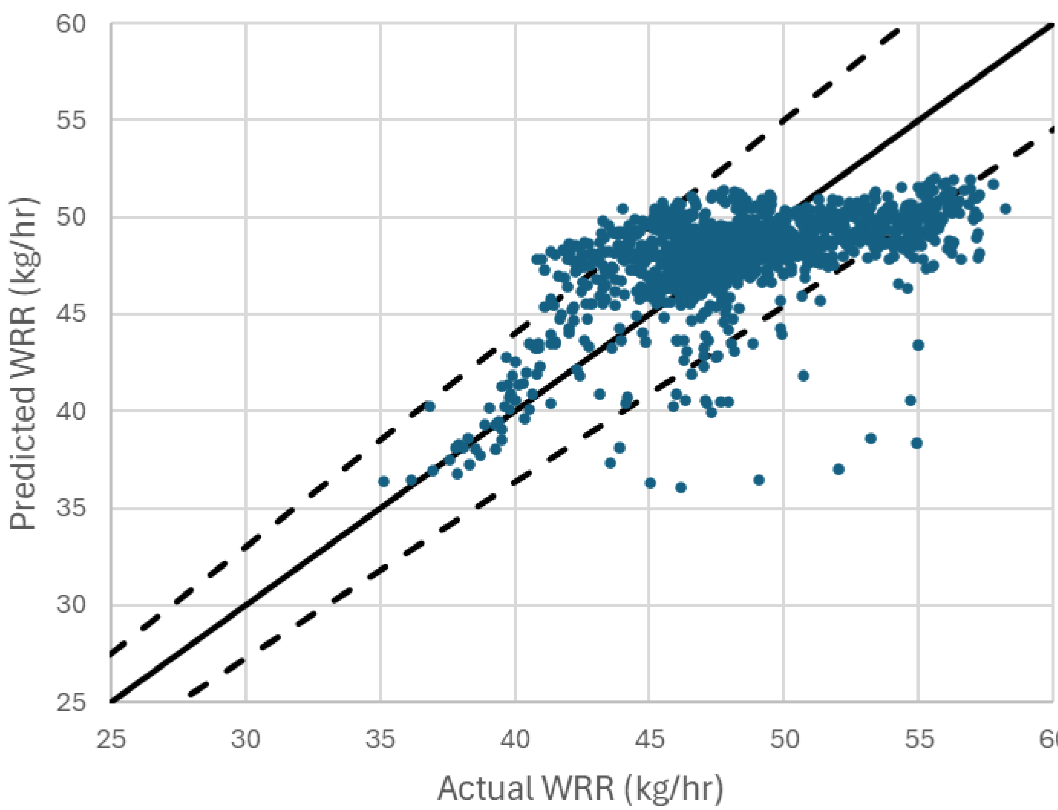

Figure 17: Linear regression of regenerator water rejection rate WRR, using inlet concentration, inlet air absolute humidity, inlet air dry-bulb temperature, and power consumption as regressors.

Modeling the Performance of a Baseline DOAS

The baseline DOAS modeled was a traditional DX-DOAS. DX-DOAS units cool and dehumidify the inlet outdoor air to a desired supply air dew point of 55°F, and a space-neutral dry-bulb temperature between 65 and 70°F. Note that for certain applications, the target supply dew point set point can be lower, such as 50°F. These systems use a DX cooling coil to first cool and dehumidify the incoming outdoor air and then reheat this ventilation air using hot gas from the DX process. The baseline unit was modeled to meet the minimum rated efficiency under Title 24 and ASHRAE 90.1 of 4.0 ISMRE2 for an air-cooled DX-DOAS unit without an energy recovery ventilator (ERV).

In a DX-DOAS application, the entering air conditions and airflow across the evaporator coil are significantly different than for mixed-air cooling applications with conventional air-handling units

(AHUs) or rooftop units (RTUs). Conventional space-cooling systems normally have airflows near 400 CFM per nominal ton of capacity with entering air conditions of 80°F dry-bulb temperature and 67°F wet-bulb temperature, since the outdoor air is tempered with around 70 percent return air. In contrast, DX-DOAS units have airflows below 200 CFM per ton, with entering air conditions equal to the outdoor conditions. In the case of this pilot location, the Fullerton airport 0.4 percent ASHRAE dew point design conditions were 75°F dry-bulb temperature, 70°F wet-bulb temperature, and a 68°F dew point temperature. During the M&V period, the Los Angeles area experienced much hotter and more humid conditions than this ASHRAE design, with dry-bulb temperatures often in the mid-90s and dew points reaching 72°F.

The baseline DX-DOAS model used a generic DX coil model developed by Henderson, Parker, and Huang (Henderson et al. 2000). This model combines empirical performance curves for total cooling capacity and efficiency. It also uses theoretical approaches for apparatus dew point (ADP) and bypass factor (BF) to find the sensible and latent cooling capacity. This semi-empirical model is the basis for the DX coil model used in the eQUEST and EnergyPlus building energy modeling programs. The model accurately predicts performance across a wide range of entering outdoor air conditions, including the outdoor air conditions in the Fullerton airport TMY3 weather file. This baseline DX-DOAS model captures the lower air velocities across the evaporator coil, down to 150 feet per minute.

Figure 18 compares the DX-DOAS model to the performance from the Desert Aire's high-efficiency DX-DOAS unit with an ISMRE2 of 6.0. The model accurately predicts the MRE at the different AHRI standard 920 rating points (A, B, C, D). These Desert Aire performance data are the only published results for each rated condition that could be found. While this DX-DOAS unit achieves higher efficiency than the Title 24 minimum of 4.0, it was useful for validating the DX-DOAS model.

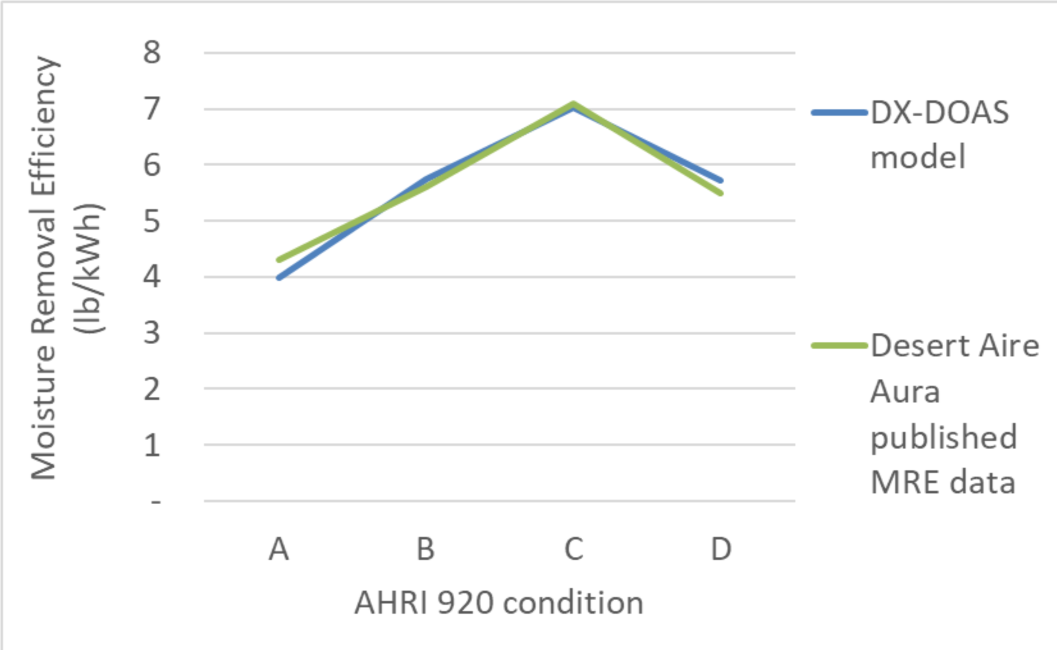

Figure 18: DX-DOAS model compared to published MRE data from Desert Aire.

Table 8 provides the MRE at each of the AHRI Standard 920 conditions for a baseline DX-DOAS meeting the minimum 4.0 ISMRE2 efficiency rating according to Title 24 and ASHRAE 90.1. This is the same model used to benchmark the baseline DX-DOAS unit's annual energy usage for the Fullerton site and other California climates summarized below.

Table 8: Baseline moisture removal rate and efficiency for a DX-DOAS meeting the Title 24 minimum 4.0 ISMRE2.

AHRI Standard 920 Conditions	MRE (lb/kWh)
A	3.0
B	4.3
C	4.5
D	2.7

Table 9 provides the results of the baseline DX-DOAS model that meets an ISMRE2 of 4.0, the minimum requirement according to Title 24 and ASHRAE 90.1. The results are based on the equipment providing 2,500 CFM of outdoor air in California Climate Zone 8 (Fullerton TMY3 weather data) with the supply fan power separated from the compressor and condenser fan components of the refrigeration system. Note that the refrigeration system power is much lower in the winter months compared to the fan power due to the reduced moisture removal required.

Table 9: Baseline DX-DOAS energy usage.

Month	Base: Supply Fan	Base: DX Cooling	Base: Total
1	437	59	496
2	395	51	446
3	437	13	450
4	423	300	723
5	437	2,393	2,830
6	423	4,558	4,981
7	437	9,270	9,707
8	437	10,394	10,831
9	423	6,809	7,232
10	437	3,128	3,565
11	423	285	708
12	437	153	590
Total	**5,143**	**37,414**	**42,557**

Annual Energy Savings Results

For the preliminary annual hourly analysis, the TMY3 weather data for Fullerton Airport in California Climate Zone 8 were used. These data show a high degree of impact from marine-layer fog, with very few hours devoted to a "hot and dry" scenario. A nearby weather station shows many more hours of hot and dry conditions, as do many other locations in California. Accordingly, this model was expanded to include a range of other weather locations to show the impact of hot-and-dry hours on the overall yearly estimates.

A Note on Regenerator Efficiency

The efficiency of the system's desiccant regenerator was observed to be markedly below that measured in previous laboratory testing and other pilot systems. This is one of the primary reasons the project would benefit from additional M&V. Over the course of the annual analysis, the year-round efficiency of the regenerator (WRE) was 7.38 pounds of water removed per kWh of electricity. Laboratory testing, shown in Table 10 below under AHRI 920 conditions, yielded a value of 10.9 lb/kWh. The reasons for this reduction are still unclear but could include inadequate controls for the ambient conditions on site, faulty components, improper initial refrigerant charge, or other factors.

The main analysis in this section focuses on the measured efficiency of 7.38 lb/kWh; however, where appropriate, results from running the model with previously observed efficiencies are also included.

Table 10: Regenerator WRR and WRE when previously tested in an environmental chamber under AHRI 920 conditions.

Conditioner	Moisture Removal (lb/h)	Power (kW)	WRE (lb/kWh)
A	133	11.3	11.7
B	174	15.1	11.5
C	141	13.6	10.4
D	116	11.8	9.8

Annual Analysis Framework

The annual analysis began with an hourly weather data file (TMY3). It was also initialized by setting the mass of the desiccant solute in the tank. For this unit, that equated to a 150-gallon tank that was initially filled to 70 percent capacity with desiccant that had a concentration of 70 percent. Other inputs included the unit's supply air humidity and dry-bulb set point, the unit's supply airflow rate, and the hours of the day considered "peak" hours, when power consumption was preferably avoided.

The first step in the model was to split up the hours of the year into three categories:

1. Hours of the year when dehumidification was required, i.e., ambient dew point is above the dew point set point
2. Hours of the year when dehumidification was *not* required but sensible cooling was, i.e., ambient dew point below the humidity set point but ambient dry-bulb temperature above the temperature set point
3. Hours of the year when both ambient humidity and ambient temperature were below the set points, thus only ventilation was required

DEHUMIDIFICATION HOURS

The first step in modeling the dehumidification hours was to calculate the exhaust air ratio (EAR) needed based on the ambient conditions and the dew point set point. From this resulting EAR estimate, the conditioner's power consumption was calculated via the corresponding formula. Using the EAR estimate, along with ambient humidity, set point humidity, and supply airflow rate, the water absorption rate (WAR, lb/h) into the desiccant via the conditioner was also calculated. This WAR, along with the amount of solute in the tank, was then used to calculate the updated bulk average desiccant concentration within the tank.

When the concentration in the tank dropped below a certain value, the regenerator turned on. The regenerator could also be set to remain off during certain hours, such as the location's "peak" hours. In this case, the regenerator operated during the hours preceding the peak period, to make sure there was enough concentrated desiccant in the tank. This control strategy was implemented successfully in the field and effectively eliminated power consumption during peak hours. When the regenerator was turned on, its power consumption was estimated via the regression presented in the previous section, based on ambient temperature, ambient humidity, and desiccant tank concentration. From this power estimate and ambient conditions, the water rejection rate (WRR) was estimated, and this WRR was factored into the changing concentration of the tank. Eventually, the tank concentration rose above a threshold, and the regenerator turned off. The system's power consumption, including both regenerator power and conditioner power, was compared with that of a DX-DOAS baseline performing similar dehumidification.

COOLING-ONLY HOURS

For cooling-only hours, when the ambient dew point was below the unit's dew point set point, the EAR did not need to be estimated using the regression developed for calculating EAR based on dehumidification performance. Instead, it was estimated based on the supply air dry-bulb temperature regression, which included EAR as an input. The regression was inverted, the supply air dry-bulb temperature was specified at the set point value, and the required EAR was calculated. This EAR was used to estimate fan power for the ES-LD-DOAS unit (regeneration was not required during this mode) and was compared with a DX baseline performing similar sensible cooling.

VENTILATION-ONLY HOURS

For ventilation-only hours, the ES-LD-DOAS power consumption was determined by turning off the exhaust airflow on the unit in the field and observing unit power consumption when there was no exhaust airflow rate. For the 2,500 CFM required of this unit, the power consumption with exhaust airflow turned off was 0.73 kW. This power consumption was compared against a DX -DOAS baseline doing similar ventilation flow rates. It was estimated that a baseline DX-DOAS would use lower fan power as a result of the lower internal resistance compared to the ES-LD-DOAS. The DX-DOAS fan was modeled to use 0.59 kW to supply 2,500 CFM ventilation air.

Annual Analysis Results

For the annual analysis of the ES-LD-DOAS unit using regressions developed from field data, the power consumption during dehumidification hours only is shown in Figure 19.

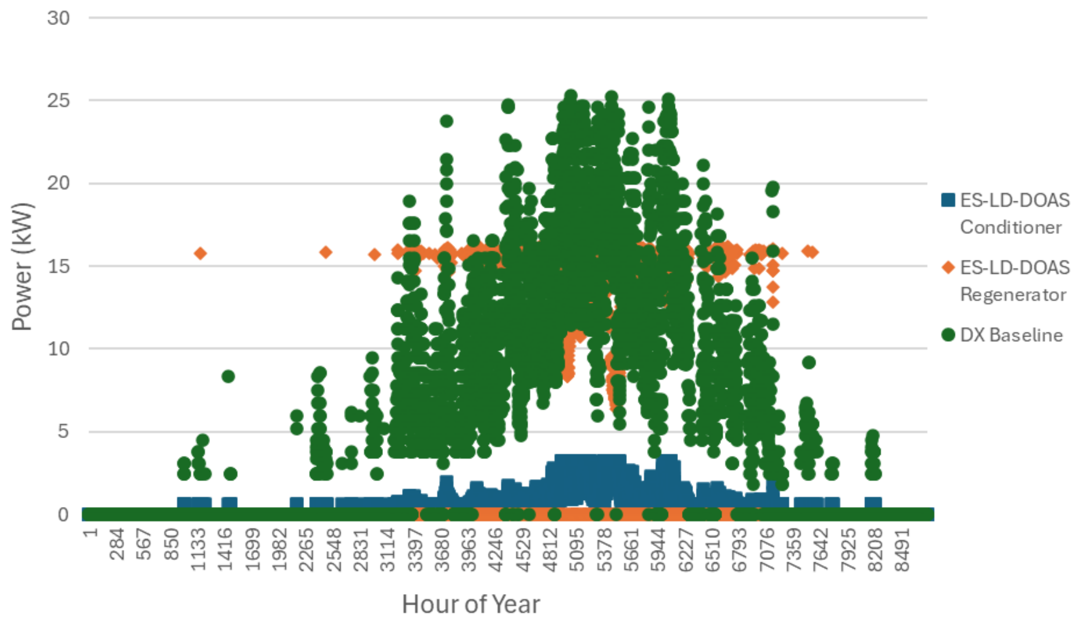

Figure 19: Power consumption estimates for the ES-LD-DOAS conditioner, the ES-LD-DOAS regenerator, and the DX-DOAS baseline during all hours that required dehumidification only.

The field-observed power consumption of the desiccant regenerator topped out at just over 16 kW. However, it should be noted that this power draw is intermittent—turning on when the desiccant was diluted and turning off when it was concentrated or when peak hours demanded it. The conditioner power consumption reached 3.3 kW and was far less intermittent, although Figure 19 still shows hours at 0 kW, because these plots represent dehumidification hours only.

Combining both power consumptions and summing over all dehumidification hours, the system demonstrated a year-round MRE of 4.3 lb/kWh, which aligned well with field data. Note that this value *should* be slightly different than the field data, as the regressions were extended to weather conditions different from those tested during the M&V period. It also differed from an ISMRE2 value, which is a weighted average of four specific test points, as opposed to the actual conditions throughout the year at a specific location, which may differ significantly from the four test points outlined in AHRI 920. When replacing the field-observed regenerator efficiency with lab-observed values, yearly MRE increased to 5.8 lb/kWh.

Figure 20 below shows the power consumption in dehumidification mode during peak hours only. This plot primarily represents just the conditioner power consumption, because the regenerator was forced off during peak hours, an operating mode that was successfully tested on the field unit. Note that the system never consumed more than 3.3 kW during peak hours. The DX-DOAS baseline, on the other hand, rose to above 23.4 kW, representing an over 86 percent reduction in peak power compared to the baseline unit. Overall, the ES-LD-DOAS only consumed 4.7 percent of all energy used for dehumidification during the peak period.

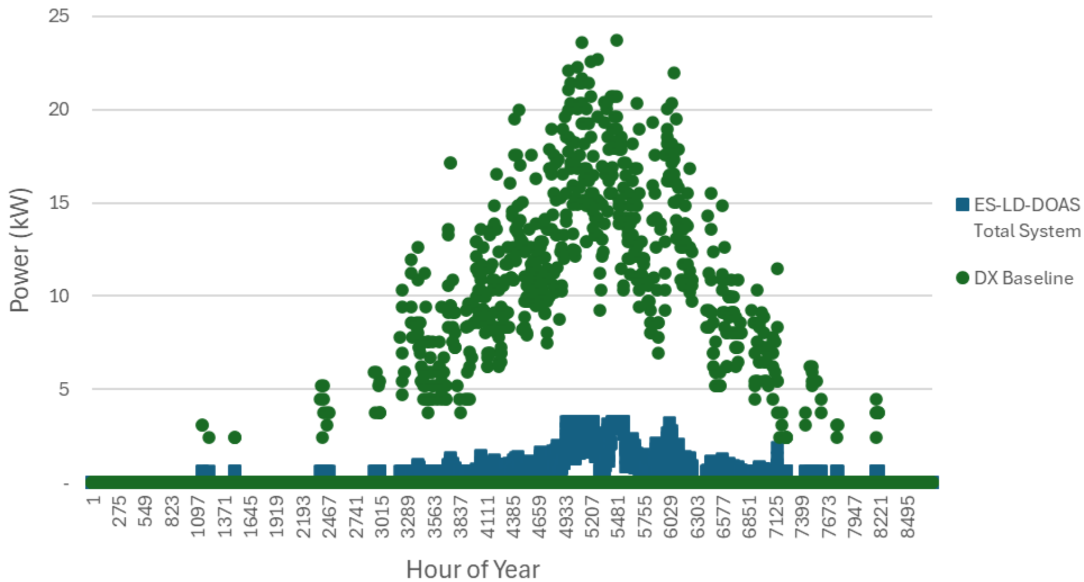

Figure 20: Power consumption estimates for the ES-LD-DOAS and the DX-DOAS baseline during peak hours that required dehumidification only.

In total, the ES-LD-DOAS consumed 18,044 kWh to perform dehumidification, 846 of which occurred during the peak period. In contrast, the DX-DOAS baseline consumed 38,215 kWh for dehumidification, 7,891 of which occurred during the peak period. Thus, during dehumidification-hours, the model indicated that the ES-LD-DOAS reduced energy use by 53 percent compared to the baseline DX-DOAS, with 89 percent less energy used during the peak period. These values are summarized in Table 11.

Table 11: Summary of annual energy consumption for dehumidification hours for the ES-LD-DOAS and the DX-DOAS baseline.

	ES-LD-DOAS	DX-DOAS Baseline	ES-LD-DOAS vs. Baseline
Total energy (kWh)	18,044	38,215	54% Savings
Peak energy (kWh)	846	7,891	89% Savings
% energy during peak	4.7%	20.6%	

For the cooling-only hours, when the outdoor dew point was low enough that dehumidification was not needed, the electric power consumption is shown in Figure 21 for all hours of the day and in Figure 22 during the peak hours from 4 to 9 p.m. Note that these figures are much sparser than

Figure 19 and Figure 20, due to the Fullerton TMY3 weather's small number of hot-and-dry hours. However, this mode could become very significant for other locations, such as the hot, drier climate of Palm Springs or nearby Riverside, which experience lower outdoor dew points since they are set back from the coast.

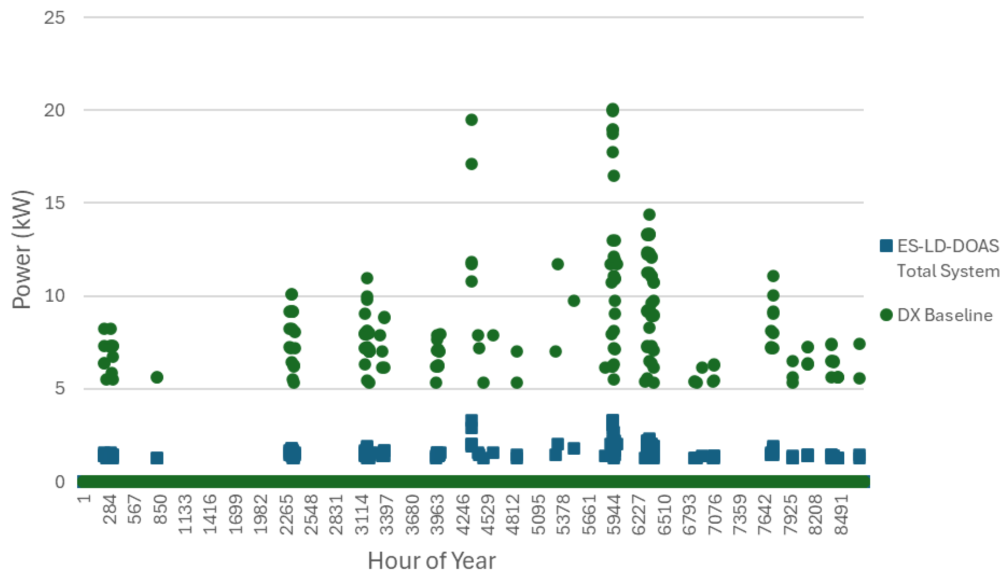

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Figure 21: Annual power consumption estimates for the ES-LD-DOAS and the DX-DOAS baseline during all hours that required cooling only, without dehumidification.

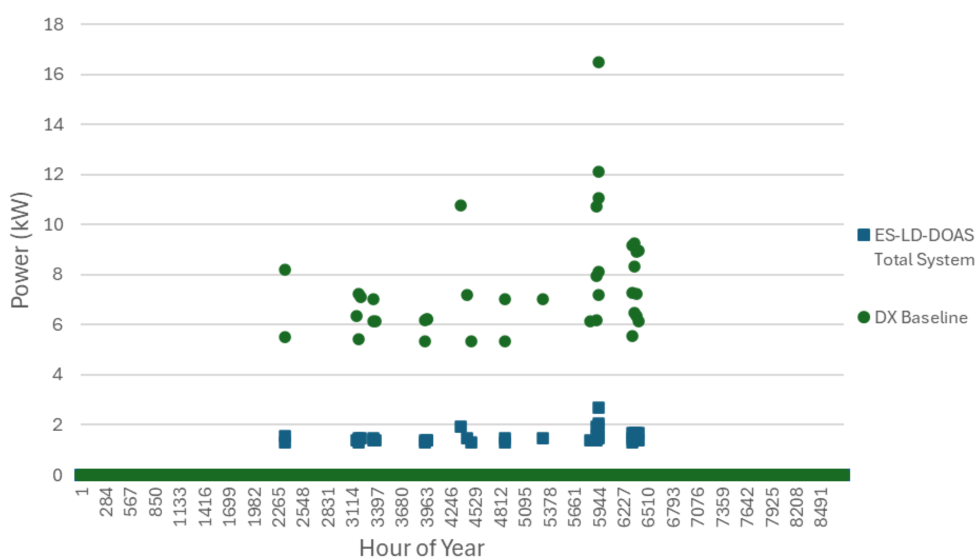

Figure 22: Power consumption estimates for the ES-LD-DOAS and the DX baseline during peak hours that required cooling only, without dehumidification.

In cooling-only mode, the DX-DOAS had a peak power draw of 16.9 kW, while the ES-LD-DOAS unit maxed out at 3.3 kW. During peak hours, the DX-DOAS unit consumed up to 13.5 kW, while the ES-LD-DOAS unit maxed out at 2.7 kW. In terms of annual energy use, the ES-LD-DOAS unit consumed 339 kWh compared to 1,214 kWh for the baseline unit, a reduction of 72 percent. During peak hours, the energy consumed by the ES-LD-DOAS and DX-DOAS units for providing space cooling only represented 18% and 16% of the total energy use for cooling-only for the ES-LD-DOAS and DX-DOAS units respectively. These values are summarized in Table 12.

Table 12: Summary of annual energy consumption for the ES-LD-DOAS and the DX-DOAS baseline during hours that required cooling only, without dehumidification.

	ES-LD-DOAS	DX-DOAS Baseline	ES-LD-DOAS vs. Baseline
Total energy (kWh)	339	1,214	72% Savings
Peak energy (kWh)	60	193	69% Savings
% energy during peak	17.6%	15.9%	

The ventilation-only hours were the one mode of operation that the ES-LD-DOAS did not save energy relative to the modeled DX-DOAS. This is largely due to the conservative estimate for fan power used for the DX-DOAS that assumed a much smaller internal pressure drop across the DX coil compared to the indirect-evaporative cooling coil. The ES-LD-DOAS consumed 0.73 kW when operating at 2,500 CFM in ventilation-only mode which was confirmed in the field monitoring. The DX-DOAS baseline was estimated to consume only 0.59 kW based on a lower internal pressure drop. Over the course of all ventilation-only hours, the ES-LD-DOAS consumed 3,675 kWh compared to 3,128 kWh for the DX-DOAS baseline representing 17% increase in annual fan energy use. During peak hours, the ES-LD-DOAS consumed 769 kWh compared to 641 kWh for the DX-DOAS representing a 20% increase in fan energy during peak for the ES-LD-DOAS.

The last step was to evaluate the impact of the emerging technology considering all modes of operation and energy used in the annual simulation. This analysis was performed for three different California climate zones including Fullerton, CA, (climate zone 8), Sacramento, CA, (climate zone 12), and Palm Springs (climate zone 15). Those results are presented in Table 13, Table 14, and Table 15.

The ES-LD-DOAS was estimated to reduce annual energy use by 48 to 69 percent compared to the DX-DOAS in three California climate zones. The peak energy savings for the ES-LD-DOAS was even more consistent with 81 to 83 percent reduction in energy used during peak hours from 4 to 9 p.m. The results show that the coastal climate in Fullerton, CA, requires the highest energy consumption due to the large number of dehumidification hours with less energy required in the hot-dry climate of Sacramento and Palm Springs. The difference in total energy savings compared to peak energy savings demonstrates the ability for the ES-LD-DOAS unit to offer load flexibility by running systems during off-peak periods. With a reasonable forecast of only a couple hours, the ES-LD-DOAS could be setup to respond to dynamic price signals or demand response events providing benefits to ratepayers and the electric grid operators.

Table 13: Summary of total annual energy consumption for the ES-LD-DOAS and the DX-DOAS baseline for Fullerton, CA (California climate zone 8).

	ES-LD-DOAS	DX-DOAS Baseline	ES-LD-DOAS vs. Baseline
Total energy (kWh)	22,057	42,557	48% Savings
Peak energy (kWh)	1,676	8,725	81% Savings
% energy during peak	7.6%	20.5%	

Table 14: Summary of total annual energy consumption for the ES-LD-DOAS and the DX-DOAS baseline for Sacramento, CA (California climate zone 12).

	ES-LD-DOAS	DX-DOAS Baseline	ES-LD-DOAS vs. Baseline
Total energy (kWh)	9,829	28,250	65% Savings
Peak energy (kWh)	1,605	7,938	80% Savings
% energy during peak	16.3%	28.1%	

Table 15: Summary of total annual energy consumption for the ES-LD-DOAS and the DX-DOAS baseline for Palm Springs, CA (California climate zone 15).

	ES-LD-DOAS	DX-DOAS Baseline	ES-LD-DOAS vs. Baseline
Total energy (kWh)	18,782	60,718	69% Savings
Peak energy (kWh)	2,573	15,038	83% Savings
% energy during peak	13.7%	24.8%	

Stakeholder Feedback

Feedback from diverse stakeholders—including building owners, tenants, architects, electric utilities, regulators, engineering and sustainability community—has been universally positive. Building Owners responded to the electricity bill savings and control of indoor air quality, specifically humidity to reduce the potential for mold growth. Tenants benefit from the potential reduction in common area maintenance expenses and improved indoor air quality. Architects are intrigued by the benefits of future proofing their designs against the trend for global warming and increasing levels of humidity. Specifically, the sensible heat ratio in buildings has generally been declining over recent decades, meaning buildings are handling a greater proportion of latent heat (moisture) relative to sensible heat (temperature). Direct control of humidity is a game changer. So too, the feature of ES-LS-DOAS to maintain and in some cases increase its capacity and efficiency under extreme conditions ensures comfortable and happy clients.

Electric utility benefits are cross-cutting meaning ES-LD-DOAS checks the box for energy efficiency, peak demand reduction, load shifting, dispatchability, resilience against increasing peak humidity and temperatures, as well as the sustainability benefits. Direct contact with regulators was limited, but generally they responded favorably regarding the ability to aggregate and manage summer peak load, ratepayer and utility resiliency benefits, and the positive benefit/cost ratio of 15-year lifecycle savings using the California Avoided Cost Calculator.

The engineering community is intrigued with the novel ability to separately control sensible and latent cooling, energy savings, and the elimination of 2%, 1%, and 0.4% design and equipment oversizing calculations. The sustainability community views the growth in building cooling as a blind spot in energy policy and therefore endorses ES-LS-DOAS including the ability to store renewable energy and shift its use to avoid the dispatch of poor heat factor generation resources that emit relatively high levels of emissions.

Beyond its efficiency benefits, ES-LD-DOAS addresses the critical need for flexible building loads that can integrate as dynamic and predictable grid resources. The technology's innovation has earned significant recognition: a global panel of industry experts recently selected it as a winner of the prestigious 2025 R&D 100 Award. Additional recent endorsements include the DOE's Technology Proving Ground, the Electric Power Research Institute's Incubate Energy, Amazon's Sustainability Accelerator, the Defense Innovation Unit, the Environmental Security Technology Certification Program, and GTI Energy's Utilization Technology Development (UTD), a consortium of natural gas utilities advancing efficient and sustainable natural gas end uses.

The market for DOAS is experiencing significant growth. In 2024, the global market was valued at $4.8 billion and projected to grow at a 9 percent compound annual rate. The factors driving growth include increased awareness of indoor air quality for health, stricter regulations related to energy efficiency and environmental sustainability, and growing demand for technologies that support sustainable building practices. Particularly as climates continue to warm, the amount of moisture in the air presents a growing challenge for today's DX-DOAS equipment, which relies on overcooling to the dew point to dehumidify air, wasting energy and delivering cold air at 100 percent relative humidity into buildings, which is both uncomfortable and wasteful.

Market Readiness

The Market Readiness framework in Figure 23 outlines the stages of developing and scaling a product from initial concept to market stability. ES-LD-DOAS mapping indicates the technology is migrating from Stage 4 to Stage 5.

Figure 23: Market Readiness framework.

Cost-Benefit Competitiveness

Following passage of the "Big Beautiful Bill," ES-LD-DOAS continues to qualify for 48E Clean Electricity Investment Credit (ITC) at least through 2033, when it is subject to a phase out. Typical projects will receive a 30 to 40 percent tax credit, which applies to both the product and the installation. Additionally:

- ES-LD-DOAS can earn electric utility program incentives for its above minimum code energy efficiency attributes.
- ES-LD-DOAS can earn electric utility program incentives for its capacity and/or summer peak-demand saving attributes.
- The customer's electric utility bill can be reduced by an order of magnitude of 30 to 80 percent annual kWh when compared to minimum-code-efficiency DX-DOAS equipment. kWh savings are amplified by the load-shifting energy storage, which absorbs relatively lower-cost off-peak kWh rates and avoids relatively higher-priced on-peak kWh rates.

- The customer's electric utility bill can be reduced by an order of magnitude of 80 to 90 percent in kW summer-peak-demand charges when compared to minimum-code-efficiency DX-DOAS equipment.
- Generally, customers in northern climates use fewer annual kWh; however, these markets tend to be capacity driven, and tariffs are typically higher-cost time-of-use rates with high peak-demand charges. While the absolute amount of kWh is lower, the dollar savings can be significant by avoiding the consumption of on-peak power and associated peak-demand charges. In southern climates, markets tend to be energy driven, and tariffs are generally lower-cost per kWh; however, the annual kWh consumption-based savings are greater. As a result, all markets and climate zones within the United States represent good markets for ES-LD-DOAS.
- Any combination of the ITC, energy savings, energy storage arbitrage, demand charge savings, and utility incentives places ES-LD-DOAS at an equivalent first cost compared with DX-DOAS equipment.

Recommendations

Study findings show that ES-LD-DOAS energy savings, demand reduction, and load-shifting capabilities are substantial (48 – 69 percent energy savings, 81 – 83 percent demand savings) when compared to a baseline DX-DOAS. In the field study, only 8 to 16 percent of the total energy used by the ES-LD-DOAS occurred during the peak hours of 4 to 9 p.m. Significant savings, as a new class of distributed energy resource, could be achieved by adopting ES-LD-DOAS configuration in the energy code as a primary pathway for system comparisons for small- and medium-sized commercial buildings.

The research team presents the following recommendations to help accelerate adoption of DOAS configurations in California.

1. Energy-code-adopting bodies should adopt a standard definition contrasting conventional compressor-based DOAS equipment to ES-LD-DOAS to ensure desired outcomes are achieved. A definition of ES-LD-DOAS would need to encompass a comparison to conventional DOAS equipment for:

    a. Ventilation-only systems that are the primary source of outdoor air filtration and fresh air

    b. Multiple types of ventilation conditioning units, such as ERV, HRV, or DX-DOAS units

2. Energy-code-adopting bodies should define minimum prescriptive criteria for this first-of-its-kind integrated demand side technology, which embodies the benefits of efficiency, demand reduction, and behind-the-meter load-shifting energy storage.

3. To accelerate market adoption of this technology and help California achieve its energy and carbon reduction goals, energy efficiency programs being developed for nonresidential buildings should consider including decoupled ES-LD-DOASs as an eligible measure in incentive programs and assess market transformation strategies to acquire the large savings

opportunity. The research team recommends that utilities consider compensating this technology for the 15-year total avoided cost benefits as a distributed energy resource, including the full impact of energy efficiency, peak-demand reduction, behind-the-meter load-shifting energy storage, and distribution grid resilience.

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