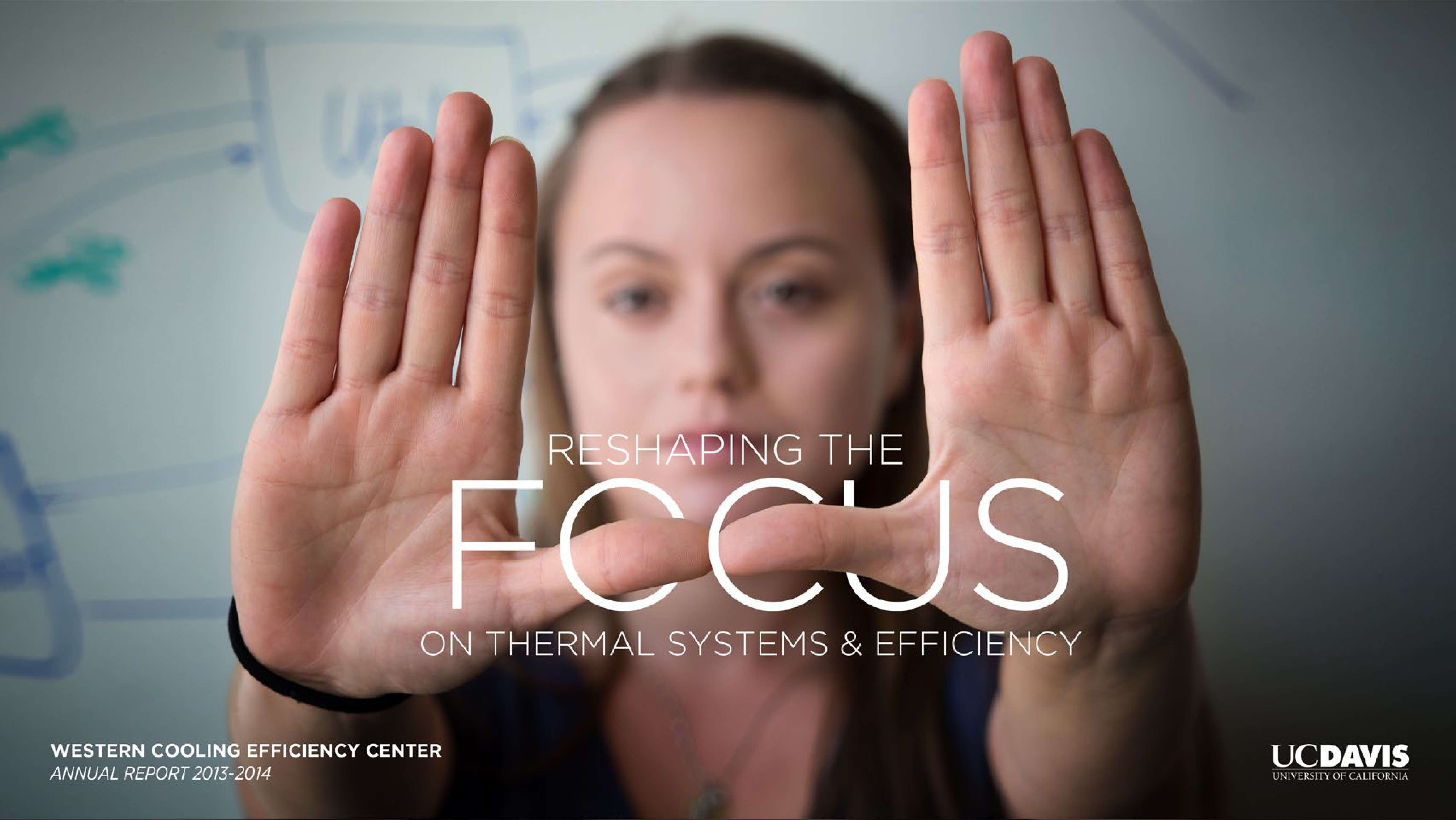


RESHAPING THE FOCUS ON THERMAL SYSTEMS & EFFICIENCY

WESTERN COOLING EFFICIENCY CENTER

ANNUAL REPORT 2013-2014

UC DAVIS
UNIVERSITY OF CALIFORNIA

Mark Modera, Ph.D | Director

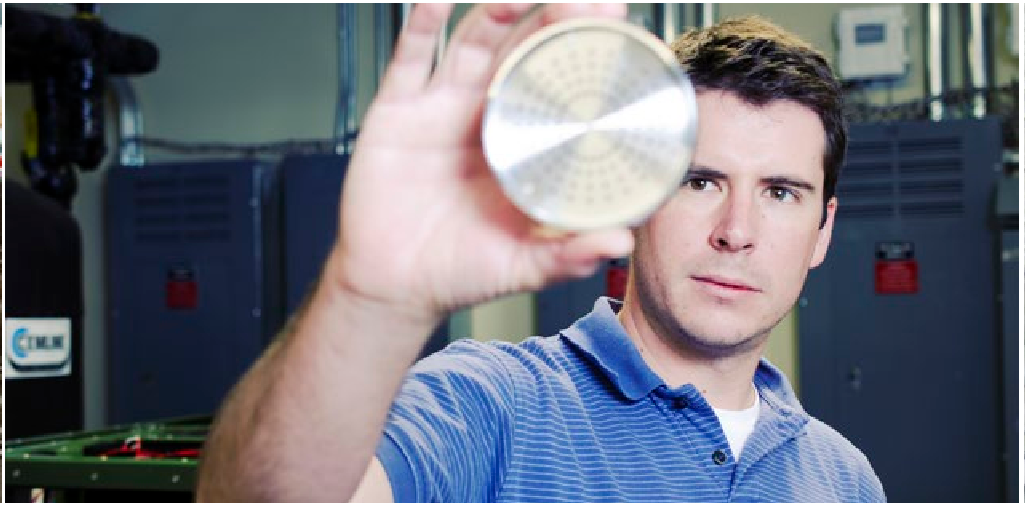
Partners and Friends,

We welcome you to WCEC's 2015 Annual Report. The pages that follow offer highlights of our research for this past year, encompassing innovation, evaluation, and commercialization of new energy efficiency solutions. The Annual Report offers a brief view into our portfolio of projects, including links to the related technical papers, case studies and academic-journal articles that we have recently produced. We are excited to share with you many new discoveries that promise great benefits for California and beyond.

WCEC is reshaping the landscape of opportunity for energy efficient building systems. We are challenging long standing precedents, and exploring solutions that promise dramatic savings. This is an exciting time. Technology is evolving rapidly and we are working closely with our Industry Affiliates to forge a strategic path forward. Together, we are developing objective insight into a broad range of solutions, and are developing new and sometimes unconventional perspectives about the future of thermal energy systems in buildings.

WATER-EFFICIENT COOLING SOLUTIONS CAN STILL MAKE SENSE FOR WESTERN CLIMATES

The Western Cooling Challenge has advanced water-efficient hybrid evaporative technologies that could reduce annual energy use for cooling by 65% in hot dry climates like California. Despite the fact that California is in the midst of the most severe drought in decades, our research suggests that it can make sense to increase on-site water-use to improve efficiency for cooling in commercial buildings. If these cooling solutions were used for every commercial building in California, the cumulative water use would only amount to 3% of what is currently used for urban landscapes, but


the energy savings would reduce annual greenhouse gas emissions by 2.77 MTonCO2e – the equivalent of taking 600,000 cars off the road. At the same time, these strategies could reduce peak electrical demand from cooling by more than 40% - an unprecedented opportunity for an electric grid that is stressed for generation and distribution capacity in the summer months. Beyond the energy savings, our research focuses on improving water-use efficiency for these systems, including dramatically reducing the use of water to maintain evaporative components. We are also exploring opportunities for alternative water sources including rainwater collection and on-site water reuse, and evaluating the logic of evaporative cooling options under the cost and energy implications of desalination.

ZERO NET ENERGY FOR NEW BUILDINGS WILL NOT RESOLVE OUR ENERGY WOES

New buildings only constitute a small fraction of our annual energy use. While improved efficiency for new buildings is important, we cannot underestimate the major need to reduce energy use in existing buildings. Thermal energy systems constitute a special challenge in these facilities because they are relatively expensive, are often intertwined with the existing building architecture, and are often very long lived. WCEC is transforming these challenges into new opportunities. Our research with multi-family buildings integrated a package of measures that can reduce HVAC energy use by more than 65%, and our work in the Multi-Tenant Light Commercial sector has outlined a path to savings of 70% or more. It is also important to recognize that 80% of HVAC manufacturer sales are for existing buildings – technology that is appropriate for existing buildings will drive the availability of high efficiency products for all applications. We are targeting the solutions that will enable success for manufacturers, building owners, and the public interest alike.

Climate appropriate cooling for all RTUs in California: Using only 3% of urban landscape water would save ***4,000 gWh and would remove the greenhouse gas emissions of 600,000 cars.***

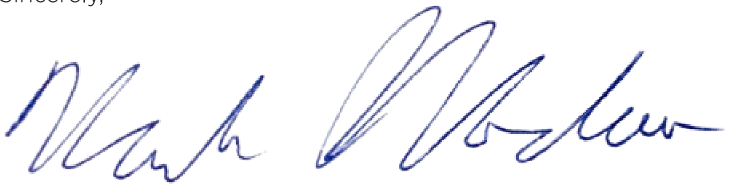
TECHNOLOGY IS ONLY ONE PART OF THE SOLUTION

The way that new technology is applied, and the ways that we use and interact with these systems, can be as important to ultimate energy savings as the technical innovation behind a new efficiency measure. WCEC's research shows that culture and demographics, geographic limitations, and entrenched industry norms can all influence the ways that a new technology is used, or whether or not it is even applied. In collaboration with Tokyo Gas Company, WCEC facilitated a comparative study of two Zero Net Energy communities: the E-Sogo Smart Community Tokyo, Japan, and the West Village in Davis, CA. This work identified opportunities for substantial savings through customized behavioral interventions that encourage the use of passive cooling techniques and other conservation strategies. In another study, we constructed a map of the motivations and interests for a cross-section of market actors that influence the application of retrofit efficiency measures for rooftop air conditioners. This work illuminated the complexity of status quo energy management decisions, and highlights possibilities for strategic interventions that could refocus and reshape the market.

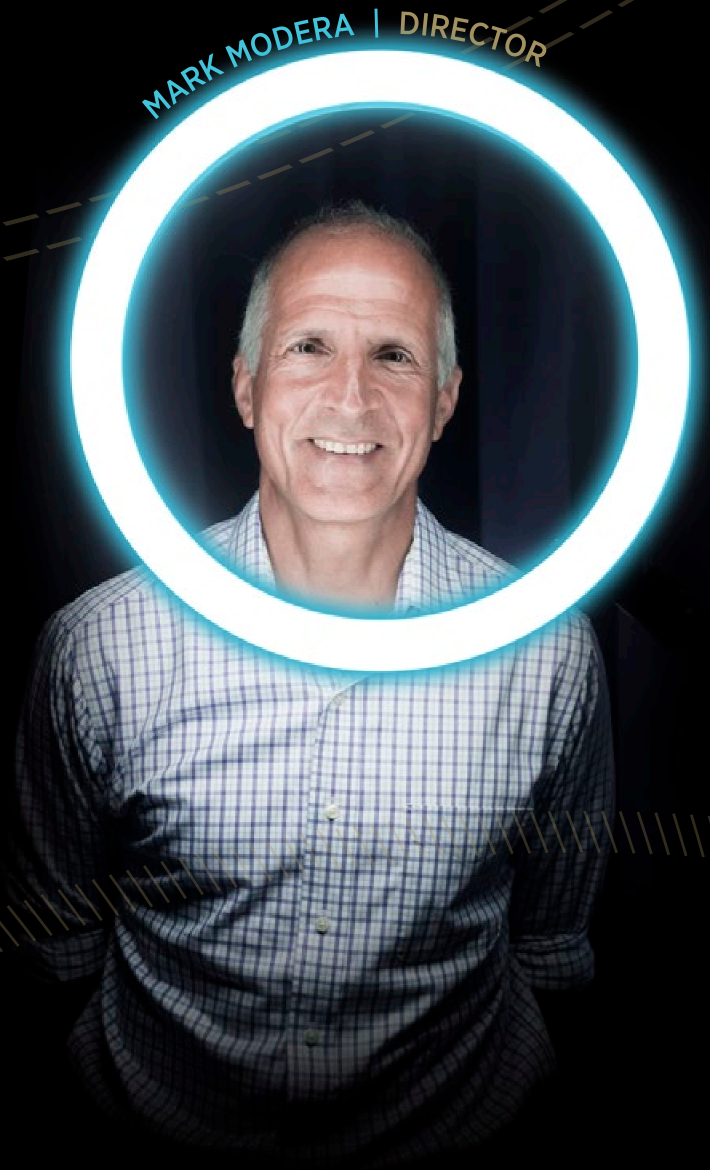
LOOKING TOWARD OUR ENERGY FUTURE

Our research successes and innovations are owed largely to the cooperative interests and combined efforts of our valued network of industry partners, collaborators, and research sponsors. You've helped to make this one of the most productive years in our history, thank you again for your continued support. In light of the growing energy and environmental challenges we face, we know these upcoming years are important. WCEC is proud to be a part of this movement to reshape the focus and direction for our energy efficient future, and we look forward to continued progress with our affiliates and partners.

Sincerely,



MARK MODERA
Director, Western Cooling Efficiency Center
Sempra Energy Chair in Energy Efficiency
Professor, Mechanical Engineering & Civil Engineering
University of California Davis



OUR STAFF

With 12 full-time engineers, 3 Graduate Student Researchers, 18 Undergraduate Student Researchers and a new Behavioral Research Specialist, WCEC's continues its commitment to advance HVAC efficiency across a variety of disciplines.

Mark Modera, the Director of the Center, is the Sempra Energy Chair in Energy Efficiency and a professor in the mechanical Engineering department at UC Davis. Currently, Dr. Modera oversees and guides the progress on over 30 projects at the Center.

Theresa Pistochini is WCEC's lead engineer on Rooftop Unit Retrofits and is responsible for researching and writing the protocol that will create an ASHRAE standard for testing evaporative pre-coolers.

Jonathan Woolley heads the Western Cooling Challenge, a multi-winner competition that encourages HVAC manufacturers to produce rooftop units that are 40% more efficient than standard ones. Jonathan is also responsible for designing the innovative thermal systems in the positive-energy home, the Honda Smart Home.

STAFF: BEHAVIORAL RESEARCH TEAM

WCEC's team of behavioral and social science experts seek to address the human factors influencing HVAC energy efficiency: from the end user, technician, sales & marketing to business and policy decision making. By understanding these factors, we can design better systems, policies and find ways to influence performance-defining behaviors.

Kristin Heinemeier has over 20 years of experience in building operation-phase efficiency issues. Dr. Heinemeier's project successes are diverse and range from writing new Title 24 policy on Fault Detection and Diagnostics, building controls and she is responsible for leading the Behavioral Research Team. Kristin has a Ph.D. in Building Science from UC Berkeley.

Sarah Outcault is a Behavioral Scientist focused on the drivers of technology adoption, use and maintenance, as well as discovering opportunities for market intervention. Before her time at WCEC, Dr. Outcault received her Ph.D. in Behavioral Economics and worked as an Assistant Policy Analyst at the RAND Corporation, and earlier studied Economic History at the London School of Economics.

STAFF: THE ENGINEERS

Caton Mande is one of WCEC's vital field engineers. He is responsible for instrumenting, installing and diagnosing issues with many of WCEC's real world testing on rooftop units across California. Currently, Caton is monitoring and distilling data from the various Western Cooling Challenge installations.

Nelson Dichter's expertise in complex fluid dynamics and modelling thermal systems are crucial to much of our research and his skills are utilized across many projects at the Center. Currently, Nelson is working on creating energy models for the Multi-Tenant Light Commercial project, the Ground Source Heat Pump project, Gas-Driven Heat Pump project, and the Smart Power for the Smart Home Project— Zne home strategies and technologies that reduce negative impacts on the grid.

David Grupp leads the Multi-Tenant Light Commercial Project, the Demonstrations Program, 3 different Residential Ground-Source Heat Pump projects and the Gas-Driven Heat Pump project. David has over 15 years experience incorporating advanced energy technology and efficiency into product R&D and policy.

Curtis Harrington is the lead engineer for the Aerosol Sealing of Building Shells project. For the past 2 years, Curtis has designed, iterated and performed real world and laboratory testing for this promising new technology. His efforts in this project led to significant improvements to the technology, with real world home leakage sealing rates up to 90% in under 2 hours time. Curtis is also responsible for the Multi-Family Ventilation project and has written the final paper detailing code change recommendations for this underserved market.

STAFF: THE ENGINEERS

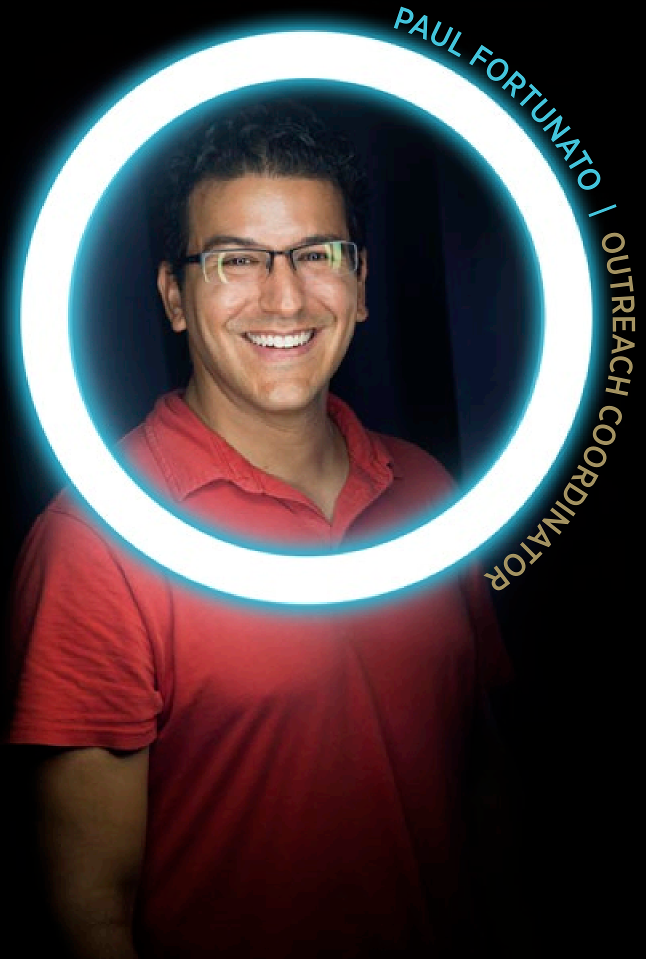
Robert McMurry leads many of the environmental chamber tests in WCEC's state-of-the-art laboratory. Together with Theresa Pistochini, Robert ensures consistent and well thought out tests for the RTU Retrofit project, the Sub-Wet Bulb Evaporative Chiller Project, and a host of other laboratory intensive projects.

Sergio Hernandez is equally comfortable in both our laboratory and out in the field. He is valued both in his ability to construct various experimental apparatus, instrument equipment in the field and even help utilize the Aerosol Sealing for Building Envelopes technology.

Jose Garcia is the lead assistant engineer for the Aerosol Envelope Sealing technology and is responsible for creating required lab testing equipment for building aerosol sealing and a new experiment for testing the aerosol technology as a possible natural gas pipeline sealing solution.

Dan Berman has been involved in a range of projects including the field installations of data acquisition systems, rainwater collection for evaporative cooling, and computer modeling of RTU performance. As an assistant engineer he continues part-time involvement with many of these projects in addition to his main of role of exploring energy saving opportunities for Multi-Tenant Light Commercial buildings.

STAFF: FACULTY & SUPPORT



Jim Rix is the Program Manager, responsible for the day to day management of the Western Cooling Efficiency Center. He also oversees its budget and helps the Director build and sustain relationships with the Center's Affiliates. Jim brings 26 years of experience from the military, where, among other things, he commanded two organizations, ran strategy, plans, resources, and training functions at a joint combatant command, and served two tours in Iraq.

Paul Fortunato is the Outreach Coordinator for the WCEC and brings with him over 8 years of professional graphic design experience. From the website, the newsletter, case studies, outreach demonstrations, webinars, tours and to this Annual Report. Paul works to elevate the image of the Center's mission. Through his design and writing, Paul strives to increase not just the public's awareness of the Center, but also in understanding the research that is vital to the advancement of energy efficiency.

Professor Ralph Aldredge is a strong asset to the Center, with expertise in computational models and algorithms for simulation of reactive-flow dynamics. Dr. Aldridge is leading WCEC's newest Graduate Student Researcher, Kris Karas, on the Phase Change Materials research for hydronic systems project.

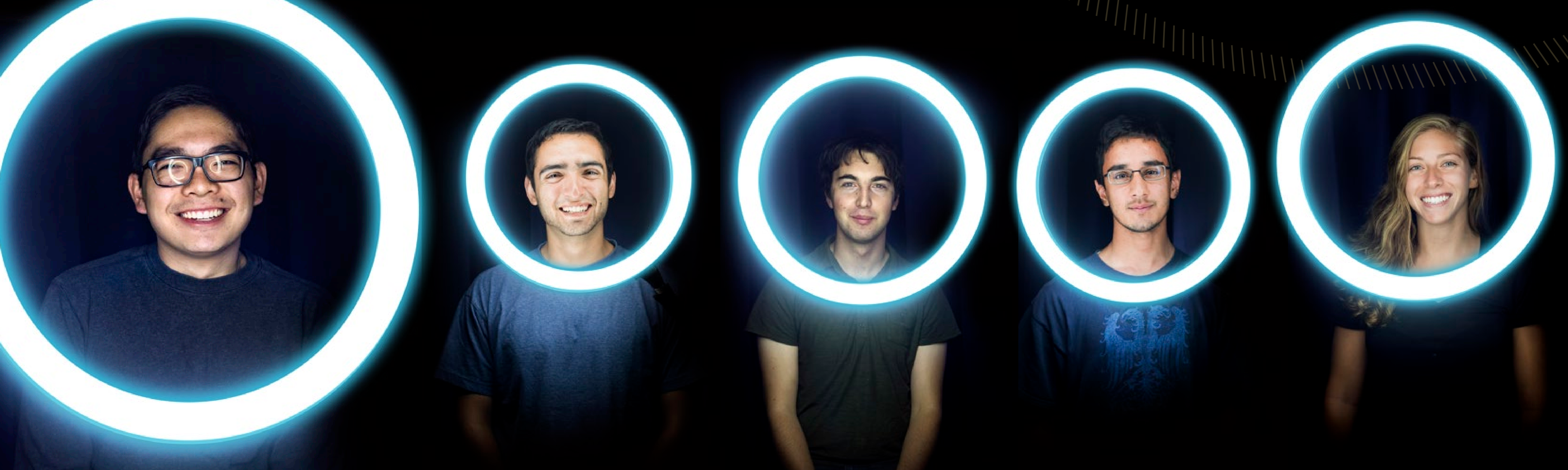
STAFF: GRADUATE STUDENT RESEARCHERS

Nasim Tajmand is a Graduate Student Researcher with an M.S. degree in Architectural Engineering from the University of Tabriz in Iran. She worked with a prestigious architect in Iran named Molavi, where she helped design government buildings. Later she was appointed Directorate for two years at Banakar Ark Company in Tabriz designing houses and landscape architecture. Today, Nasim is researching rainwater reclamation for evaporative systems.

Marco Pritoni received his Masters' Degree in Industrial Engineering from the University of Bologna, Italy. Today, Marco is working on a hardware-agnostic, self-configurable building automation system for small and medium commercial buildings. He is also responsible for a significant number of academic journal publications for smart thermostats, behavior and building controls.

Kristoffer Karas is the graduate student researcher responsible for the Phase-Change Materials (PCMs) for Hydronic Systems project. Working closely with WCEC's faculty advisor Professor Ralph Aldredge, Kris has completed laboratory research on PCMs and is currently installing and testing this technology in a building at UC Davis.

STAFF: STUDENT RESEARCHERS



Jacob Cabrerra
Major: Computer Science
WCEC Project(s): OpenBAS

AFTER GRADUATION
"Work for money, live to eat sushi... and other delicious foods."

Dan Enriquez
Major: Mechanical Engineering

Andrew Baltay
Major: Mechanical Engineering
WCEC Project(s): Ground Source Heat Pumps

Keshevan Kope
Major: Mechanical Engineering
WCEC Project(s): Western Cooling Challenge

Kinsey Meade
Major: Mechanical Engineering
WCEC Project(s): Western Cooling Challenge

AFTER GRADUATION
" I would like to pursue a career in engineering, but I am still learning about the different fields."

STAFF: STUDENT RESEARCHERS

Kaitlyn Thatcher
Major: Civil Engineering
WCEC Project(s): Ground-Source Heat Pumps, MTLC

AFTER GRADUATION
"After I graduate, I hope to use the knowledge I have gained from my classes and working at WCEC to increase energy efficiency and decrease environmental impact of homes."

Zhengmao (Jack) Liu
Major: Mechanical Engineering
WCEC Project(s): Ground-Source Heat Pumps

Julie Wurzbach
Major: Mechanical Engineering
WCEC Project(s): Aerosol Sealing

AFTER GRADUATION
"I would like to be a failure analyst. I enjoy figuring out why something is not working properly or why a component may fail."

Arshia Firouzi
Major: Electrical Engineering
WCEC Project(s): Ground Source Heat Pumps

AFTER GRADUATION
"Long term my goal is to one day work for NASA, a dream I have had since I was very little."

Cyrus Ghandi
Major: Mechanical Engineering
WCEC Project(s): RTU Retrofits

TABLE OF CONTENTS

AEROSOL-SEALING OF BUILDING SHELLS

Automating the process of sealing leaks in buildings

Building shells are notorious for leaking, causing unintended air flows between conditioned and unconditioned spaces, which results in additional heating and cooling loads that the HVAC equipment must remove. A significant effort has been made to reduce the leaks in building shells through current construction practices, but the problem remains one of high labor costs, constant vigilance and quality control. The WCEC has received funding from Build America and the California Energy Commission to investigate building shell sealing in both retrofit and new build applications. The objective of this research is to develop and demonstrate a remote sealing process that uses aerosolized sealant to simultaneously measure, find and seal leaks in a building. The process involves pressurizing a space with a fog of sealant particles that will travel to building leaks, and as they escape, seal them.

Last year there has been significant progress on the development of the aerosol envelope sealing technology advancing it down the path toward commercialization. The WCEC performed five new demonstrations including the Honda Smart Home in Davis, CA, and four apartments in Queens, NY. There was also an effort to characterize the aerosol produced by nozzles as a function of the compressed air pressure and sealant injection rate by measuring the particle size distribution produced under different operating conditions.

WCEC ENGINEER CURTIS HARRINGTON CALIBRATING AEROSOL NOZZLES IN THE HONDA SMART HOME AT WEST VILLAGE, UC DAVIS.

ENVELOPE SEALING OF HONDA SMART HOME IN DAVIS, CA

The Honda Smart Home is a net-zero energy home built to showcase some of the most advanced strategies to reduce the carbon footprint of U.S. homes. The Western Cooling Efficiency Center at UC Davis worked with Honda Motor Company to design the mechanical systems for the home, as well as demonstrate the aerosol envelope sealing process to reduce building shell leakage for better ventilation control and lower infiltration loads for the building.

A recent demonstration of the aerosol envelope sealing process on the Honda Smart Home, a two-story single-family home, showed a reduction in building air leakage from 5.5ACH50 to 1.0ACH50. To put this in perspective, the ICEEE minimum requirement is 3ACH50. Photographs from this installation, including examples of seals formed, are shown on this page. This building was initially sealed using standard methods and the photos clearly show where the aerosol found leaks that were not sealed properly using foam and caulk. The ultimate goal was to meet the very aggressive Passive House standard of 0.6ACH50, which also requires that the air barrier be applied to the external envelope of the building.

The contractor was asked to use their standard methods to seal leaks larger than 0.25” in the smallest dimension since the time required to seal a leak has been shown to increase with the square of the size of the leak in the smallest dimension (e.g. it takes four-times longer to seal a leak that is 0.5” than to seal a leak that is 0.25”).

Figure 1-1 summarizes the result of the demonstration showing three discrete phases in the sealing process. The first sealing demonstration used an airless nozzle injection system with five injection points using no temperature or humidity control which reduced the building leakage from 5.5ACH50 to 3.3ACH50. After the first demonstration, three contractors spent 24 man-hours attempting to further seal the building manually with expanding foam and caulk, resulting in an almost negligible impact on the overall tightness of the building shell. Finally, we applied the aerosol envelope sealing process again, this time with air-atomization nozzles and controlled temperature and humidity during the process, and were able to further reduce the building leakage from 3.2ACH50 to 1.0ACH50.

This demonstration provided a superb comparison of the performance between the airless and the air-atomization nozzles, as well as the impact of temperature and humidity control. We found that while the airless atomization nozzles create a uniform particle size distribution, the air-atomization nozzles project the aerosol with more initial momentum, allowing the aerosol to fill the building space better and promote evaporation of water surrounding the sealant. Some evaporation of water contained in the sealant mixture is critical to allow the particles to adhere to leak sites.

The two aerosol sealing tests also differed in that the first test using the airless system had five injector nozzles in the house while the air-atomization test only used one injector nozzle (the system was only capable of one injection

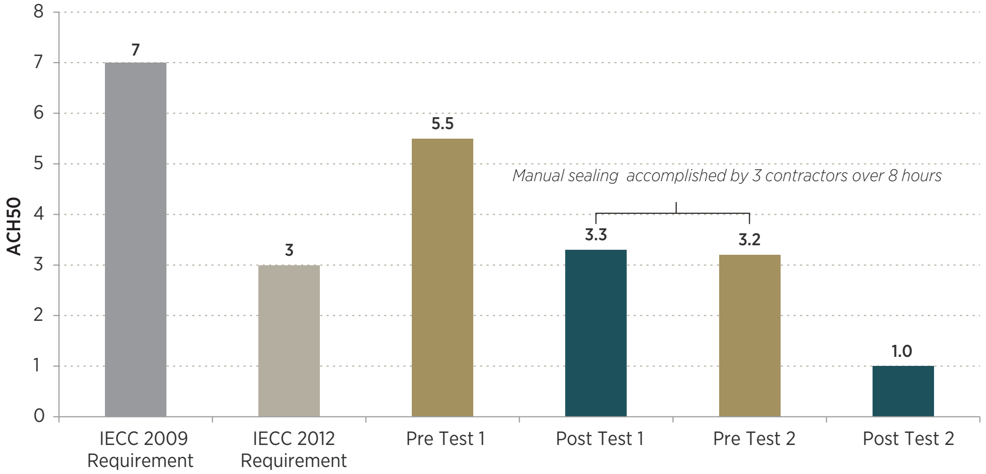
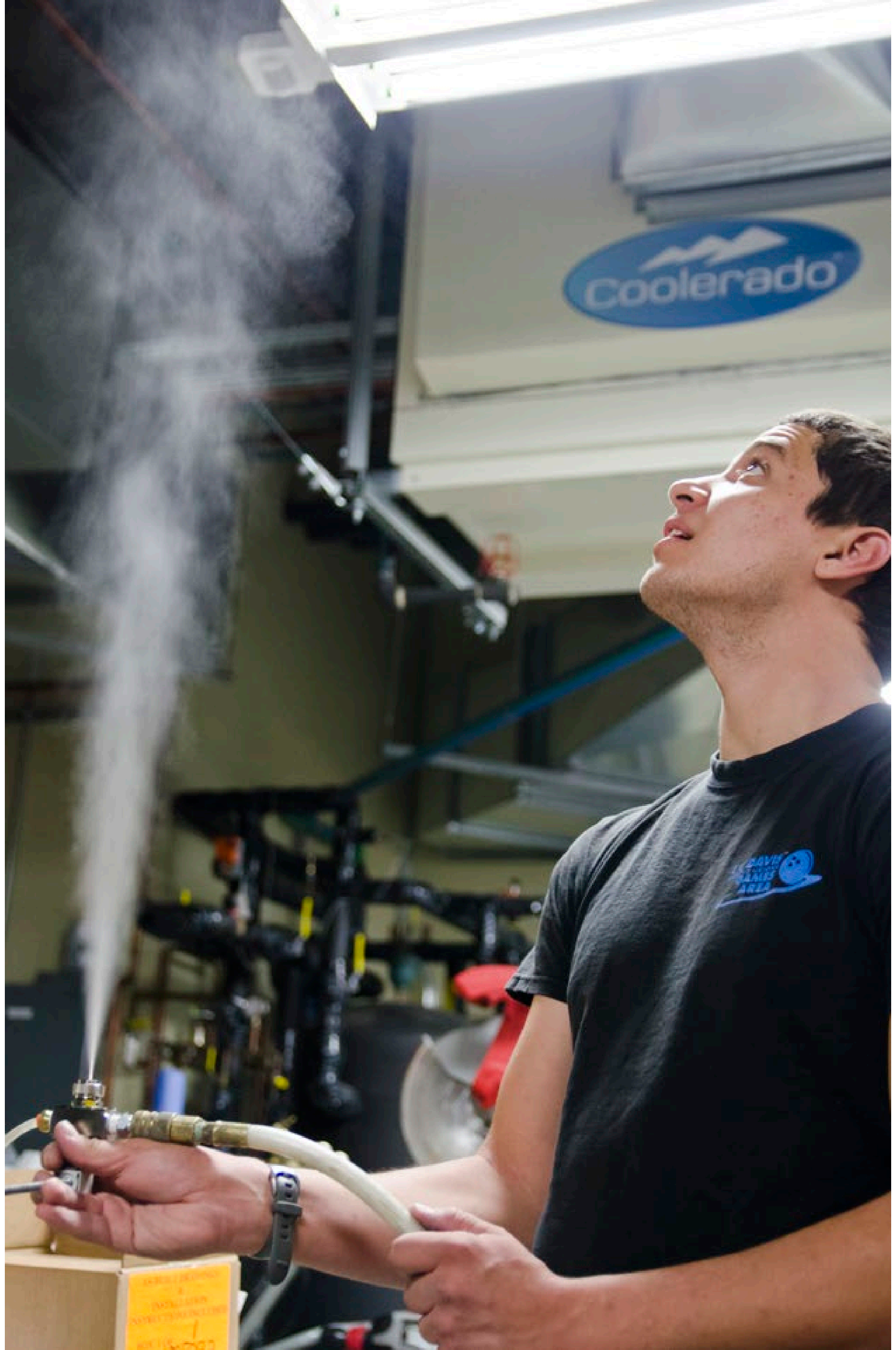


Figure 1-1: Summary of results from aerosol envelope sealing demonstration in Honda Smart Home.

site). The airless system used about five-times as much sealant to seal a similar amount of leakage, showing lower sealing performance than the air-atomization system.

In summary, this demonstration revealed the advantage of using the aerosol envelope sealing process over standard manual sealing methods. The results demonstrated that relying on manual sealing to accomplish the level of air-tightness desired would have required a substantial amount of time and labor. We also found that an air-atomization nozzle system is more promising than one that utilizes airless nozzles. We found in subsequent demonstrations that the performance of the air-atomization system significantly improves as we expand to multiple injection points since the single injector nozzle in this test had to be moved around the building.



AEROSOL ENVELOPE SEALING DEMONSTRATIONS

The latest version of the technology is capable of multiple air-atomization nozzles to generate the aerosol "fog" and has achieved sealing rates more than ten-times those of applications with previous versions of the equipment as shown in Figure 1-2, which includes the latest field testing done in 4 apartments in New York.

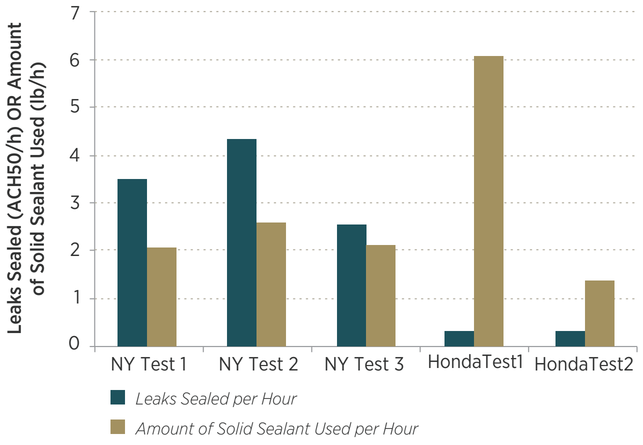


Figure 1-2: Sealing rates and solid sealant injection rate for latest demonstrations

ENVELOPE SEALING OF SEVERAL APARTMENTS IN QUEENS, NY

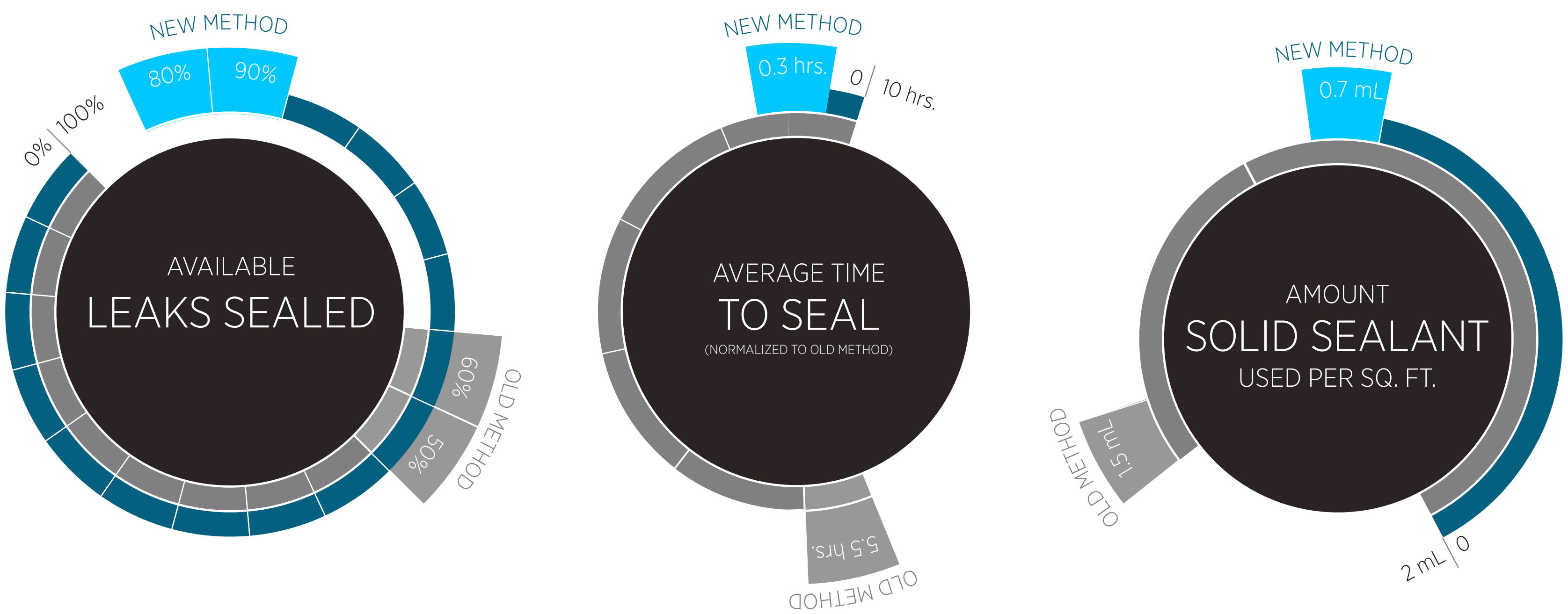


Figure 1-3: Sealing Results from New York utilizing new nozzle and injector system

The latest aerosol system technology demonstrated sealing of at least 80% of the air leaks in less than two hours at a New York apartment.

Following the successful application of the aerosol envelope sealing process on the Honda Smart Home, tests of a new air-atomization injection system capable of multiple injection points was conducted through funding from both the California Energy Commission and the Department of Energy's Building America program. The first application using the new injection system was performed on several apartments in Queens, NY. The pictures above show one apartment before sealing and example seals formed around electrical box, and what the contractor sees during the process to track the sealing performance on a laptop.

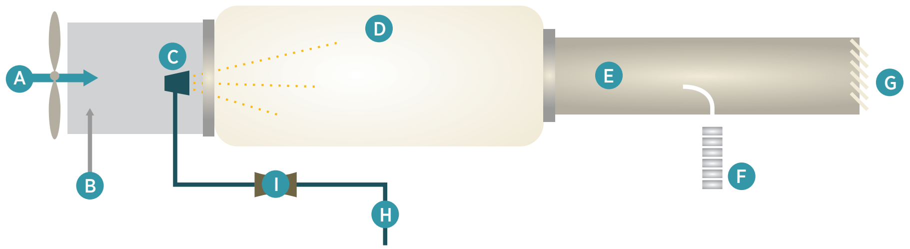
Figure 1-3 shows the sealing performance from all four sealing demonstration on the apartments in Queens, NY. Figure 1-3 shows that the process was capable of sealing at least 80% of the air leaks in less than two hours. The plateau in sealing rate occurs when all smaller leaks have been sealed (<0.5" in the smallest dimension) and only large leaks that cannot be sealed by the aerosol process remain. Depending on the initial bulk-sealing level of the building this plateau will occur at different points.

PARTICLE SIZE TESTING

Several cascade impactor tests were completed this year to measure particle size distribution from injection nozzles under different operating conditions. These tests will allow the WCEC to characterize the aerosol produced for envelope sealing applications improving our understanding of how to control the process, as well as provide information for future modelling efforts for simulating particle transport in buildings. A cascade impactor uses a series of stages with circular jets machined into them. As an aerosol passes through the jets, larger particles escape the streamline causing them to impact a collection plate mounted below the jet; smaller particles continue on through the cascade impactor to the subsequent stages that are designed to capture progressively smaller particles. The size of the jets, number of jets, and the airflow rate through the impactor are what determine the size particles that are captured. This device is typically used to measure flue gas constituents, ambient air particle concentrations, and spray characteristics for medical delivery devices.

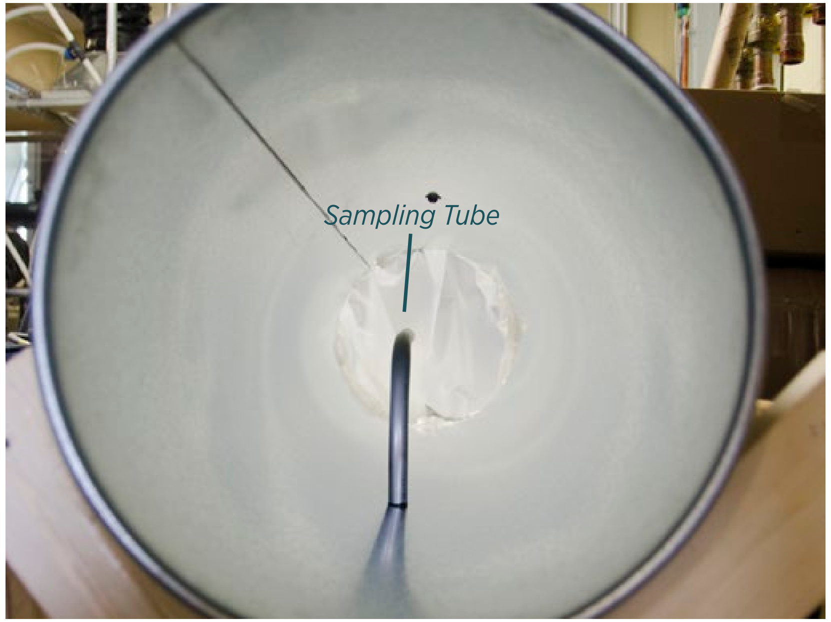
The laboratory tests were set up to measure the particle size distribution of an aerosol as it travels through a duct. Since the sealant used for the aerosol envelope sealing process is diluted with water, particles are expected to change in size as they travel down the duct. For the initial tests, we sampled the aerosol approximately four meters from the point of injection. Figure 1-4 shows a schematic of the laboratory apparatus used for the cascade impactor testing.

A calibrated fan is used to control the airflow rate through the duct in order to match the velocity in the duct with the velocity of the air that enters the sampling tube for the cascade impactor. The temperature and humidity of the air entering the duct system is measured before going through



A. *Flow, ambient air*
B. *T, RH ambient air*
C. *Spray nozzle*
D. *Layflat Duct*
E. *14" Rigid Duct*
F. *Cascade Impactor*
G. *Damper for pressure control*
H. *P, T compressed air*
I. *Flow, compressed air*

Figure 1-4: Schematic of laboratory apparatus used for the cascade impactor tests.



the fan and the pressure of the duct is controlled. The flow rate of compressed air used for atomization is measured using a venturi mass flow meter, and the sealant injection rate is controlled with a peristaltic metering pump. Some photos of the experiment including the duct (cascade impactor sits up-right below the duct) and the sampling tube pointed into the flow are on the right.A number of cascade impactor tests have been completed at various nozzle operating conditions. Pictures of the impaction plates show the deposition pattern of the various stages.

The particle size distribution of an air-atomization nozzle is expected to rely on the ratio of the mass flow rate of liquid to the mass flow rate of compressed air. As this mass flow ratio increases the particle size distribution is expected to increase. Figure 1-5 shows the mass median diameter calculated based on the results of several cascade impactor tests.

The mass median diameters in Figure 1-5 follow the expected trend indicating larger particle size distributions produced as the mass flow ratio of sealant to compressed air increases. Having a method established for characterizing an aerosol allows alternative sealants and nozzles to be tested and compared systematically, as well as better input assumptions for modeling aerosol transport in buildings.

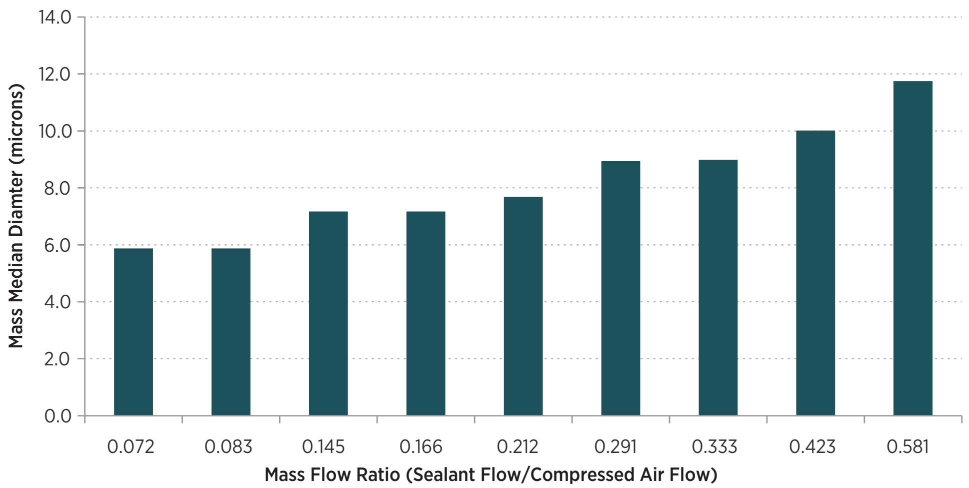
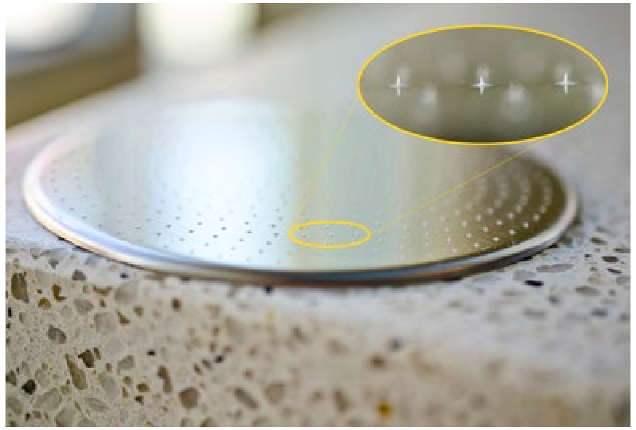


Figure 1-5: Mass median diameter calculated from cascade impactor results at different operating conditions

PATH FORWARD

The next quarter will focus on both laboratory and field testing with an emphasis on making this technology commercial ready. First, we will test the use of controlling humidity on the evaporation rate for the sealant. This test will determine if, in much larger structures, adding humidity may allow the sealant to remain tackier longer as it travels to find a leak. In order to accelerate the commercialization of this technology, WCEC will begin training other researchers in Minnesota on how to use this system. This training will be a valuable learning process for understand the learning curve of this technology in the hands of someone that has never used it before. Also happening this quarter, WCEC will be sealing a large single family home (over 2,000 square feet) in Fresno, CA. The emphasis for this field test will be speed of overall installation. With that in mind, WCEC will be using 8 nozzles simultaneously and will not be entering the home during the process to move the nozzles. The overall goal of this test is to get a better understanding of the real time it will take for contractors to install this technology which will help determine the real-world system economics and feasibility.



NASIM TAJMAND RECEIVED THE 2014 ASCE-SACRAMENTO "IMPROVEMENT ENERGY PROJECT" AWARD FOR HER WORK IN RAINWATER RECLAMATION

RAINWATER STORAGE FOR EVAPORATIVELY COOLED AIR CONDITIONING SYSTEMS

The cities of California's Central Valley have a climate that is typically very wet in the winter and very dry in the summer. Capturing and storing the abundant winter rainfall for summer use helps to sustain our regional water system. One goal of this project is to outline rainwater harvesting from the perspective of sustainability and public acceptability, placing it within a social science context. Another goal is to understand the value of harvesting rainwater for non-potable use in a residential evaporative cooling application. The following benefits of this application are explored: (**1**) potable water conservation; (**2**) scale prevention in heat exchange units; (**3**) surface water quality protection; and (**4**) reduced risk of flooding.

Previous research successfully show the viability in both sufficient quantity and quality of rainwater for use in evaporative systems. The water demand for a season of evaporative cooling was met from a few rain events, and the water meets EPA guidelines for use in evaporative systems even after being stored for months. The next phase of research will determine the effects that rainwater may have on a copper condenser coil. In order to investigate both tap water and rainwater effects in cooling systems, a laboratory test with a small-scale, copper coil evaporative condensing unit was used. Various water sources for use in a residential evaporative condenser, representing tap water characteristics typical to California, were tested. The potential sources included groundwater-derived municipal water, surface-water-derived municipal water, and harvested rainwater. The project evaluated the interplay between water quality, evaporative-condenser fouling and performance, and water burden for each water source.

CALIFORNIA WATER QUALITY ANALYSIS BY WATER DISTRICT AND CLIMATE ZONE

Water quality information for the State of California was obtained from California Department of Public Health, and contained measurements of pH, conductance, total hardness, calcium and magnesium, hydroxide alkalinity and carbonate alkalinity for each water district in the state.

The data set was reduced to remove outliers and filtered to contain only districts that serve 30,000 people or more and had 30 or more observations for each of water quality parameter. The data was used to calculate summary statistics for water quality variables for each water district. Then, the water districts were categorized by **1)** drinking water source of either groundwater or surface water from a source assessment map and **2)** climate zone location in California .

Figure 2-1 represents the range of calcium and magnesium in California's water, discriminated by climate zone, for both groundwater and surface water sources. Water sources are categorized based on their mineral content as very hard water and moderately hard water areas in this research study. Hardness is often defined as the sum of polyvalent cations (e.g., Mg++, Ca++) and is expressed in units of CaCO3. More than 150 mg/L as CaCO3 was categorized as very hard water and less than 150 mg/L as CaCO3 was categorized as moderately hard water.

Using the water quality data analysis produced in this research study, the water quality characteristics for California municipal tap waters were replicated to create artificial water for the experiment.

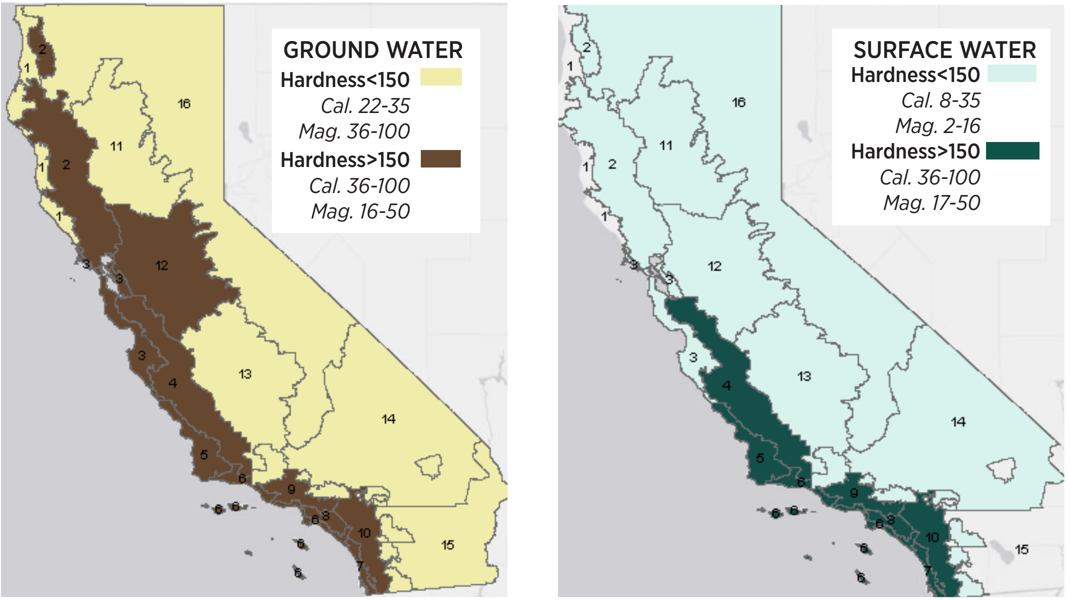


Figure 2-1: The range concentration of total calcium (mg/L) and magnesium (mg/L) in California's tap water discriminated by climate zone with hardness (mg/L as CaCO3) higher and lower than 150.

Nasim Tajmand inspects the small scale testing apparatus

SYSTEMATIC TESTING OF INFLUENTIAL WATER QUALITY PARAMETERS

The effects of various water quality parameters were assessed to determine their influence on scale formation. Water quality parameters assessed include two water quality scenarios to represent the breadth of water quality conditions in CA, being sure to adequately capture the range of water conditions in California's drinking water supply. In this experiment, four setups were examined in parallel with low (about 7%) bleed rate systems with two different tap water qualities. Bleeding of a system is defined as the rejection of a portion of the cooling water in the system either continuously or at regular intervals during operation. The volume removed was replaced with the tap water source.

The small scale apparatus was designed to run up to four tests simultaneously to reduce the variability in test conditions. The strategy applied was to compare low hardness and high hardness water source systems in a small scale of aqua chill and also to have an understanding of the effect and the presence of previously precipitated solids in the system, by using a newly made copper coil and an old copper coil (previously coated with solids from the previous experiment). The four parallel small scale units were run for 15 days.

Evaporation of water increases the concentration of minerals and if the process is carried in a sufficient time the sump is supersaturated. Vaporization of water over the copper coil leads to direct deposition on the surface of the coil. Figure 2-2 shows the summary results of solution mineral analysis for the experiment. The amount of precipitation for each test was calculated based on the measured influent and effluent concentrations.

Calcium was observed to be largely precipitated (about 90% precipitation) in the first and third test (Low Hardness) and the sump concentrations of calcium were actually lower than that of influent. The calcium concentration in sump was 0.03 mM for new coil test and 0.12 mM for the old coil test.

Calcium precipitated in the second and fourth test (High Hardness) about 25% for the new coil and 22% for the old coil.

Magnesium scale (probably magnesium carbonate) formed in all cases. Magnesium was observed to be precipitated (about 9% precipitation) in the first and third tests (Low Hardness). Magnesium concentration in sump was 0.02 mM for new coil test and 0.03 mM for the old coil test. Magnesium precipitated in the second and fourth test (High Hardness) systems about 3% for the new coil and 12% for the old coil. In the high hardness systems, magnesium contributed higher to mineral scale formation compared to the low hardness systems. The amount of precipitation was increased with the old coil system (400% increase). indicating that previously precipitated solids on the coil can lead to excessive precipitation and therefore reduces solution concentration especially when the influent concentration is high such as the fourth test. In the other words, the presence of nucleation sites on the copper coil may encourage the formation of scale on the surface. This effect was lower (45% increase) when the effluent had a low concentration as was observed in low hardness systems such as the first and third test.

FIGURE 2-2: SUMMARY OF AQUEOUS CHEMISTRY RESULTS

System	Bleed (%)	pH	Calcium				Magnesium			
			Feed (mM)	Sump (mM)	Deposition		Feed (mM)	Sump (mM)	Deposition	
					mols	%			mols	%
New Coil, Low Hardness Water	7	7.6	0.37	0.03	0.36	91	0.18	0.02	0.03	9
New Coil, High Hardness Water	7	7.6	2.1	18.17	0.57	25	1.54	0.05	0.33	3
Old Coil, Low Hardness Water	6	7.6	0.37	0.12	0.36	91	0.18	0.03	0.04	13
Old Coil, High Hardness Water	7	7.6	2.10	15.22	0.50	22	1.54	0.20	0.70	12

mM: average steady state sump concentration in milimolars

FUTURE RESEARCH: CREATING STANDARDS TO OPTIMIZE WATER USE

Recent work at the WCEC indicated that the two principal elements contributing to water hardness – calcium (Ca) and magnesium (Mg) – behave very differently in an evaporative condenser in the low bleed rate scenario. In this investigation, the effects of the examined water quality parameters will be assessed to determine their influence on scale formation in the high bleed scenario (25%). An analytical model will be developed to determine optimized bleed rates based on the defined tap water quality. The results of this study will be used to develop bleed recommendations for evaporative condensing equipment operating in in different climate zone in California, with the objective of optimizing water use while minimizing scale formation

New and old coils used for testing

INNOVATIVE GROUND SOURCE HEAT PUMP STRATEGIES

Traditional geo-thermal techniques require expensive drilling rigs that can bore vertically 200 feet into the earth. Large Diameter Earth Bore (LDEB) and Directional Bore installations aim to reduce these costs by reducing the drilling depth while maintaining an adequate amount of heat exchange with the earth. The LDEB's innovative system utilizes a 24" diameter 20' deep helical coil constructed of 1/2" diameter HDPE tubing placed into the bore hole and backfilled with dirt from the drilling, sand, rock, or other fill. Drilling for these shallow bore heat exchangers is quick, and far less expensive than conventional techniques. Typically each bore may take less than an hour to drill, allowing around 8 to be completed in a typical work day. A day of work may yield around 150 linear feet of heat exchange depth, however on a per foot basis the LDEB exchanger has more capacity due to the effective increase in surface area. The Directional Bore system drills many shallow lanes across a plot of land creating a large amount of heat exchange surface area in a short amount of time and at a reduced cost to more conventional GSHP.

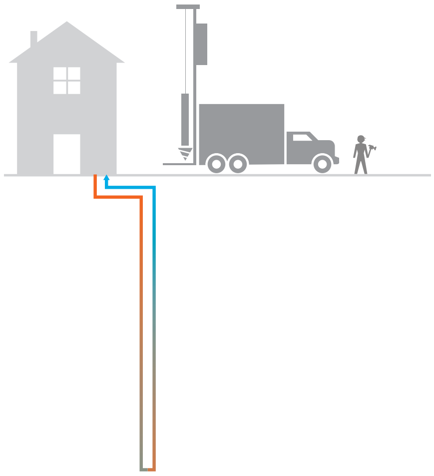
In collaboration with the CEC and our Utility partners, WCEC is able to expand the scope of this project to include an even greater number of field tests. Ultimately, this research will lead to a more comprehensive understanding of the benefits and shortfalls of a more diverse set of GSHP strategies.

WCEC STUDENT RESEARCHER, KAITLYN THATCHER ADJUSTS THE GEO-THERMAL HELIXES AT THE CAPAY HOUSE INSTALLATION.

GROUND SOURCE HEAT PUMP TECHNOLOGIES

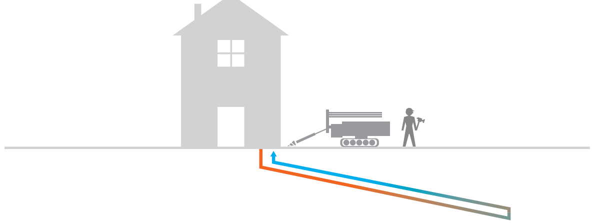
CONVENTIONAL VERTICAL BORE EARTH EXCHANGER

- 150+ foot drill hole
- Large, expensive drilling rig



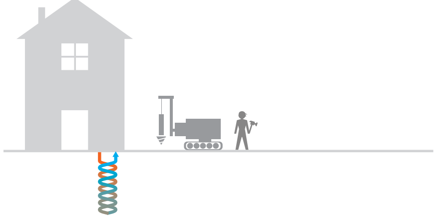
DIRECTIONAL BORE EARTH EXCHANGER

- 20 foot deep borehole, 150-feet across
- Compact, less expensive, drill rig
- Simultaneous drilling and pipe installation



LARGE DIAMETER BORE EARTH EXCHANGER

- 20 foot deep borehole
- Compact, less expensive, remote-controlled drill rig
- Borehole drilled in less than 1 hour



CONVENTIONAL VERTICAL BORE EARTH EXCHANGER

Conventional vertical boring is constructed with deep vertical boreholes typically 60 – 200 feet in depth and around 4" – 6" in diameter. Into each bore a U-tube heat exchanger is buried and grouted into place. Fluid is pumped through these heat exchange pipes and transfers heat with the ground. Roughly 270 to 350 feet of piping can provide 12,000 Btu/hr of heat pump capacity, but this rough estimate is subject to pipe surface area and length, temperature difference between the ground, load profile, and other factors.

Closed loop ground source heat pump systems have heating COP ratings between 3.1 and 4.9, while cooling EER ratings range from 13.4 to 25.8. Air source heat pumps, on the other hand, typically have COP ratings between 3 to 3.5 and rapidly loose efficiency at temperatures below freezing and in high temperature regions.

The costs of ground source heat pump equipment is marginally more expensive than the air cooled equivalent, but this is mostly due to the low volume of production as GSHP make up only a small fraction of the total market. The equipment has the potential to be less expensive due to the needs of smaller condenser heat exchangers and pumping motors. The majority of the cost associated with ground source The typical cost of creating vertical deep wells is mostly dictated by field installation expenses. The cost of the HDPE tubing used and couples may only be $1 - $2 per foot. The installation costs however may drive expenses to $25 - $40 per foot.

DIRECTIONAL BORE EARTH EXCHANGER

Horizontal boring, used largely as an alternative to trenching when laying pipe or running underground conduit, can also be used for the installation of geo-exchange fields. The technique takes advantage of the wide availability of the relatively inexpensive and easily transported horizontal boring equipment. Unlike vertical drilling, where a new setup is required for each bore, a directional bore field takes advantage of being able to originate all bores from a single central location. This eliminates multiple set-ups and simplifies the connection and manifolding required to connect the earth exchange field to the mechanical equipment. The technique also allows ground source technology to be considered on parcels that would be too small for conventional vertical boring techniques by allowing the bores to be drilled under housing structures, landscaping, and other obstacles.

LARGE DIAMETER EARTH BORE EXCHANGER

Traditional geo-thermal techniques require expensive drilling rigs that can bore vertically deep into the earth. Large Diameter Bore Earth (LDBE) installations aim to reduce these costs by reducing the drilling depth while maintaining an adequate amount of heat exchange with the earth. This innovative concept utilizes a 24" diameter 20' deep helical coil constructed of 1/2" diameter HDPE tubing placed into the bore hole and backfilled with dirt from the drilling, sand, rock, or other fill. Drilling for these shallow bore heat exchangers is quick, and far less expensive than conventional techniques. Typically each bore may take less than and hour to drill, allowing around 8 to be completed in a typical work day. A day of work may yield around 150 linear feet of heat exchange depth, however on a per foot basis the LDBE exchanger has more capacity due to the effective increase in surface area.

DIRECTIONAL EARTH BORE EXCHANGER DEMONSTRATION: RIO MONDEGO

The project at Rio Mondego was a demonstration of a ground source heat pump system utilizing directional boring technology. The construction of the heat exchanger utilized 5 directionally bored holes of approximately 130' in length emanating from a single point manifold. Into these bores a conventional u-tube heat exchanger was placed and the bore was filled with grout.

The performance of the earth heat exchanger was shown to be adequate during summer cooling months without any failures; however inspection of the peak entering water temperatures (as referenced to the heat pump) and ambient temperatures showed that these temperatures are nearly the same and as compared to other GSHP systems the daily range of temperatures experienced appears to be higher than typical. This may be an indication that the field was undersized for the load that it is experiencing.

Overall the system proved it was capable of fairly high efficiencies, ranging from 10 – 20 EER in the summer and 3.5 to 6 COP in the winter. However, even though the system was capable of achieving very high efficiencies, the numbers over the complete season for this system were found to be EER of 10.9 for cooling and COP of 3.9 in for heating if the extra energy recovery from the desuperheater is ignored. If this energy is credited, the efficiency numbers are 12 EER and 4.6 COP. The low overall efficiency is most likely the consequence of an undersized or underperforming geo-exchange loop. If the unit was able to operate around 10 F above or below earth temperature EER in the range of 17-18 and COP of around 4.7 would be expected.

The residential home at Rio Mondego where the horizontal bore GSHP demonstration took place (left). A new gas water heater was also installed (middle). Image of the geo-thermal pipes (right).

RIO MONDEGO: THERMAL ANALYSIS

The system was installed in the middle of summer and started collecting data just after an extended time period of high temperatures. Figure 3-1 shows the daily high and low temperatures for outside air as solid lines. The ground loop temperatures are indicated by dashed lines, with makers. Areas in which markers are absent indicate days when the heat pump system did not operate at all. The maximum and minimum ground loop temperatures are recorded. The maximums and minimum ground loop temperature is can be from either the GEO_EWT or the GEO_LWT sensor, so during cooling season the minimum will be from the GEO_EWT sensor, but during the heating season the GEO_LWT will record the minimum temperature. The average ground loop temperature is the average of the GEO_EWT and GEO_LWT temperature over the entire 1 minute date points taken throughout the day.

Figure 3-2 shows the entering water temperature (EWT) and leaving water temperature (LWT) as referenced from the GSHP for the peak cooling and peak heating day of the year. It is of interest to note that each cycle of the GSHP changed the EWT by approximately 5 degrees F, but over a complete day the change in EWT might be greater because of multiple cycles each starting at an EWT successively higher (when cooling) or lower (when heating). During the heating period on 12/8/13 it was noted that the GSHP reached a lower temperature limit with LWT from the GSHP approaching freezing. During the peak cooling day in the summer it can be seen that a significant rise in EWT over the course of the day is apparent. These are both indications that the geoexchange field was not well matched to the load.

This figure illustrates that it may be possible that during certain hours of the day, and in certain conditions, it may not always be better to use a GSHP. At least during the peak cooling day, there are times in the late afternoon when air temperature has fallen below the ground temperature.

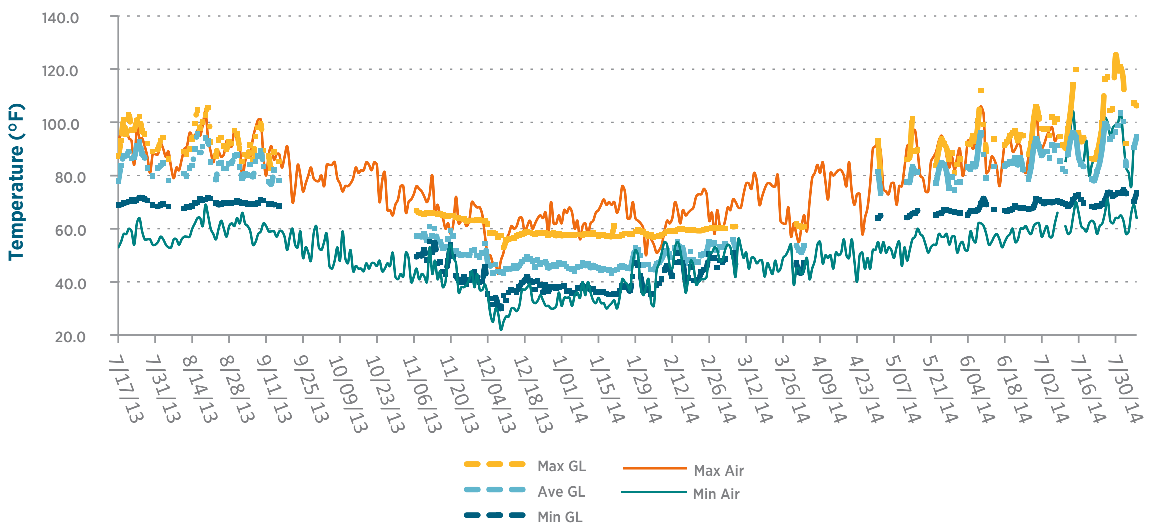


Figure 3-1: Ground loop temperatures as a function of outside air temperature

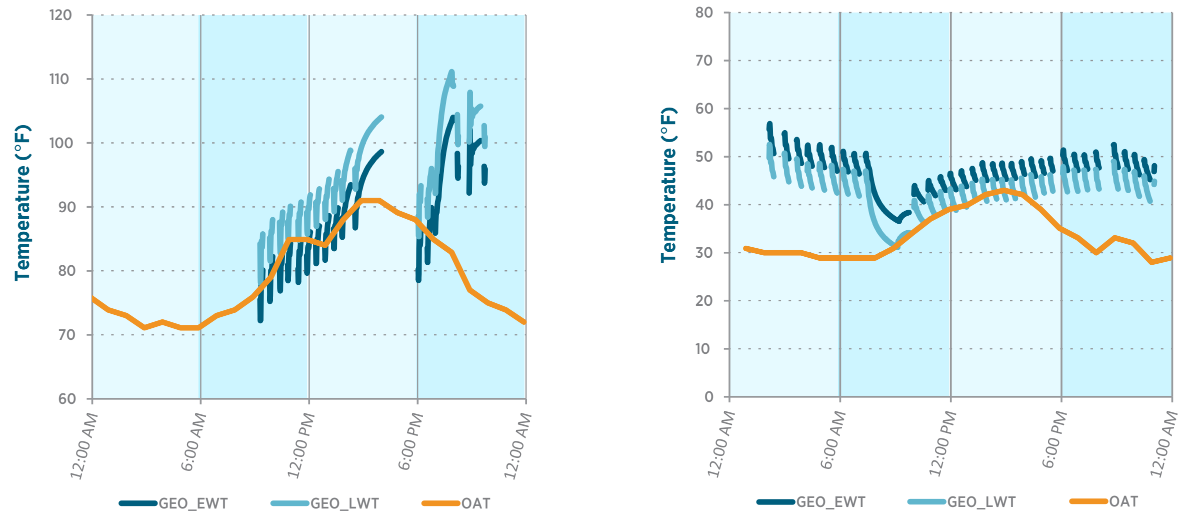


Figure 3-2: Entering Water Temperature (EWT) and Leaving Water Temperature (LWT) during the peak cooling (6/10/14) and peak heating (12/8/13) day of the year.

Calculations were made for the thermal energy delivered to the home, as well as a metric for heating degree days (HDD) and cooling degree days (CDD). HDD and CDD were calculated using the sine wave approximation method. The base temperature was adjusted so that good correlation could be made between the xDD calculation and Q_del to the building and may not match other sources for tabulations of HDD and CDD.

A visualization for the amount of heat delivered to the space and the calculated degree days was produced in Figure 3-4. It was found that a fairly good correlation could be obtained if the thermal energy was plotted against the quantity [HDD – CDD].

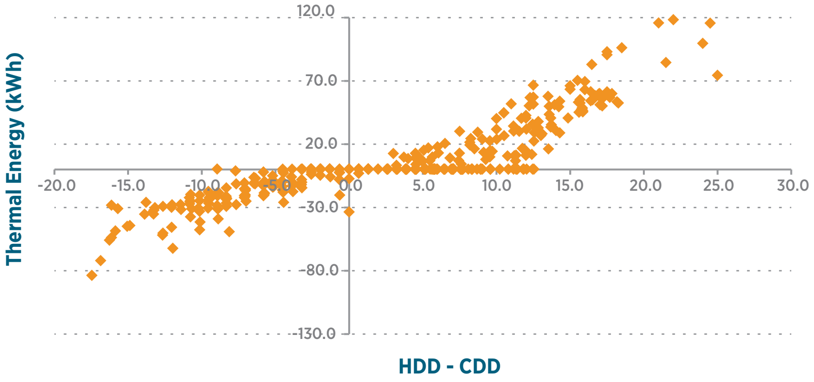


Figure 3-3: Delivered Heat vs. heating degree days minus cooling degree days

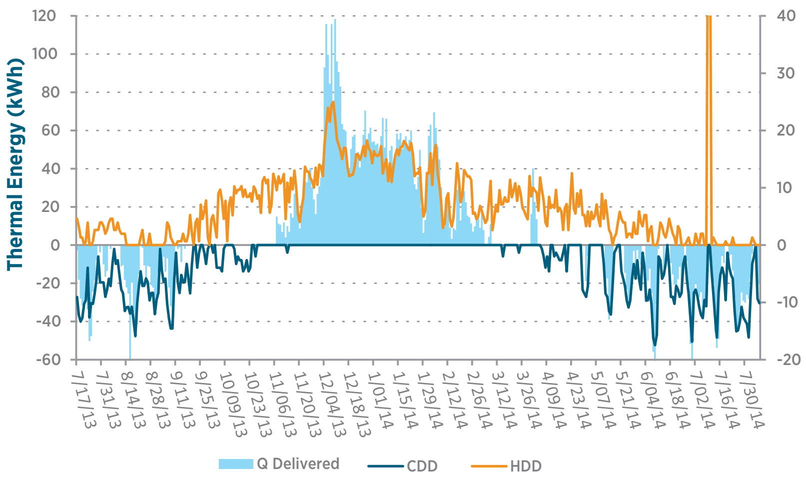
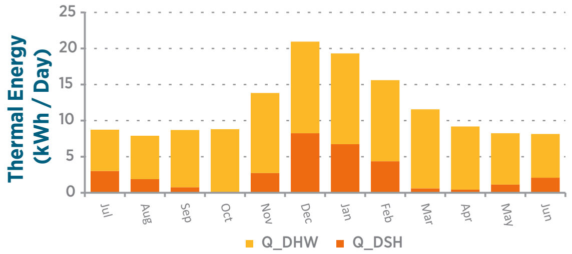


Figure 3-4: Amount of heat delivered in kWh

Measurement of the domestic hot water energy with the fraction heated by the NG heater and the heat pump was one of the most challenging calculations to make. The system installed utilized a hot water preheat tank that was heated by the desuperheater. The pre-heated water from this tank was drawn into the NG hot water heater and was heated to the final supply temperature.

A distinct increase can be seen in total heating energy for hot water during the winter season. Upon analysis it was found that two factors contributed to this increase. First, during the winter months somewhat more water was used. More importantly though, it was found that the entering water temperature was much lower in winter months, thus requiring more heat to bring the DHW up to its final delivery temperature and also requiring more DHW to mix with DCW to reach the desired usage temperature.

Over the year it was found that 36% of the DHW need was supplied by the GSHP desuperheater, the remaining 64% was supplied by the natural gas fueled hot water heater.



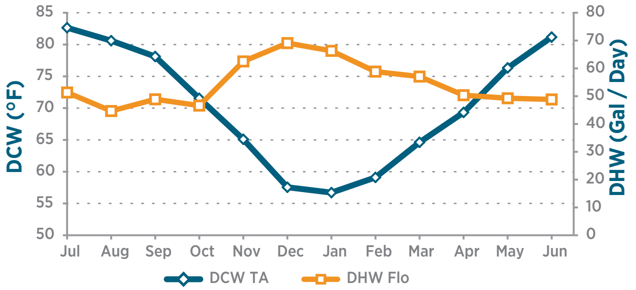


Figure 3-5: Domestic hot water production, inlet average temperature and consumption

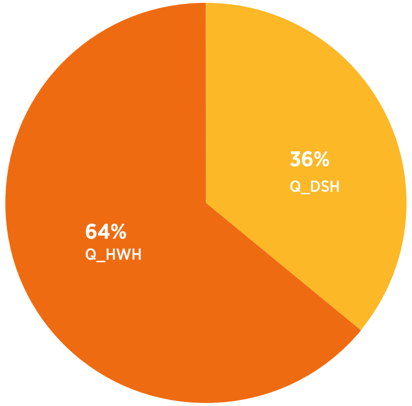


Figure 3-6: Domestic Hot Water demand percentages met by the hot water heater (Q_HWH) and the desuperheater (Q_DSH)

Heat pump input energy was evaluated in two different ways. Figure 3-7 shows a plot with input energy split out by component for Fan, Ground Loop Pump, and Compressor.

The heat pump energy was also split out by operating mode. Figure 3-8 shows the same energy split out of the total by mode and condenser and AHU. The condenser unit represents the energy used by the compressors and water pump, while fan power is the power consumed by the indoor air handling unit.

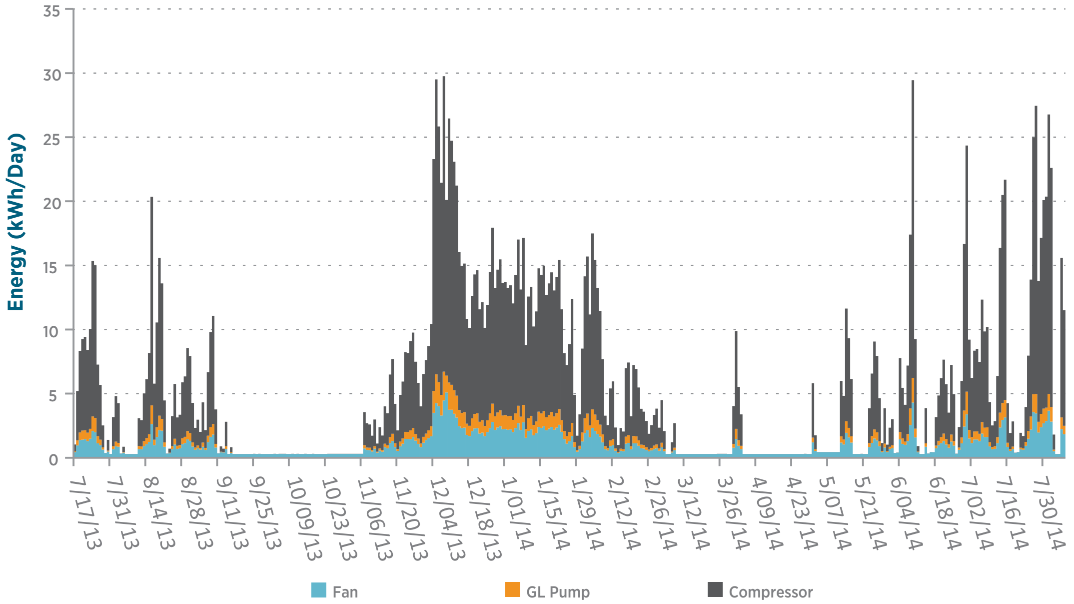


Figure 3-7: Heat pump input energy by component

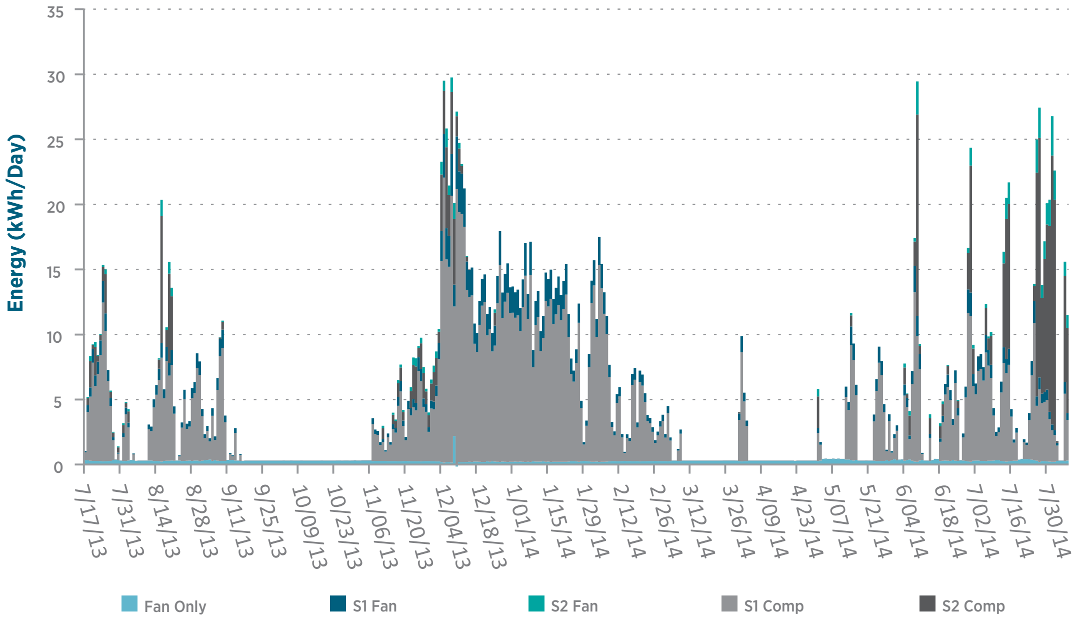


Figure 3-8: Heat pump input energy by mode

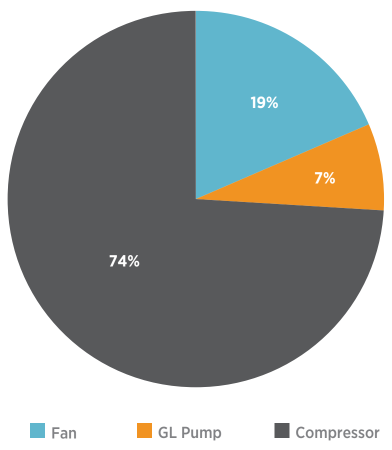


Figure 3-9: Input Energy by Mode

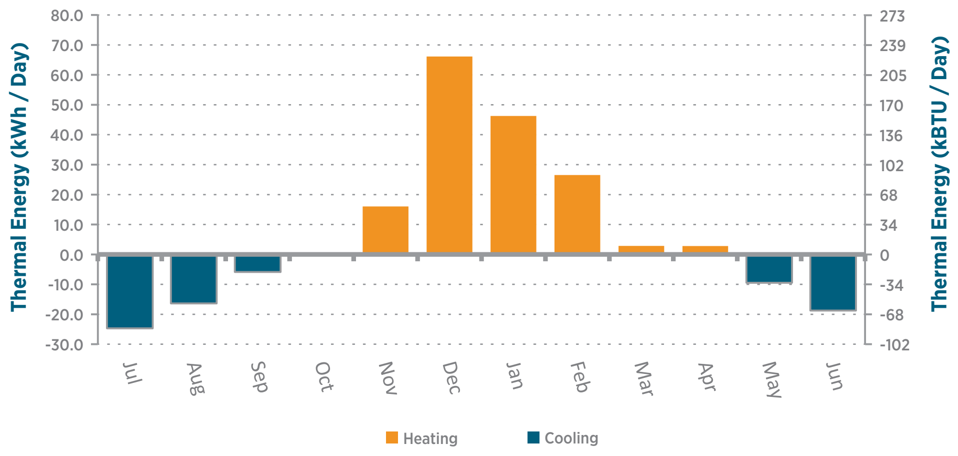


Figure 3-10: Heating/Cooling delivered to home during observation period

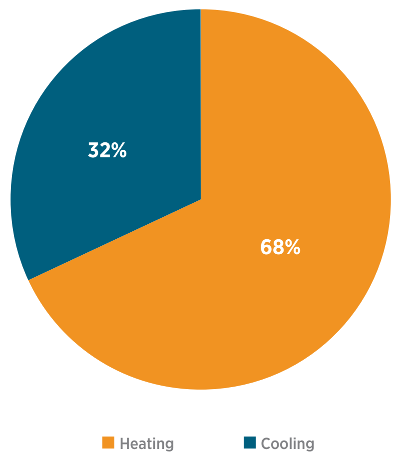


Figure 3-11: Total heating and cooling delivered by the GSHP system

Figure 3-9 shows the split of input power over the complete season. As can be seen the ground loop pump uses less than half of the energy as the indoor supply fan. The majority of the energy is used by the compressor.

Figure 3-10 shows the amount of heating or cooling delivered to the home over the period of observation. As can be seen in Figure 3-11, heating accounts for 68% percent of the thermal energy delivered to the home.

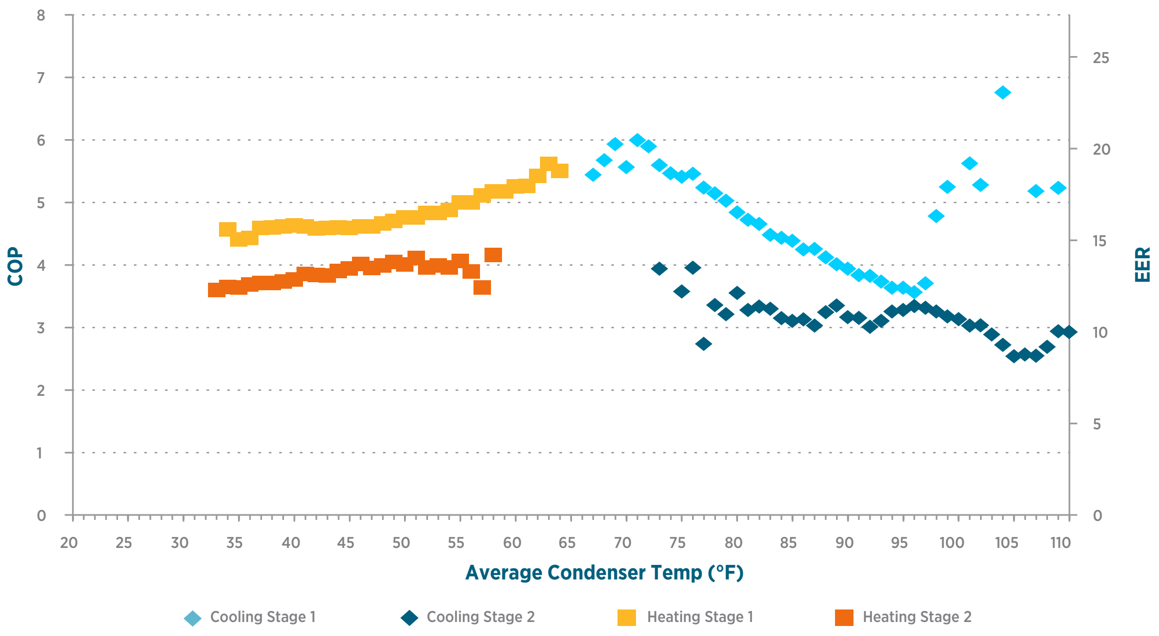


Figure 3-12: Efficiency of installed system as a function of the average condenser temperature

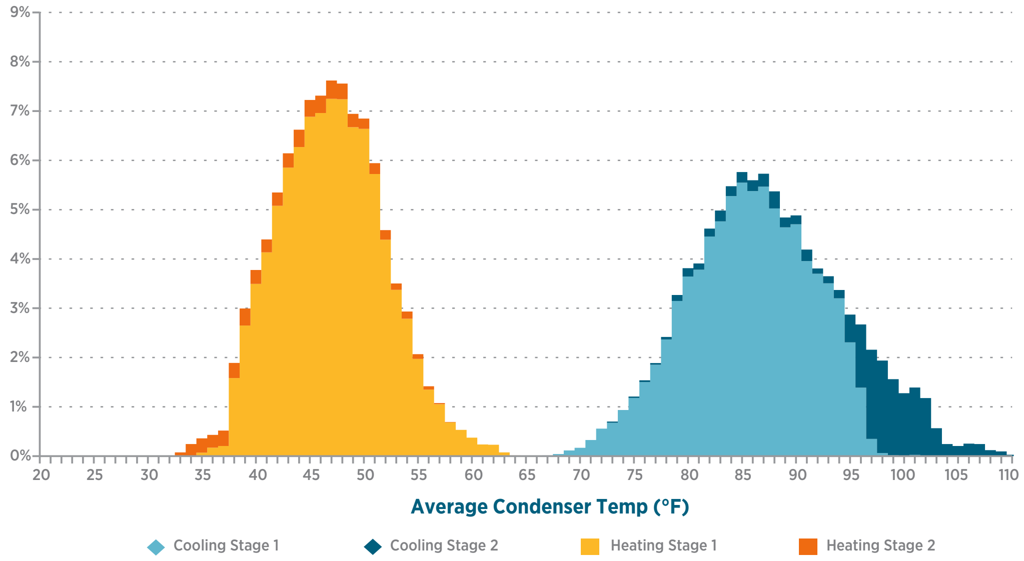


Figure 3-13: Proportion of time unit spent in each mode based on the condenser temperature

Figure 3-12 shows the efficiency of the system plotted against the average condenser temperature. As expected, the efficiency of stage 1 operation is generally higher than the corresponding stage 2 operation. Efficiency also improves as the average condenser temperature approaches the ground temperature, which the data would suggest as being around 66 F.

Figure 3-13 is a histogram showing how much time the unit spent in each mode binned for different temperatures. This plot shows that the mean temperature of operation was around 46F in heating, and around 86F in cooling.

The installation at Rio Modego showed that a horizontal drilling technique can be employed to install ground loops on small parcels of land with minimal disruption to surface features. Based on performance of the system, it is possible that this geo exchange loop was undersized, or under-performing as demonstrated by the temperature lockout experienced during the peak heating day of the year. Greater efficiency can be expected if the EWT temperature excursions can be minimized during the day.

LARGE DIAMETER EARTH BORE EXCHANGER DEMONSTRATION: HONDA SMART HOME

A large diameter earth bore (LDEB) technique for building geo-exchange fields has been installed at the Honda Smart Home at the UC Davis West Village ZNE community. The installation is testing two different field configurations using earth bores 24" in diameter and 20 feet in depth. In both of these configurations a coil of ½" polymer tubing just slightly smaller than the hole is inserted into the hole to exchange heat with the earth. One configuration is testing a dry borehole construction backfilled with dirt from the original hole. The other configuration utilizes a construction which places a large polymer pipe liner in the hole with the coil heat exchanger inside. The pipe is filled with cobble and grey water from the house and is allowed to percolate from the bottom of the bore to the top. This design allows for geo-exchange with the earth but also heat recovery from greywater produced in the house.

The Honda Smart Home is now completely built and tenants have been found and have recently moved in. Data aquisition is currently ongoing and analysis of that data will be worked on soon.

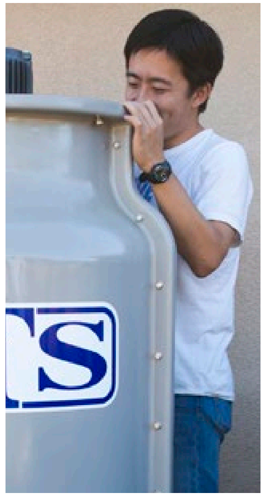
Installation of the LDEB system at the Honda Smart Home in West Village, Davis and the completed home.

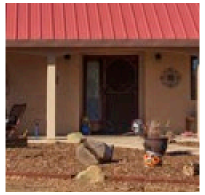
LARGE DIAMETER EARTH BORE EXCHANGER DEMONSTRATION AT CAPAY, CA

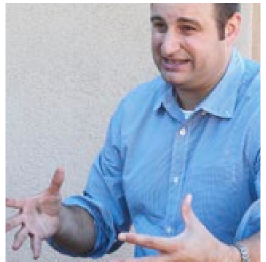
This project proposes a system utilizing uninsulated storage vessels buried underground to store water to be cooled during favorable conditions at night to later be used during the day when building cooling loads are the highest. In this way full advantage can be taken of California's large diurnal swings in ambient temperature by storing a complete day of cooling load heat energy in the water reservoir storage system and then rejecting this heat at night when conditions are most favorable. The complete system will integrate thermal energy storage, a modified residential split system compressor unit, and an appropriately sized evaporative fluid cooler to reject the heat at night time.

The implementation of this system as a retrofit would require only minor changes to the existing system. The system could use any water storage reservoir that already exists, such as naturally occurring stream or underground water storage tanks. To take advantage of thermal storage the existing split system air conditioner could be retrofitted with a water-to-refrigerant heat exchanger, a pump and a controller. As a result, the required space for this system is minimal, aside from the water reservoir, and could be integrated into existing construction. Also of note, should the storage system be undersized, or a night of adverse weather conditions prevent the thermal energy from being completely rejected from the water storage – the air conditioner still would function as originally designed without adversely affecting customer comfort.

This project demonstrates both the technical and economic feasibility of this system. The thermal reservoir allowed the condensing section of the vapor compression system to operate at lower, and consequently more efficient, temperatures. Fan energy necessary to move air through the air-cooled condenser was replaced with the much more efficient process of pumping a small amount of water through the water to refrigerant heat exchanger. Additionally, the cooling load was shifted from the day to the night resulting in a peak load reduction on the power grid.







SYSTEM DESIGN AND CONSTRUCTION

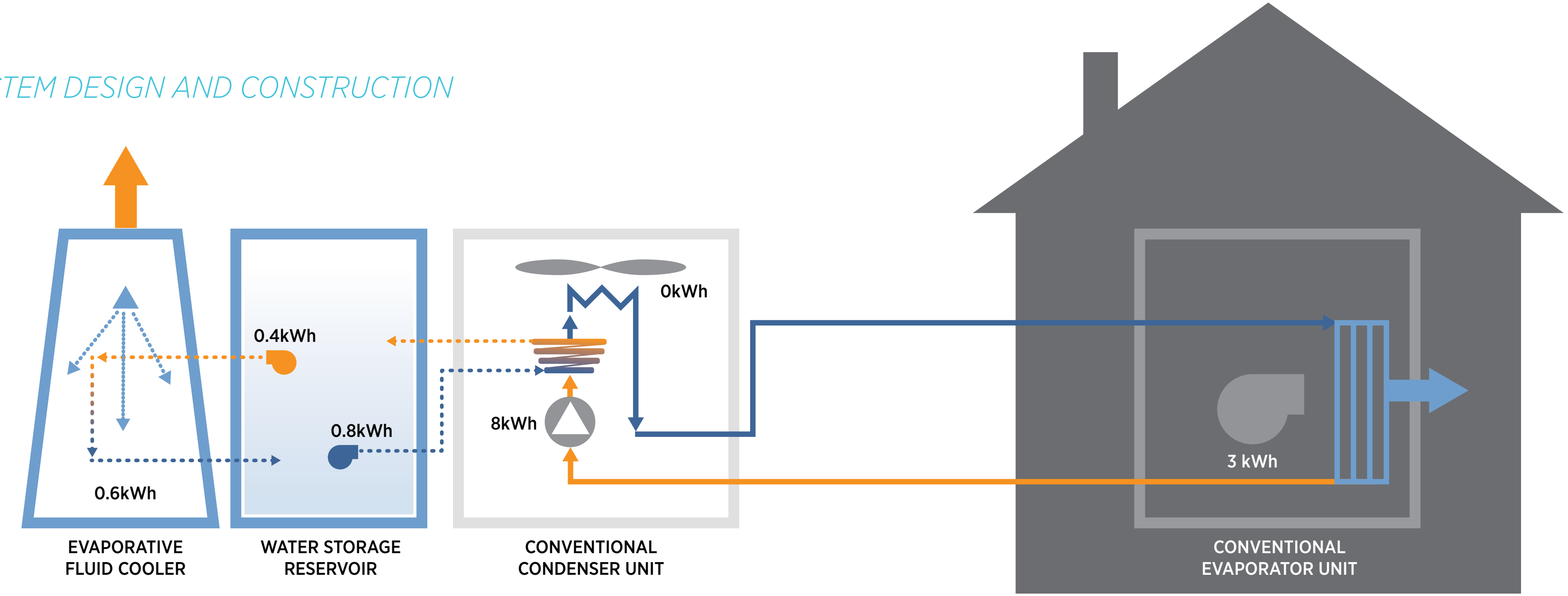


Figure 3-14: System design diagram for the large diameter earth bore exchanger at Capay, CA

INDOOR EVAPORATOR UNIT

For this project the indoor evaporator unit did not require any modification. This demonstrates one of the advantages of this retrofit, namely that all modification and construction can take place outside of the house without affecting any of the interior systems.

CONVENTIONAL CONDENSER UNIT

The outside condenser was replaced with a new unit. This was performed to facilitate testing and so that service would be interrupted for the least amount of time for the test site volunteer. The water heat exchanger was integrated with the condenser unit where the liquid line and suction line would normally interface with the house. For this installation the suction line from the house entered the unit at the same point, only the liquid line was diverted to run through the water cooled heat exchanger before entering the house.

Modifications to the controller and electronics were also minimal. The only internal change made to the condenser unit was to intercept the condenser fan power with a normal closed relay. When the controller signaled that the unit should operate in water cooled mode, the fan power was interrupted, and the water pump was enabled.

WATER HEAT EXCHANGER

This retrofit of an air conditioning condenser unit was an important part of the project to prove out the concept that the system might be installed as a retrofit to currently installed systems used widely throughout California. In order to accomplish this task a conventional split system condenser, the type that is typically used in residential construction, was retrofit with a coaxial water cooled heat exchanger.

THERMAL STORAGE GEO HEAT EXCHANGER

Many designs were contemplated for the construction of the hybrid heat exchanger and thermal storage component. The design that was ultimately chosen was constructed of HDPE culvert pipes, which were capped with HDPE plates. Internal to these pipes, before sealing, a polymer HDPE pipe heat exchanger consisting of 4 parallel ¾" braided pipes was inserted. The thermal storage heat exchanger was manufactured offsite and constitutes one of the major advantages of this design . This construction technique has the potential to lower costs by leveraging manufacturing economy of scale advantages.

As a final step, a second external HDPE heat exchanger consisting of 4 parallel pipes measuring 39' each, was wrapped around the pipe in order to allow testing of both internal and external arrangements.

BORING AND INSTALLATION

Large bore auger equipment typically used for piling drilling was used to drill 3' diameter holes 23' into the earth. After drilling, 6" of concrete was poured into the bottom of the holes, the pipes were placed, and then each heat exchanger was cased in concrete in a two-step process. In the first step, a small amount of concrete (about 6") was cased around the bottom of the heat exchanger. This was allowed to set before the remaining length of the pipe was cased. This was necessary to prevent the tank from being forced out of the hole by buoyancy forces. The installation was finished by connecting the heat exchangers to the reset of the system via HDPE pipe and back filling the hole with sand and native soil.

HEAT EXCHANGER FLOW CENTER

The pump for the heat exchanger loop was a GSHP non-pressurized type that did not require the typical flushing, sealing and pressurization that is typical of these systems. This results in quicker installation and ultimately costs less than traditional GSHP units.

COOLING TOWER AND PUMP

The cooling tower chosen was an open system fiberglass model nominally rated at 8 tons of cooling capacity. These types of cooling towers are inexpensive, quiet and easy to ship and install. The pump for the cooling tower was a high efficiency VFD type that was capability of variable flow for maximum efficiency. The pump was installed at the lowest point in the system, in the valve box with the water cooled heat exchanger. This ensured that the pump would always be primed and would work properly. It also protected the unit from freezing.

Figure 3-15 shows the operating characteristics of the system during the hottest day of the year in climate zone 12. The condenser inlet and outlet temperatures show characteristics of fast temperature rise from an initial point on the order of a couple minutes then transitioning to a steady state temperature rise on the long time scales. The initial temperature rise is due to the low volume of fluid within the heat exchanger loop coming up to temperature, the slower temperature rise thereafter is due to the bulk temperature rise of the storage thermal fluid mass. After each cycle the fluid temperature within the loop comes into equilibrium with the bulk fluid temperature within the tanks, and upon the start of the next cycle, starts at the bulk fluid temperature of the tanks.

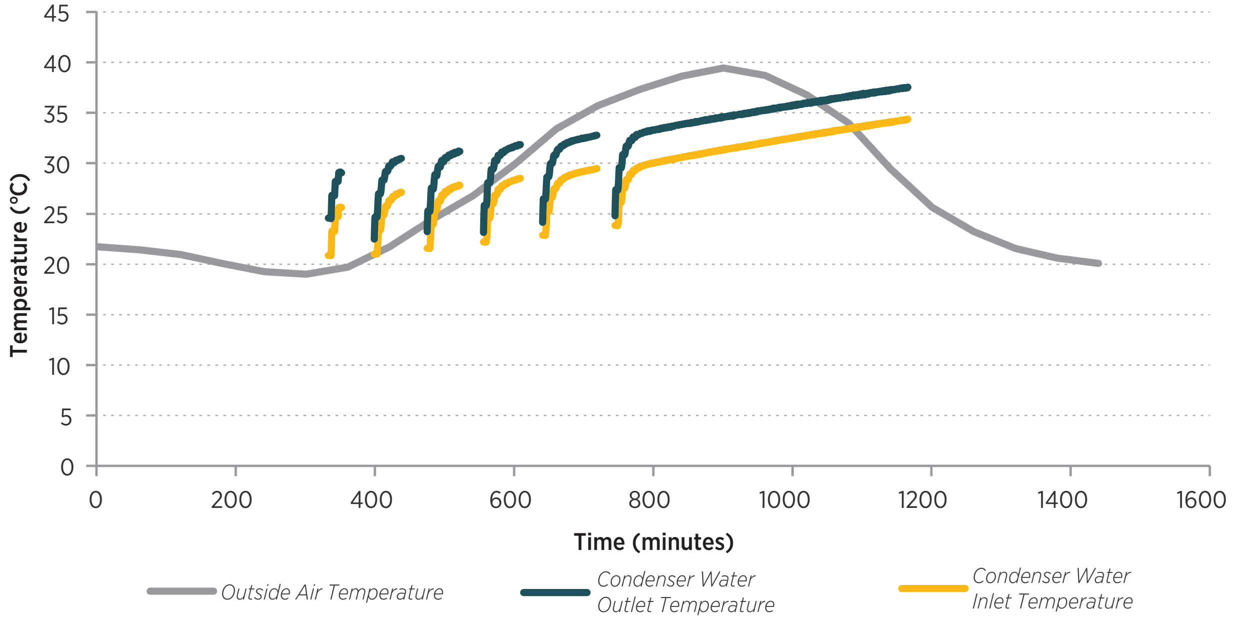


Figure 3-15: [CZ 12] System Temperatures (Peak Cooling Day)

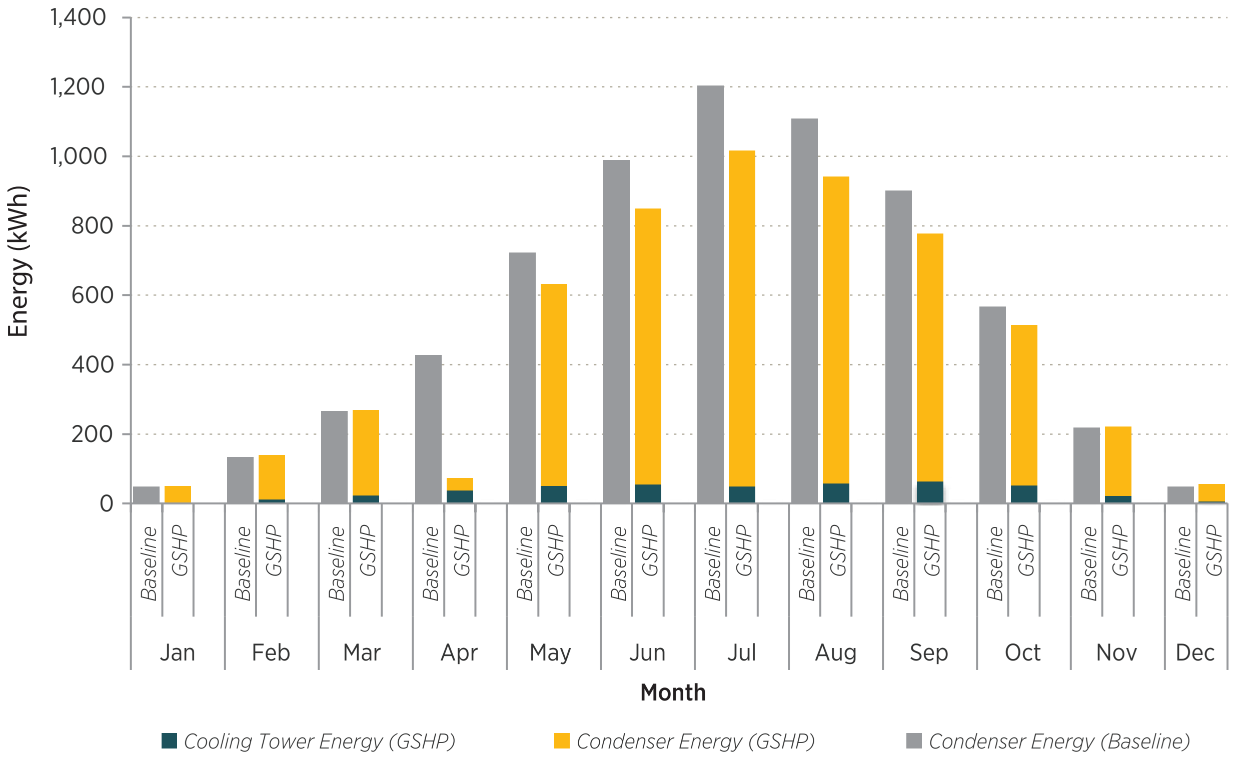


Figure 3-16: [CZ 12] Total Monthly Energy Use

A look at the energy usage breakdown reveals that the energy do to the additional pumping and cooling of water at nighttime in the cooling tower is a very small percentage of the total energy consumption of the proposed system. The proposed system shows reduced energy consumption in nearly all months of operation.

The efficiency advantage of the proposed system over the baseline system is most apparent in the summertime. This is expected due to the high daytime temperatures encountered and the ability of the proposed system to utilize lower temperature water in the condenser.

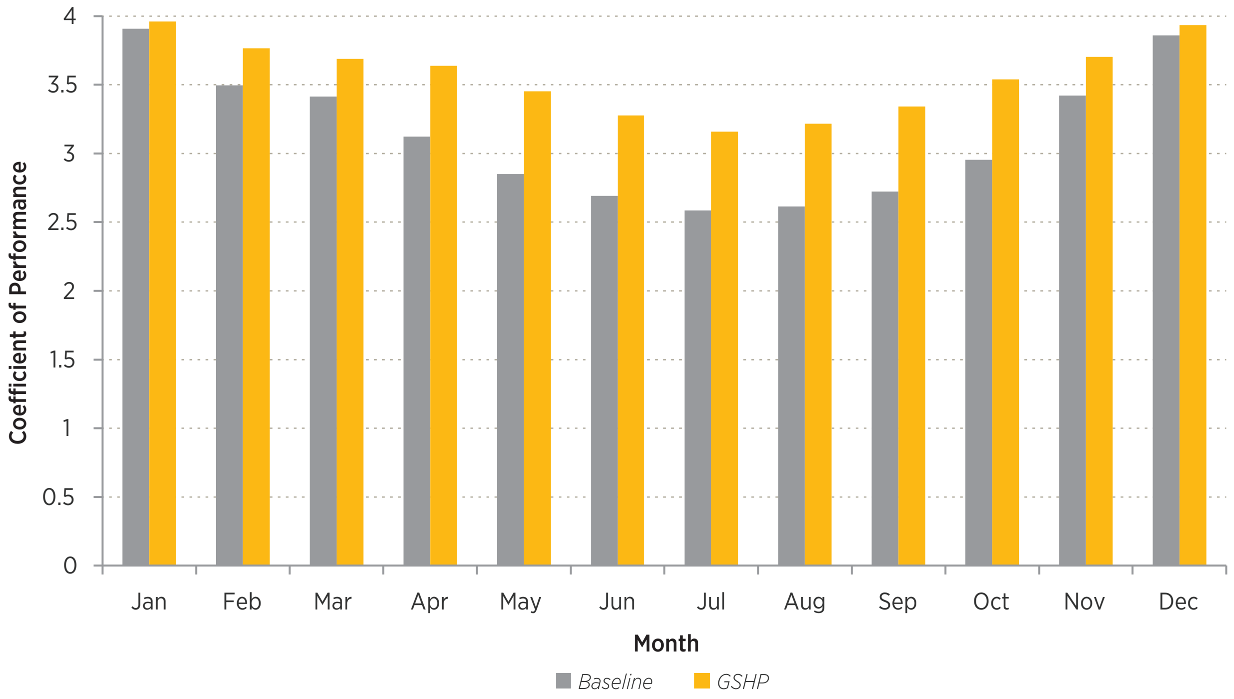


Figure 3-17: [CZ 12] Average Monthly CoP

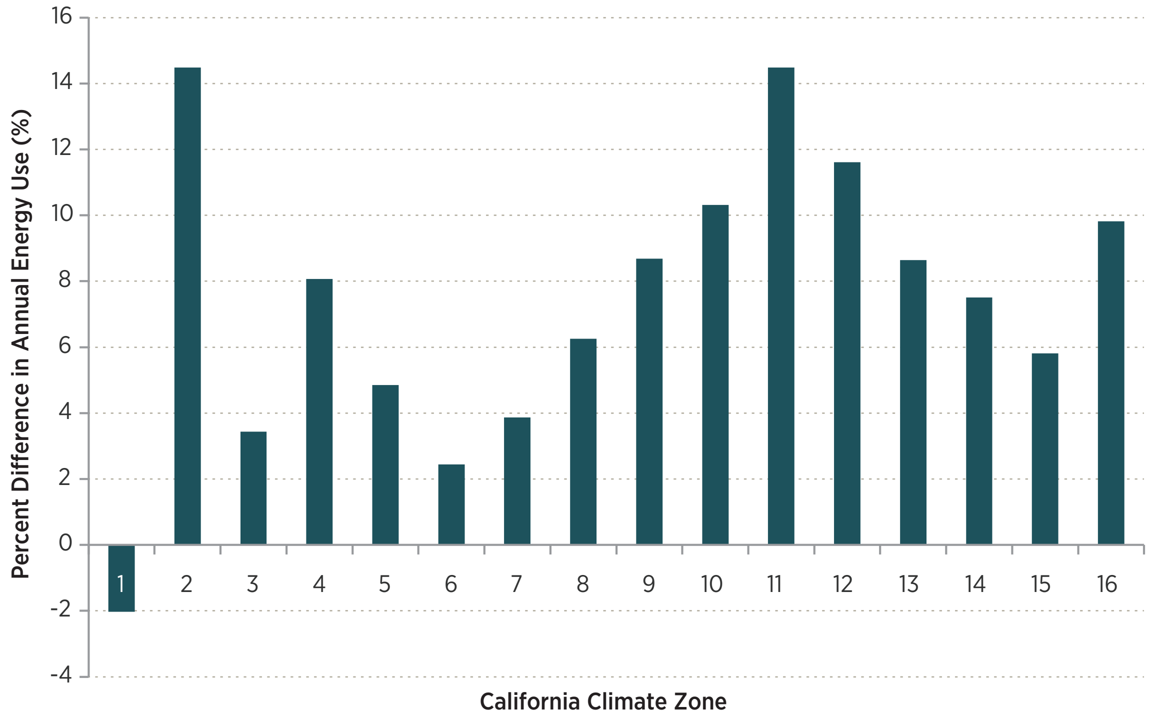


Figure 3-18: [CZ 12] Baseline to GSHP Energy Use Comparison

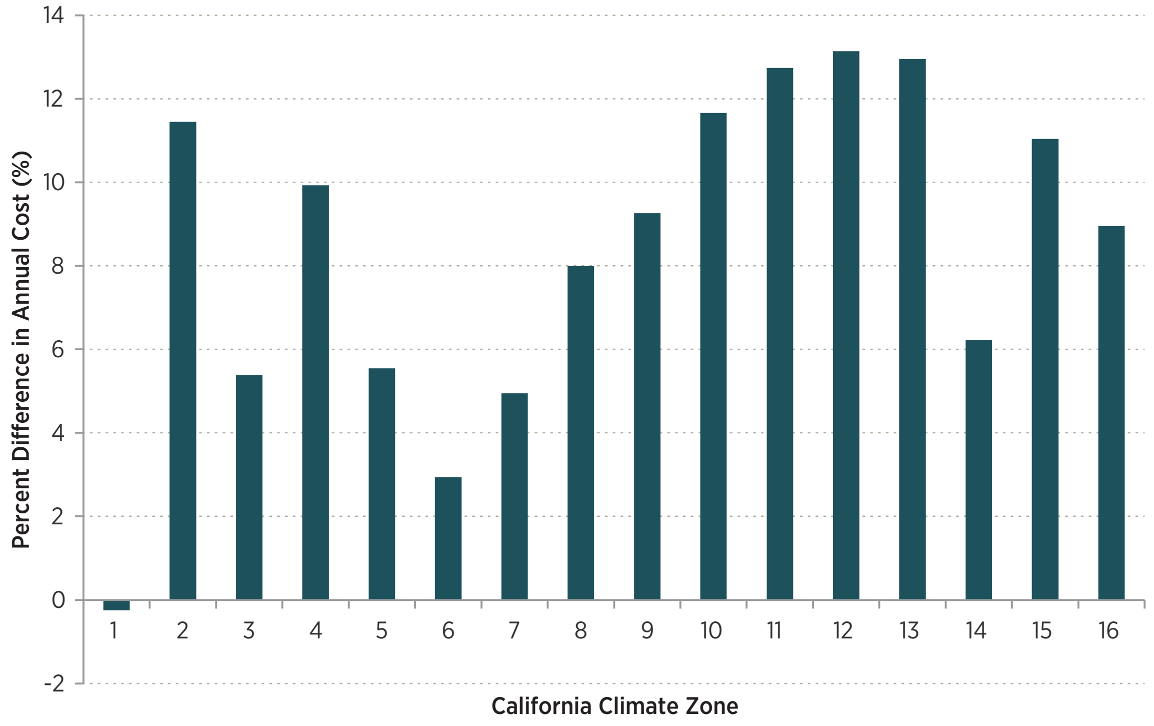


Figure 3-19: [CZ 12] Baseline to GSHP Energy Cost Comparison

Looking at the system performance across all climate zones it can be seen that savings can be up to roughly 14%. Climate Zone 1 which represents the north coast from just north of San Francisco to the top of the state actually shows negative savings over the baseline system. This indicates that the control strategy has not been completely optimized because the proposed system is able to operate in the same manner as the baseline, and therefore should never do worse that the baseline system.

An analysis of cost of operation savings in a time-of-use pricing structure was performed. The TOU pricing for the PGE E-6 rate structure (Figure 3-21) was used and it was assumed that the total residential usage did not exceed the first tier of consumption. The savings over the baseline system are up to around 13%. This system should have the ability to completely shift loads to off peak hours. It is believed that with further optimization of the control strategy that the savings could be greatly improved.

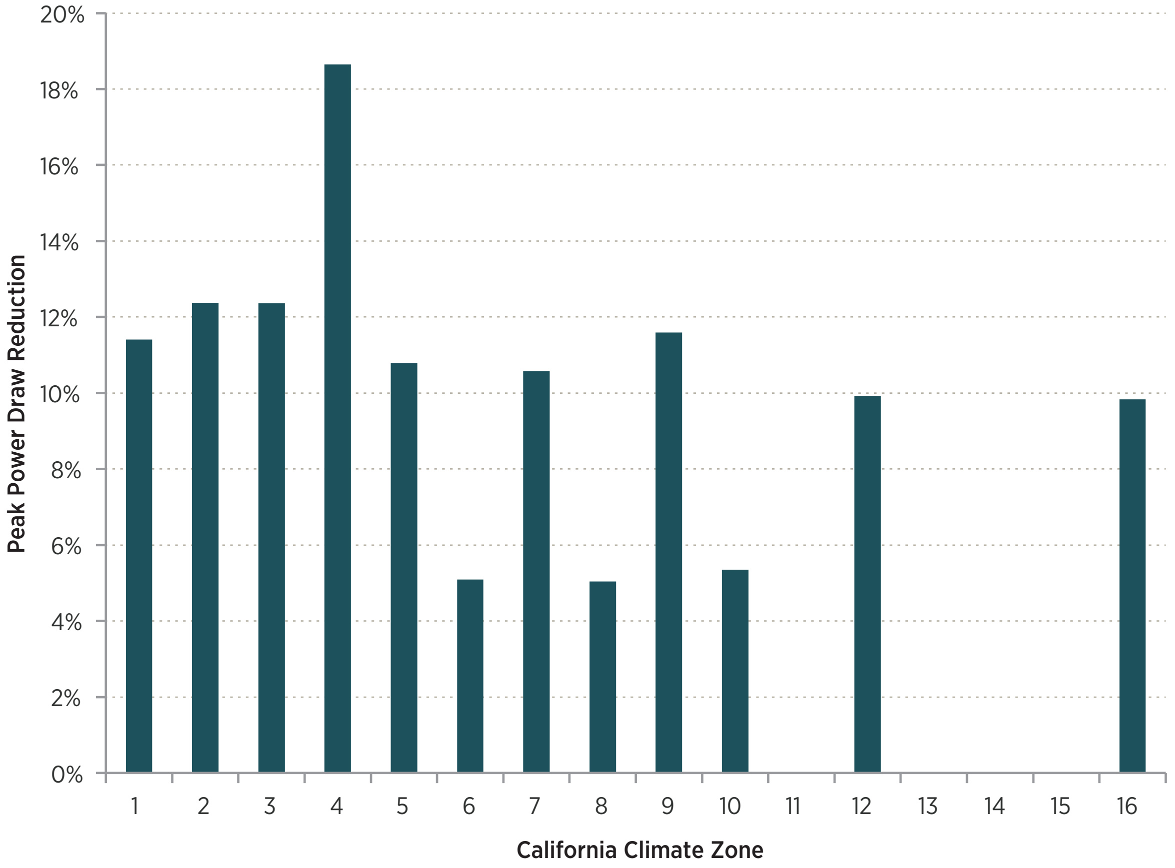


Figure 3-20: Peak Reduction

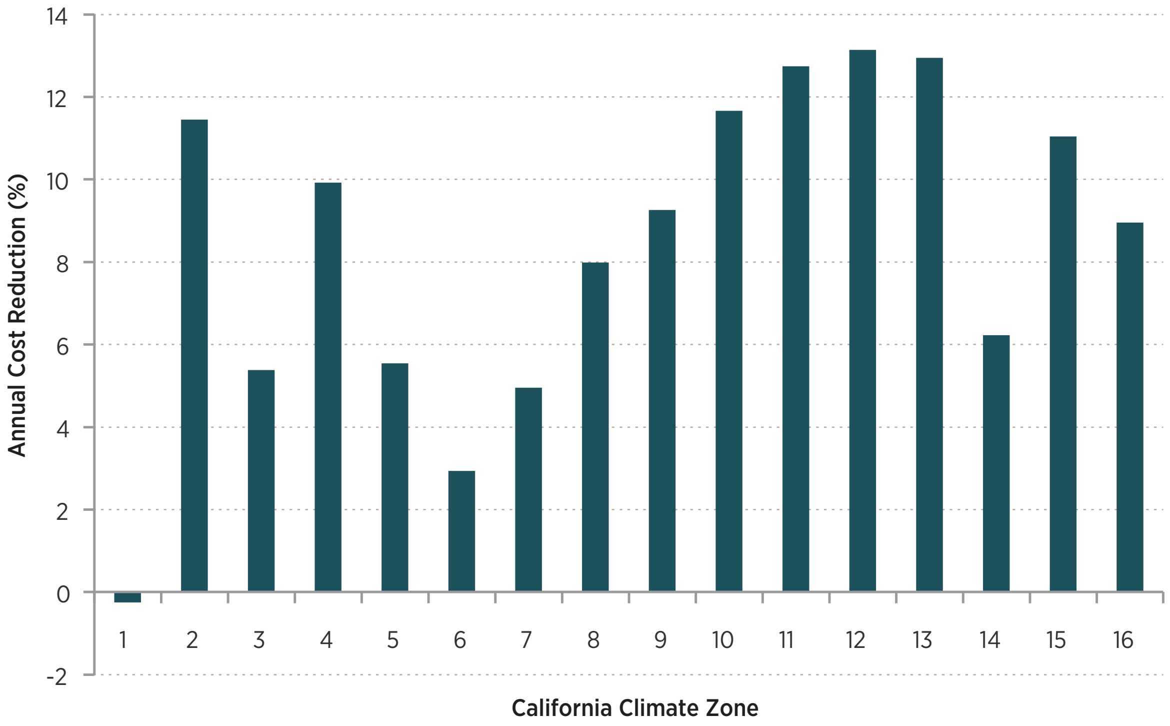


Figure 3-21: Annual Energy Cost Reduction

PEAK LOAD REDUCTION

By using the water thermal storage to reduce the peak temperature that the condenser experiences the peak load will also be reduced. During peak summer months, air temperatures may be in excess of 100 degrees in many hotter climate zones. By using cooler water to operate the system during these periods, load reductions were shown to be achievable. Figure 3-20 shows the amount of reduction in peak power for the proposed system. Many climate zones see peak savings in excess of 10%, with some savings as high as 18%.

The proposed system offers the opportunity to shift loads associated with cooling the thermal storage reservoir to off peak and nighttime periods without system performance degradation. This allows for a large amount of control to optimally respond to time-of-use energy pricing structures.

Figure 3-21 shows the energy cost savings that can be achieved in a time-of-use pricing structure.

This project explored the use of underground thermal storage reservoirs, a cooling tower, and a modified air conditioner condenser unit to reduce energy use and peak power in residential applications. The project consisted of a modeling study of the expected system performance, laboratory testing, and a field installation of the proposed system.

The model constructed for the system shows that the proposed system can save energy, reduce peak power, and reduce costs when operated in a typical time of use (TOU) pricing structure. As might be expected, not all climate zones are predicted to result in the same level of savings. Because the scope of the project was to look solely at the air conditioning savings, cooler coastal climate zones such as 1,3,5,6, and 7 are expected to have only modest savings for cooling, between 0% and 6% annually. However, in all climate zones other than the coastal zones, cooling savings are estimated to be between 6% and 13%.

Ground heat exchangers (GHE) were constructed with large HDPE culvert pipes and HDPE pipe. The construction techniques used for manufacturing these (GHE) worked well and are well suited to factory production techniques. In large scale deployments the GHEs can be constructed offsite, and trucked to the site. Pipe installation can be accomplished quickly with readily available earth auger equipment and a single man crew. The process has the potential to be cost effective for residential installations such as the one examined.

Condenser modification for the water heat exchanger presents some challenges in a retrofit situation; however these modifications could be readily integrated into new designs with modest costs and then be integrated into residential constructions that include GHEs, swimming pools, or other methods of thermal storage.

RECOMMENDATIONS

This research has shown that energy savings can be achieved by utilizing lower cost ground heat exchanger concepts. It has also demonstrated the ability for even greater percent savings in operating costs when operated within a time-of-use pricing structure. Challenges remain though, and further research in some key areas would be beneficial in eliminating questions that still remain.

This concept would benefit from further research in the following key areas:

1) Expanding the modeling and the installation to also perform space heating by using a heat pump, and adding other components that would aid in operation in cool ambient temperatures.

The scope of this project was limited to looking at reducing energy due to cooling loads, however, there are many California climate zones that experience greater heating loads than cooling loads. Additionally, to maximize the utilization of the unique components involved in the construction of this system, both cooling loads and heating loads should be addressed with a heat pump. Further research focusing on satisfying heating loads and integrating this with cooling loads would be a logical next step.

2) Exploring cost reductions and improved installation techniques for the large diameter shallow bore ground heat exchangers that this project utilized.

The ground heat exchanger (GHE) developed during this research represents a unique design that has not been well characterized. There remain many opportunities for improvement within this design for cost reductions, improved methods of installation, and in understanding expected performance of the design in various installations.

3) Further development of the proposed system, including component optimization and system control algorithm changes to improve performance and reduce costs.

Further research into the design and construction of heat pump systems capable of utilizing air or water source heat exchangers, and controlling them for optimal efficiency or demand reduction would also be beneficial. Cost reductions could be made by delivering this feature from the manufacturer rather than by installing as a retrofit.

DEMONSTRATION FOR ADAPTIVE THERMOSTATS AT SEGUNDO HOUSING COMPLEX IN DAVIS, CALIFORNIA

TECHNOLOGY DEMONSTRATIONS PROGRAM

As part of WCEC's mission to accelerate the successful application of energy efficient HVAC technologies, the Center engages in a variety of technology demonstrations and beta-testing activities. The sheer breadth of market-available efficiency products creates a daunting task for institutional decision makers who have neither the time, nor the expert judgment to prioritize the value of the various technologies. Thus a significant focus for WCEC's demonstration efforts is to highlight some of the most appropriate HVAC technologies, and to provide a reliable, unbiased perspective on the market readiness, cost effectiveness, and project-by-project appropriateness for various strategies. This work, to design and facilitate the market adoption of energy-efficient technologies in lighting and HVAC, relies heavily on the continued support from our partners: SPEED (the State Partnership for Energy Efficient Demonstrations), CEC (California Energy Commission) and CIEE (California Institute for Energy and the Environment). Our demonstration activities are public-private collaborations that foster the deployment of advanced technologies, with special focus on implementing energy efficiency strategies in coordination with facilities managers and planners at large public institutions such as the University of California, the California State University, the Department of General Services, and local municipalities.

The sheer breadth of market-available efficiency products creates a daunting task for institutional decision makers who have neither the time, nor the expert judgment to prioritize the value of the various technologies.

Thus a significant focus for WCEC's demonstration efforts is to highlight some of the most appropriate HVAC technologies, and to provide a reliable, unbiased perspective on the market readiness, cost effectiveness, and project-by-project appropriateness for various strategies. These institutions regularly set the bar for best practices in building design and facility management, so the focus is partly to build familiarity with the next generation of efficiency technologies amongst decision makers and champions within these agencies. WCEC manages trial installations and beta tests in collaboration with these institutions and then develops case studies, fact sheets, web resources, education, and training activities based on the mutual learning derived.

Technologies that are successful in trial demonstrations can end up on a fast track toward wide spread use through these institutions, while technologies that fall short of performance or cost effectiveness thresholds receive feedback about necessary improvements learned in field installations and monitored operations. Advanced HVAC technologies face many barriers to market success. These demonstrations work to overcome the general mistrust about new technologies, prove cost effectiveness and build understanding about the characteristics and caveats for application of various efficiency technologies, inform revisions to building energy performance codes and standard specifications, generate group purchasing agreements, and feed information into utility incentive programs. The collective learning from these activities lead to broader adoption through energy efficiency implementation programs, and highlights the needs for specific research and development activities within the industry. The benefits of this program are widespread.

Manufacturers benefit from expert feedback about the market readiness of their advanced products and by gaining an ushered market introduction. Institutions benefit from learning about the appropriateness of market available efficiency strategies. And the public benefits as the program fosters progress toward state goals for energy and peak demand reduction, climate change mitigation, environmental responsibility, and economic vitality.

Provide a reliable, unbiased perspective on the market readiness, cost effectiveness, and project-by-project appropriateness for various [HVAC] strategies.

INTERNET-CONNECTED ADAPTIVE THERMOSTATS DEMONSTRATION

Many recent field evaluations for communicating and occupancy-responsive thermostats have shown significant annual HVAC savings on the order of 10-20%. However, the form and function for technologies in this space vary widely.

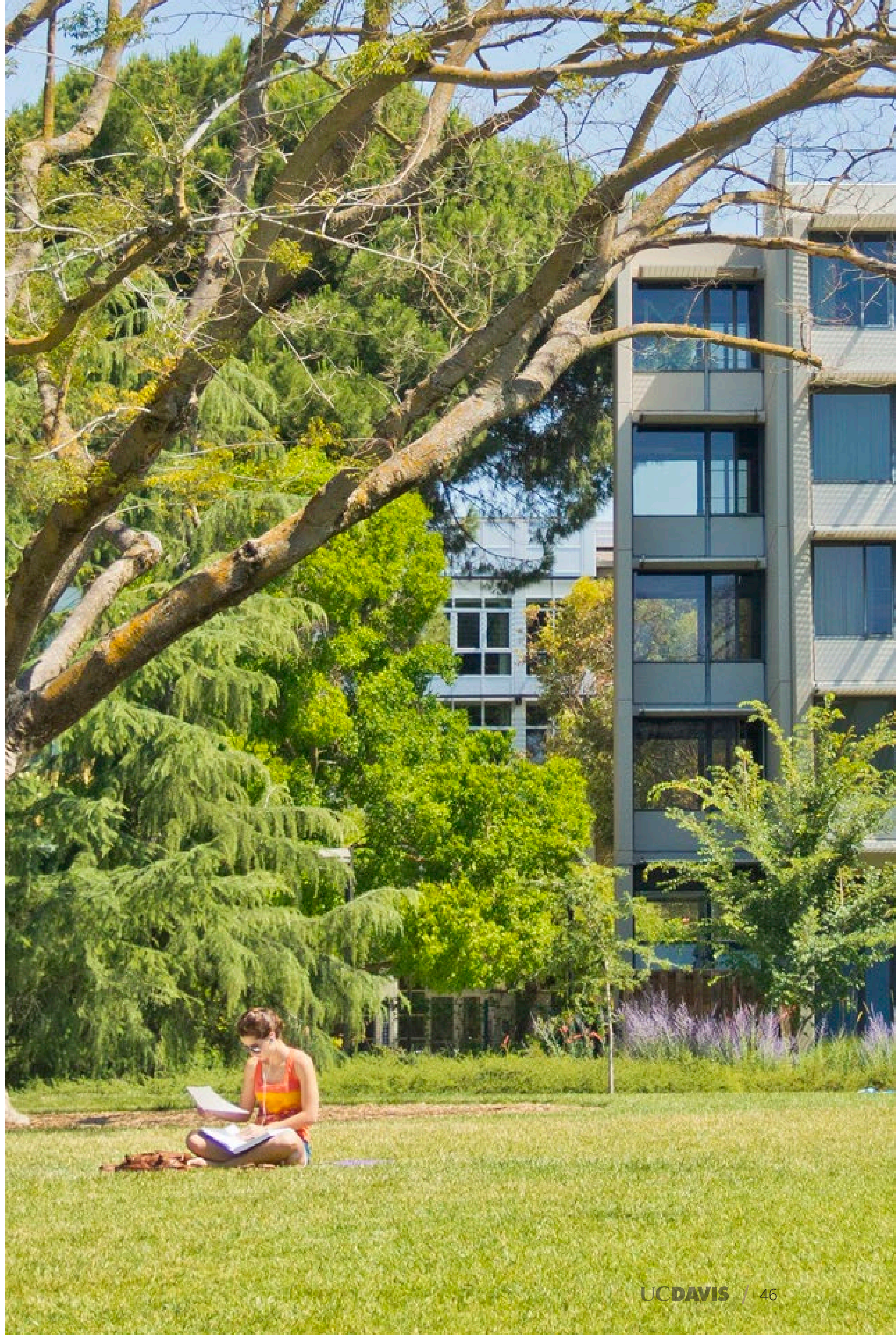
Occupancy responsive thermostats adjust mechanical system operating parameters to reduce energy consumption when a conditioned space is vacant. Unlike occupancy controls for lighting, the value of occupancy control applied to heating and cooling depends on a range of dynamic factors that are difficult to measure and assess with precision. For instance, the efficiency of heating and cooling equipment changes with weather conditions and part- or full-load runtime capacity, while thermal loads depend on the aggressiveness of indoor temperature set-points, and their dynamic relationship to a variety of physical and environmental factors.

This study focuses on field evaluation of 4 residence halls (110 units) at UC Davis, using one occupancy responsive adaptive thermostat technology provided by Telkonet. The thermostat system learns about response capabilities for the heating and cooling equipment and automatically programs a set-back for vacant periods that will allow for a timely recovery to the comfort set-point when a room is again occupied.

TELCONET PERFORMANCE RESULTS FROM 110 BUILDINGS AT UC DAVIS

Operation mode	Heating		Cooling	
Occupancy level	*Low*	*High*	*Low*	*High*
H/CW energy in period (kWh)	44,291	198,544	61,163	38,413
Energy Savings	7%	7%	25%	3%
Site Energy savings (kWh)	16,513		16,486	
Distribution Efficiency	0.8		0.8	
Plant Efficiency	0.8		3	
Source Energy Savings (kWh)	25,801		6,869	

Download the full report » ***http://bit.ly/SPEEDthermostats***



GRADUATE SCHOOL OF MANAGEMENT BUILDING ASSESSMENT DEMONSTRATION

Gallagher Hall and Conference Center is an 86,000 square-foot building at the University of California Davis. The building, opened in 2009 houses the Graduate School of Management and contains a mixture of classrooms, office space and conferencing facilities. The building is located outside of the central campus and does not have access to the campus district heating and cooling systems. This presented a challenge to the designers – but also an opportunity to think creatively and design a building for high efficiency from the ground up. The result was a building design that achieved LEED Platinum recognition. Many systems and design features made this possible, but most can be grouped into three main categories – the radiant heating and cooling system, the dedicated outside air system, and the solar management features.

Solar loading is reduced with an innovative architectural rain screen on the building walls with solar exposure. The stone facade is separated from the main building envelope by up to 10 inches, which shields the envelope from solar radiation, and provides an insulating air bubble around the building. Spectrally reflective window film, a reflective white roof, and architectural window shading further reduces the solar load on the building. Solar panels on the roof generate a portion of the power used on site, when power generation exceeds demand the excess power is sold back onto the grid for others to use.

Gallagher Hall utilizes an innovative ground-coupled hydronic system to manage its space heating and cooling needs. By moving water instead of air, this system distributes thermal energy much more efficiently than a forced air system in a typical building. Heating and cooling is delivered through the cement slabs in the floor and ceiling, which act as large area radiant surfaces.

Eighteen miles of tubing are buried 16 feet beneath the building to exchange heat with the earth. This ground source heat exchanger provides a source of nearly constant temperature water for the conditioning equipment, and in some conditions can even be pumped directly through the building without additional heating or cooling energy. For additional cooling capacity the system includes an evaporative fluid cooler and chiller. A high efficiency condensing gas boiler and heat pump can provide additional heat.

Since the bulk of heating and cooling is provided by the radiant system, air distribution can be limited to only what is needed for indoor air quality. A network of sensors throughout the building monitor carbon dioxide concentrations and control the amount of fresh air according to demand. The dedicated outside air handlers take advantage of California's arid climate by cooling air with a high efficiency indirect evaporative system plus DX cooling when additional capacity is required. In humid conditions an active desiccant wheel removes moisture from the ventilation air to ensure that water does not condense on the radiantly cooled surfaces. Displacement ventilation techniques introduce fresh air at floor level through under-floor plenums on the upper floors.

DEMONSTRATION ENERGY HIGHLIGHTS

Source EUI (Gallagher Hall)	101 kBTU /sq. ft.
Source EUI (CBECS Building Average)	180 kBTU /sq. ft
% of total energy supplied by Solar Energy	20%
Source EUI savings vs. similar buildings	**49% (Compared to CBECS average)**

*Download the full report » **http://bit.ly/SPEEDGSM***

RTU EFFICIENCY OPTIMIZER DEMONSTRATION

COOLING ENERGY & CO_2 SAVINGS
24-56%

ENERGY REDUCTION
365 kWh/yr-ton

PROBLEM

Packaged cooling equipment also known as Rooftop Units (RTUs) are used in 46% of all commercial buildings, and serves approximately 69% of the commercial building cooled floor space in the U.S. The ubiquitous use of these pieces of equipment is due to the ease by which they can be designed into a building, low capital cost, and a modular nature that allows for easy demarcation of energy billing and maintenance responsibility between multiple tenants of a single building. However, RTUs are notoriously inefficient because they're often oversized, improperly installed, and inadequately maintained. In addition, even though the technology for improving RTU energy efficiency is well understood, the forces driving design tend to favor low first costs and ease of installation rather than energy efficiency and robust design.

SOLUTION

Several new retrofit controllers are now available for single-zone rooftop-unit (RTU) air conditioners that take advantage of energy saving techniques not previously economically possible. These retrofits work by replacing the simplistic stock control unit with new digital controls, new sensors, and often upgrade the single speed supply fan motor to take advantage of variable frequency drive (VFD) motor controllers. The controllers make use of multiple energy saving techniques and will often reduce supply airflow to better match partial building loads, more carefully control outside air ventilation to the minimum amount necessary to maintain indoor air quality, implement advanced economizer controls eliminating the need to operate the compressor when advantageous ambient conditions prevail, and also implement continuous monitoring and failure detection and diagnostics (FDD) to notify the user when the RTU needs maintenance.

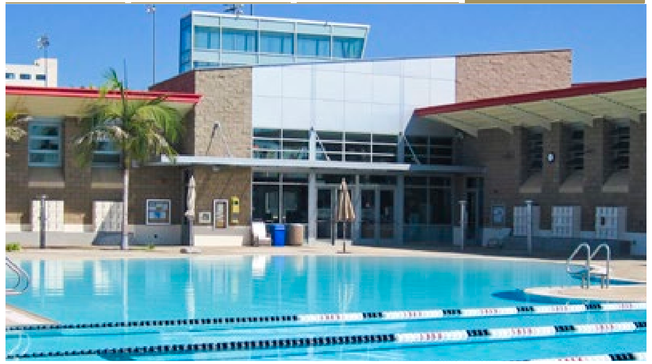
Download the full case study » ***http://bit.ly/SPEEDcatalyst***

CSU LONG BEACH, DANCE COMPLEX

Climate Zone	System Size	Heating	Savings
6	10-ton	Natural Gas	51%

SAN DIEGO STATE UNIVERSITY, AZTEC AQUAPLEX

Climate Zone	System Size	Heating	Savings
7	8-ton	Natural Gas	29%



AUTOMATED DUCT SEALING DEMONSTRATION

Ductwork in forced air systems can leak significantly, causing poor air balance, direct losses of conditioned air, short-circuiting between supply and return systems, and increased fan power requirement to achieve desired diffuser flow rates. Sealing ducts in existing buildings is frequently unfeasible due to difficulties accessing the ductwork in shafts and plenums. Aerosol duct sealing is a method for repairing leaks without having to locate and access points of leakage. Instead leaks are repaired by injecting aerosolized sealant into the ductwork and allowing it to find the leaks which are sealed as the sealant deposits on the edges of the leaks.

This report details the sealing of the UC Davis Art building duct system using the Aeroseal process, and describes the savings that can be expected based on measurements of the pre-seal airflows and historic energy usage, combined with measurements of the degree of sealing achieved. Savings are predicted due to both reduced fan energy required to deliver air to the registers, and to the elimination of loss of conditioned air.

SITE OVERVIEW

The UC Davis Art building is a 32,000 sq. ft. 3-story (plus basement) building. The building is used for a combination of offices and studios and utilizes a 100% outside air ventilation system with ducted supply and exhaust. Outdoor air is drawn into the basement, where three air handling units condition air for supply to the building. Each air handler supplies a single floor, each with three zones, for a total of 9 zones. Three exhaust units on the roof remove air from the building. The exhaust fan speeds are controlled to maintain pressure in the corridors at zero with respect to outdoor air pressure. Both supply and exhaust ductwork runs are primarily in corridors and plenum space and run in and out of conditioned spaces.

DEMONSTRATION SAVINGS

Peak Savings	19%
Total Conditioned Energy & Co_2 Savings	19%
Energy Reduction	42,085 kWh/yr
Heating Energy Reduction	3,651 Therms/yr
Lifetime Energy Cost Savings	$113,060* (*for 20 yr life)

Pre-install testing and recording of flow rates from each of the registers in the building

Download the full report » ***http://bit.ly/SPEEDaeroseal***

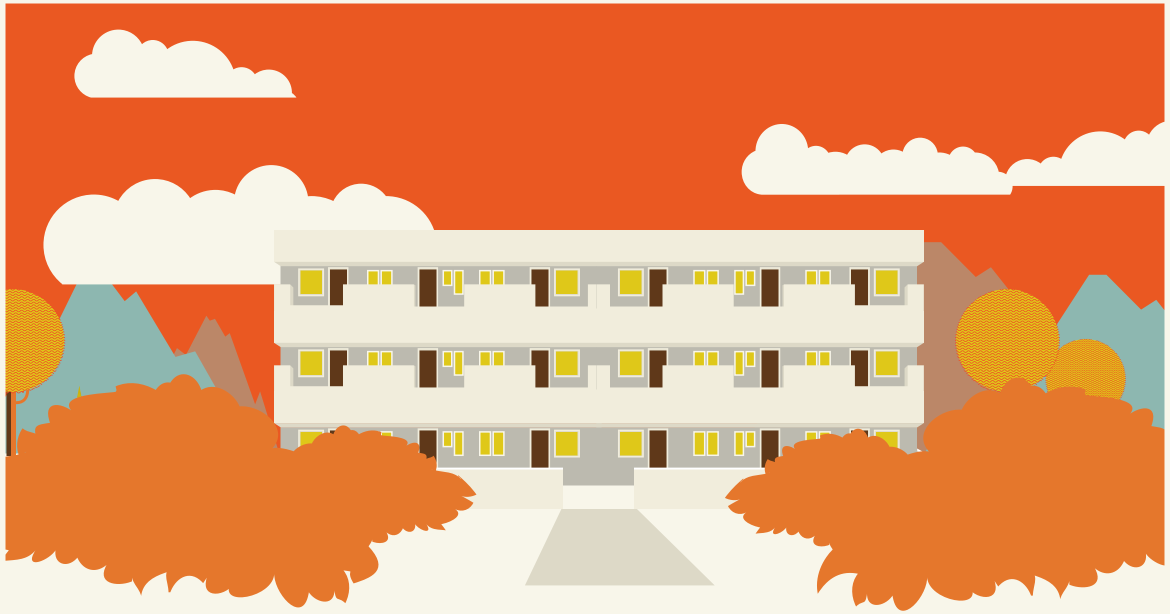
BEHAVIORAL RESEARCH: COMPARATIVE COOLING STRATEGIES IN JAPAN AND THE US

The typical US household uses two to four times as much electricity as a typical Japanese household. Although household sizes (number of people) are the same, American homes have 3 times the floor area, per person (see the graph below for an illustration). Despite greater consumption levels, spending on electricity and gas represents only 3.5% of American household expenditures, compared to 4.7% among Japanese. Energy prices bely the trend in consumption. While prices rose in the US, consumption rose, too. Concerns about climate change have policy makers searching for ways to encourage conservation.

Developing zero-net energy (ZNE) buildings is a growing trend that relies on on-site generation with (primarily) renewable resources and delivers energy savings by ensuring efficient design, effectively bypassing much of the behavioral challenges traditional construction faces to overcome weak building envelopes, little opportunities for passive lighting, heating or cooling. California is the national leader in adopting ZNE goals: by 2020 all new residential construction must be ZNE.

The Western Cooling Efficiency Center has been asked by Tokyo Gas to study energy use in their ZNE apartment building in Yokohama, Japan (named E-Sogo) and a large, mixed-use ZNE complex in Davis, CA (named West Village). Although West Village residents consume far more energy than those in E-Sogo, both communities have wide variation in consumption across apartments, with high users consuming approximately 10 times more energy than low users. In both cases, ZNE goals have not quite been met, and efforts to encourage efficiency and conservation have been ongoing.

WCEC BEHAVIORAL SIGN USED IN THE WEST VILLAGE BEHAVIORAL INTERVENTION RESEARCH PROJECT.



E-SOGO: YOKOHAMA, JAPAN

Research at the E-Sogo apartments in Yokohama centered on a pilot intervention to encourage reduction in air conditioner use. The intervention included such behavioral tactics as consumption feedback, positive reinforcement of improvements made, asking for a commitment to make behavioral changes, setting targets and goals, and establishing norms by making comparisons with other units. Although the apartments at E-Sogo are already very efficient and the users operate their systems in a very efficient manner, most were able to achieve additional savings.

For those units that had used almost no cooling energy the previous summer, we conducted interviews to identify how they managed it. We found that these occupants successfully implemented coping strategies (such as use of sophisticated floor fans, personal cooling accessories like ice pillows and towels, and changing activity patterns), before resorting to use of air conditioners. It was notable that uncomfortable conditions were somewhat acceptable to these residents in certain circumstances, which expanded their ability to avoid air conditioning.

WEST VILLAGE: DAVIS, CALIFORNIA

Meanwhile, at West Village, the developers have tried several strategies to reduce electricity consumption. Most recently, WCEC has implemented a pilot intervention aimed at encouraging the adoption of passive cooling techniques to reduce AC usage by utilizing the design features of the ZNE apartments to capture night breezes and precool the apartment, to avoid use of the air conditioner the next day. Through raising awareness and providing feedback on the environmental impact of their efforts, the intervention was successful in encouraging a majority of respondents to modify their cooling strategies in favor of less energy-intensive strategies, and some have committed to continue utilizing these energy savings recommendations even after the conclusion of the study.

Despite the success, numerous participants were not willing or able to significantly reduce their AC usage by utilizing alternative cooling strategies. The impediments cited included: discomfort, noise and safety concerns with opening windows, differing preferences among roommates, and lack of motivation to save energy. Although their housing style is relatively unique (i.e., modern ZNE student apartments), West Village residents are certainly not the only people who live in climate zones with great potential for passive cooling who face these challenges.

West Village

DAVIS, CALIFORNIA

Building Statistics

662 Apartments

2,000 Residents

Power Users

4.6x

The amount of A/C power used by the highest users at West Village versus the average user at West Village.

Impact of Intervention

43%

of participants used passive cooling instead of A/C more often than before. (N=7)

43%

of participants plan to continue using passive cooling in the future. (N=7)

ENERGY USE AND COSTS

Not surprisingly, given the differences in average housing size, American households (and those in the Western region, which includes California) use twice the amount of electricity as Japanese households, whether among single family homes or multi-family homes.

The cross-country differential in household electricity use has persisted for decades, as Figure 5-1 shows, although the gap is narrowing, in relative terms. It is due to the fact that electricity use has grown faster among Japanese households than American ones. From 1990 to 2009, the average amount of electricity used rose 45% in Japan, compared to 20% in the U.S.

Another factor that may contribute to higher electricity consumption among American homes, is the lower residential electricity prices they have faced, relative to their Japanese counterparts. Since 1990, American households have paid less than half what Japanese households pay per kWh, as shown in Figure 5-3. Overall, electricity prices have declined in Japan, although that trend has reversed in recent years.

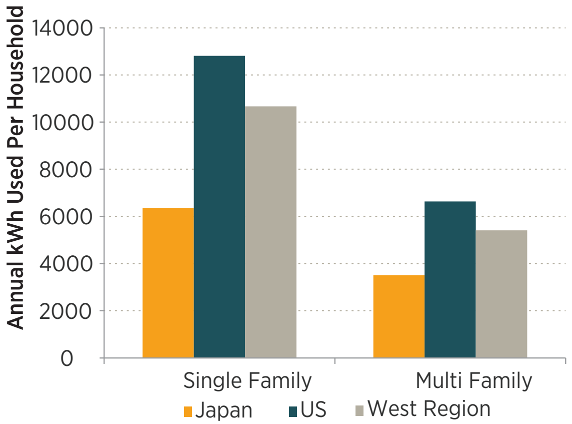


Figure 5-1: Annual kWh used per household in Japan, US and West Region

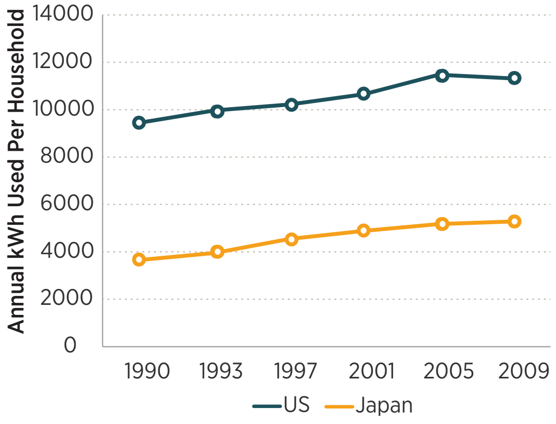


Figure 5-2: Annual kWh used in US and Japan from 1990-2009

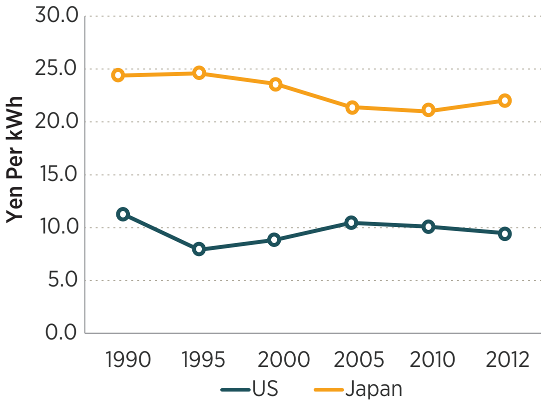
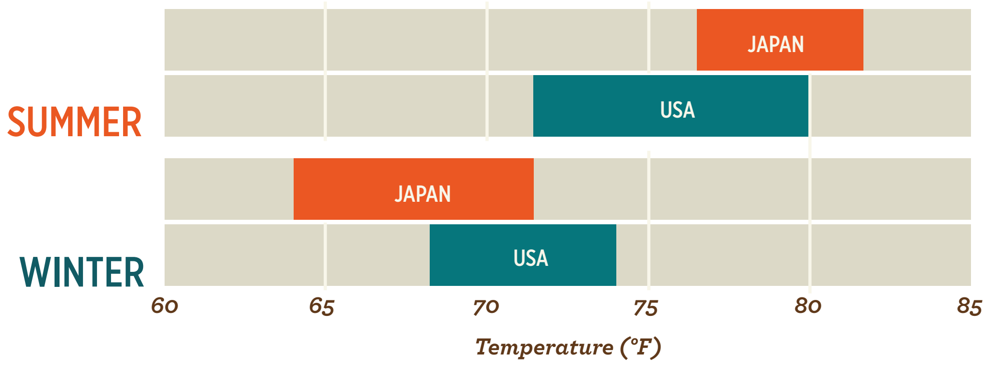


Figure 5-3: Cost of electricity for US and Japan in Yen

Cultural norms and expectations regarding thermal comfort play a key role in influencing energy consumption derived from space conditioning. In the U.S., ASHRAE Standard 55 effectively drives decisions about building materials and heating and cooling technologies, and in turn influences the norms and expectations of the acceptable range of indoor temperatures.

Figure 5-4 shows two examples of what may be considered acceptable comfort ranges in the U.S. and Japan, during summer and winter, from the sources cited below. There are two key differences to note. The first is that the comfort ranges of the two seasons overlap in the U.S., whereas they do not in Japan, suggesting the Japanese expect (or at least accept) seasonal differences in thermal comfort. The result is that the overall thermal comfort range is much narrower in the U.S. than in Japan, at least according to the particular sources cited. The second observation is that the comfort range in the U.S. is relatively cooler in the summer and warmer in the winter, relative to Japan. All else equal, this drives up energy use in the U.S., compared to a set of more conservative ranges.

Another significant difference between Japan and the U.S. is the manner in which households typically cool their homes. The predominant source of mechanical cooling in Japanese homes is room ACs (mini-split systems). In fact, by 2009, 88% of households in Japan owned one or more room AC units. In the US, central AC is the dominant (and growing) cooling technology used in both the U.S. and California. By 2009, more than 60% of American households and 40% of California households lived in homes with central AC.



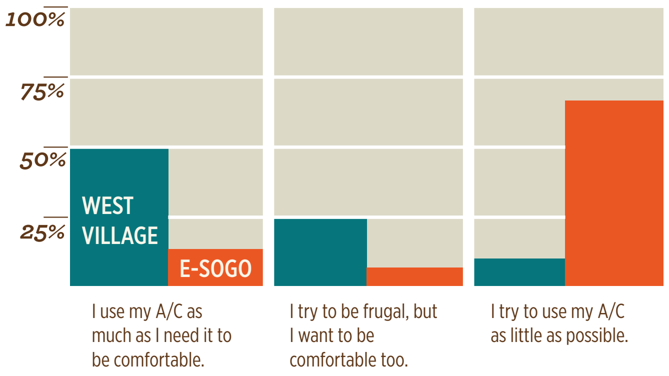


Figure 5-4: Acceptable temperature comfort range for US and Japanese citizens

E-Sogo

YOKOHAMA, JAPAN

Building Statistics

22 Apartments

65 Residents

Power Users

2.3x The amount of A/C power used by the highest users at E-Sogo versus the average user at E-Sogo.

Impact of Intervention

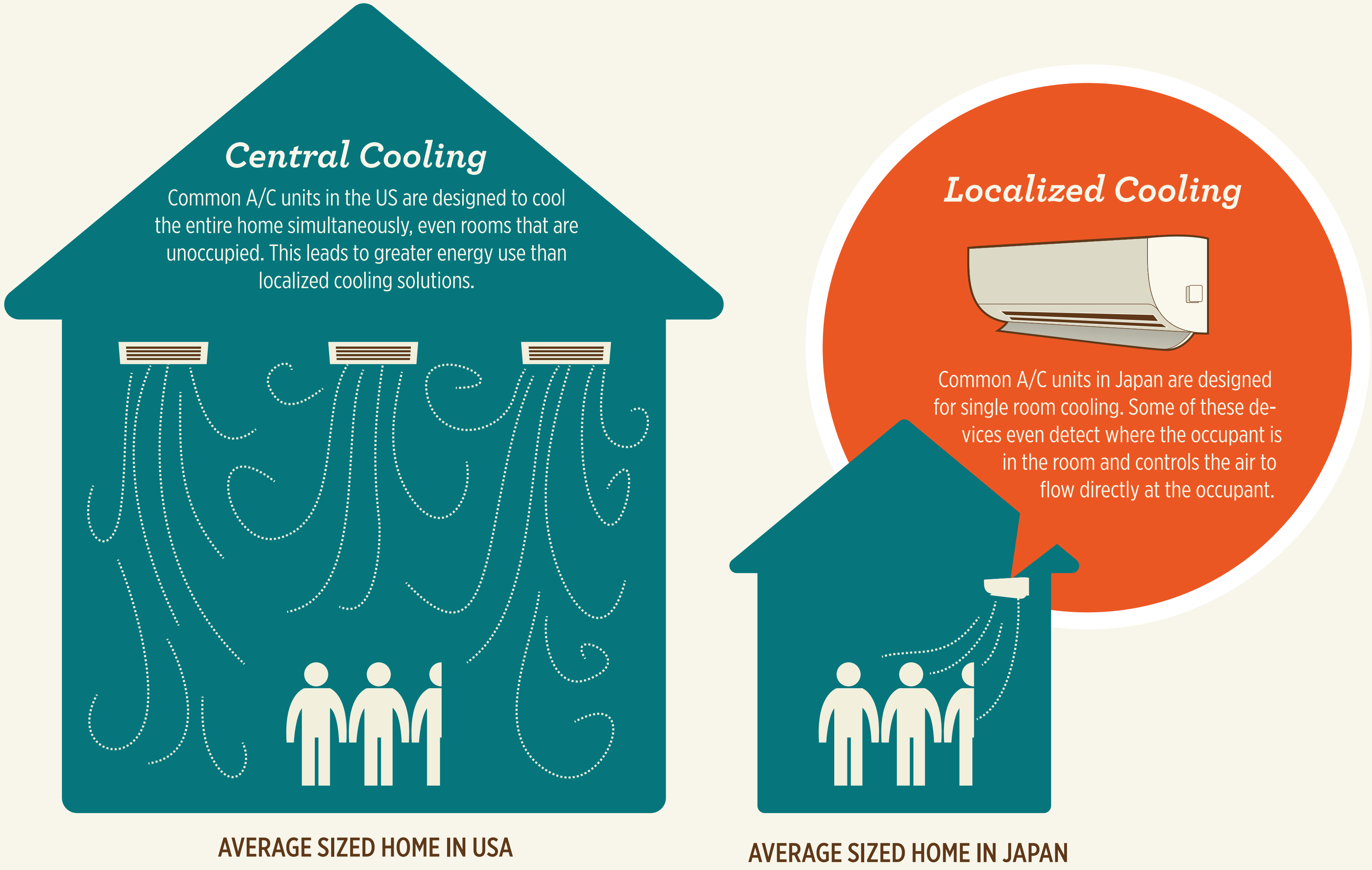
45% of participants used passive cooling instead of A/C more often than before. (N=11)

STUDY RESULTS

★ ★ ★ ★ ★

7% ENERGY SAVINGS

Housing Characteristics Matter



CONCLUSION

The 7% reduction in AC use achieved through behavioral intervention was a very positive finding of this study. Broader programs throughout Tokyo Gas territory or nationwide may be warranted. Before doing so, however, Tokyo Gas may want to evaluate and carefully design the materials used for obtaining commitments, reminders, etc. The savings was realized for a small sample of households. Pilot studies in traditional homes should be implemented to assess generalizability of results. A broader program would likely have different savings, however it is important to consider that a broader implementation could have impacts on both participants and non-participants, as it becomes more standard practice.

Challenges to encouraging conservation through passive cooling:

E-SOGO

- Discomfort with summer heat and humidity
- Few desirable alternatives to nighttime AC
- Family members have different preferences, needs

WEST VILLAGE

- Discomfort, noise and safety concerns with open windows (not a problem so much at E-Sogo, but could be for other Tokyo Gas customers)
- Design flaw: privacy trumps cross ventilation (not a problem so much at E-Sogo, but could be for other Tokyo Gas customers)
- Roommates make decisions independently, not jointly (perhaps not roommates, per se, but the extent to which decisions are made jointly or independently will certainly vary across the households of other Tokyo Gas customers)
- Use of alternative cooling strategies can be increased and AC decreased using behavioral initiatives that address/incorporate:
- Education & awareness
- Feedback
- Social norms
- Commitment
- Reminders
- Environmental altruism (intrinsic motivation)

Study results may suggest a lower bound, given that most Americans pay for electricity (and WV residents that have moved out have adopted passive cooling more frequently) and many Japanese are more cost conscious than E-Sogo residents, on average.

WCEC STUDENT RESEARCHER, STEPHEN MARCOTT WORKS ON A VENTILATION FAN FOR THE MULTI-FAMILY VENTILATION PROJECT.

MULTI-FAMILY VENTILATION

The multifamily ventilation project funded by the California Energy Commission (CEC) was completed this year. The ultimate goal of this project was to propose changes to current California ventilation codes to address issues with ventilation in multifamily buildings. The project used a characterization effort followed by modeling and a field demonstration to determine the most appropriate methods that can be codified to improve ventilation in multifamily buildings. The following is a description of the suggested changes to Title 24 proposed by the WCEC.

OVERVIEW OF PROPOSED CODE CHANGES

The following code change proposals are a result of research conducted for the Unique Multifamily Code Relevant Measures (UMCRM) PIER project. The ventilation component of this research evaluated:

- » Current California code requirements for indoor air quality ventilation of multifamily buildings[1];
- » Existing California multifamily building stock, construction practices, and ventilation systems;
- » Modeled energy use and airflow of individual unit vs central shaft exhaust systems; and
- » Measured energy use and ventilation airflow from field retrofits of one high-rise multifamily building with central shaft exhaust ventilation systems.

This final report proposes changes to the 2016 California Title 24 Building Energy Efficiency Standards regarding indoor air quality ventilation of multifamily buildings. In summary, we recommend (a) unifying all multifamily residential ventilation requirements by extending current requirements for new low-rise multifamily buildings to new high-rise multifamily buildings, and (b) for high-rise multifamily buildings that use central shaft ventilation systems, two new requirements that are necessary to ensure that these systems perform as energy efficiently as possible and do not under- or over-ventilate homes.

The 2008 Title 24 Part 6 residential standards began requiring mechanical ventilation of new low-rise homes by incorporating most of the requirements of ASHRAE Standard 62.2-2007—V*entilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.*[2]

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[1] "Indoor air quality" ventilation is distinct from ventilation of unoccupied spaces such as attics and crawlspaces.
[2] ASHRAE is the American Society of Heating, Refrigerating, and Air Conditioning Engineers.
[3] CEC. 2010. ASHRAE Standard 62.2-2010 – Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.

The 2013 residential standards reference a version of Standard 62.2-2010 that for the first time specifically addresses multifamily buildings—particularly the need for “compartmentalization” or air-sealing between homes in low-rise multifamily buildings to limit the transfer of potentially polluted indoor air between attached homes.[3]

Meanwhile, the ventilation and indoor air quality needs of apartment/homes in high-rise multifamily buildings--which are much more similar to the needs of homes in low-rise multifamily buildings than to any nonresidential occupancy--have been long neglected. High-rise residential buildings in California are covered by Title 24 nonresidential standards, which do not clearly or adequately address those needs.

In addition to extending low-rise residential ventilation requirements to high-rise residential buildings, we also propose new requirements for improving the energy efficiency and ventilation performance of high-rise residential buildings that use central shaft ventilation instead of a separate ventilation system for each apartment. Unless these vertical ventilation shafts are well-sealed to minimize air leakage, and the ducts connecting each apartment to the central ventilation shaft have dampers that automatically maintain a constant airflow, the rooftop ventilation fans at the top of each central shaft waste significant energy, and apartments tend to be over- or under-ventilated during most of the year.

DESCRIPTION OF PROPOSED CODE CHANGES

The proposed code changes will reduce space heating, air conditioning, and ventilation fan energy use; improve ventilation consistency and indoor air quality, and clarify ventilation requirements for high-rise multifamily buildings. The change will affect both residential and nonresidential sections of Title 24.

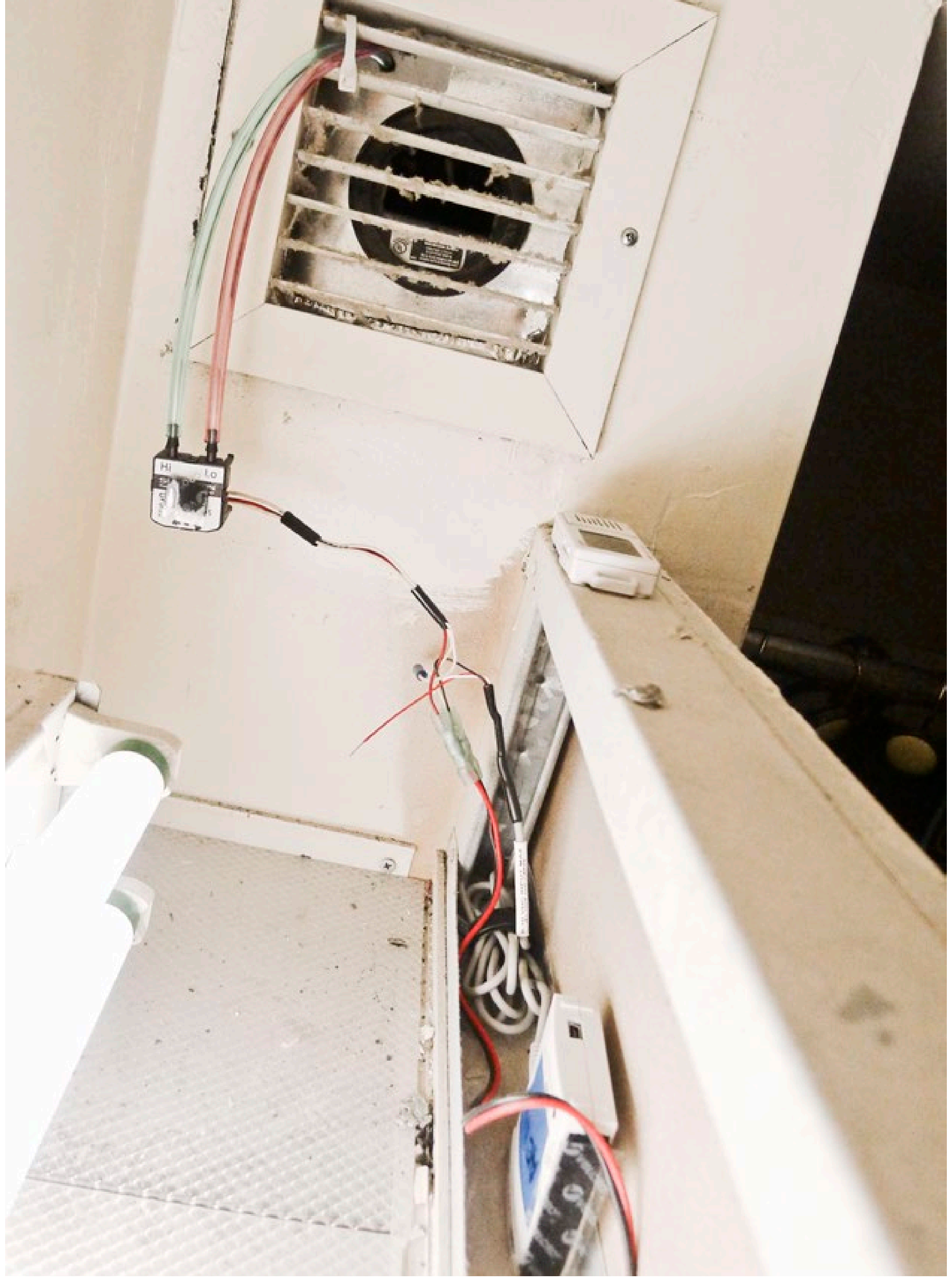
The key aspects of the proposed code changes are:

1) Extending low-rise multifamily ventilation requirements to high-rise multifamily buildings. This single change includes:

- Requiring mechanical ventilation of homes in high-rise multifamily buildings,
- Reducing current high-rise ventilation rates to match low-rise ventilation rates, and
- Limiting indoor air transfer between homes in high-rise multifamily buildings.

2) Requiring that high-rise multifamily buildings that use central ventilation shafts:

- Seal central ventilation shaft leakage to no more than 5% of total rooftop fan flow, and
- Install self-balancing dampers in the ventilation grille of each apartment.



Requirements for ventilation of multifamily buildings in California are currently based on two distinct sets of Title 24 codes: high-rise multifamily is covered by the nonresidential standards and low-rise multifamily is covered by the residential standards. Without any clear technical rationale for having two significantly different sets of ventilation requirements for occupancies with identical use patterns, we propose to use the most appropriate set of ventilation requirements to address all multifamily buildings.

We propose extending low-rise residential ventilation requirements to high-rise multifamily buildings in California. This proposed change is necessary because current Title 24 requirements for ventilation of high-rise residential buildings are unclear, out-of-date, and inadequate to ensure both energy efficiency and a consistent supply of outdoor air in high-rise multifamily apartment/homes. That this change is also prudent is evidenced by ASHRAE's 2014 decision to extend Standard 62.2 residential ventilation requirements to high-rise residential buildings on a national level.[4] By unifying low- and high-rise multifamily ventilation requirements in the 2016 code, California will not only be aligned with national energy code trends, but will also be taking a significant step toward enabling all new multifamily buildings to become zero net energy (ZNE) as soon as possible.

The other proposed code change is necessary to ensure the energy efficiency of central shaft ventilation systems, which are sometimes used in high-rise residential buildings instead of installing a separate "individual unit" ventilation system in each apartment. Central shaft systems use a rooftop fan to ventilate several apartments at once. Each rooftop fan sits at the top of a large vertical sheet metal shaft, which connects to individual apartments by smaller horizontal ducts that end at the ventilation grille in each apartment/home. Each high-rise building typically has several central ventilation shafts, each serving at least one apartment on each floor. The rooftop exhaust fans operate continuously to draw air from each home, which is replaced by air being pulled into the home from "outside" areas.

[4] *Bruce Wilcox. Feb 2014. Personal communication with Judy Roberson.*

Central shaft ventilation systems are prone to two major problems that impact energy efficiency and indoor air quality. The first problem is basically duct leakage on a large scale, as leaks in the central shafts compromise energy efficiency by introducing excess air from spaces other than the apartments. Our literature review and field measurements indicate that central shaft leakage is often 25% or more of total fan flow. Limiting central shaft leakage to 5% of fan flow will reduce this performance penalty. The energy and airflow modeling conducted for this project confirm that unless central shafts are sealed to ≤ 5% leakage, rooftop fans must move significantly more air--and use significantly more energy--in order to ensure at least the minimum ventilation rate in every apartment served by the central shaft system.

The second issue affecting the performance of central shaft ventilation systems in high-rise buildings is stack effect--a natural force that generates pressure and drives vertical airflow in buildings in response to indoor-outdoor temperature differences. The taller the building, the greater the stack effect, which is also stronger in winter when outdoor temperatures are lower and excess outdoor air is to be avoided. Stack effect drives infiltration and exfiltration, and causes apartments on the lowest floors to be under-ventilated while apartments on the highest floors are chronically over-ventilated. Central shaft systems facilitate the stack effect by providing vertical "chimneys" that enable vertical airflow and contribute to inconsistent ventilation rates among apartments on different floors of the same high-rise building.

To mitigate this problem, we propose that the 2016 energy code require self-balancing dampers in the ventilation grille of each apartment served by a central shaft system. These dampers maintain a constant, factory-calibrated airflow (e.g., 30 cfm) through a duct whenever the pressure across the duct is within a given range, such as 0.2 to 0.8 inches water gauge, which is 50-200 Pascals. The energy and airflow modeling and field measurements previously reported for this project confirm that--in conjunction with sealing central shafts to ≤ 5% leakage—these self-balancing dampers ensure that:

» Each apartment receives an adequate amount of ventilation,
» Ventilation rates among apartments in the same building are more consistent, and
» Rooftop ventilation fans use no more energy than needed to provide adequate ventilation.

These proposed code changes would require that if a central ventilation system is used in a new high-rise multifamily building, the shaft (duct) leakage shall be no more than 5% of the total fan flow and that self-balancing dampers are installed in each apartment served by the central shaft system. These changes will help ensure that central shaft ventilation systems work as intended to improve indoor air quality in high-rise multifamily apartments without wasting rooftop ventilation fan energy.

TYPE OF CHANGES

The proposed measures would introduce new mandatory measures for ventilation of California high-rise residential buildings. They would require high-rise residential buildings to be included in the language in Section 150(o) *Ventilation for Indoor Air Quality* of Part 6 of Title 24, and that a sub-section be added to describe new mandatory measures for central shaft ventilation. Language would also need to be added to Section 4.6 *Indoor Air Quality and Mechanical Ventilation* of the Residential Compliance Manual. We recommend that these new measures not be prescriptive, because their absence would significantly and negatively affect high-rise multifamily indoor air quality and ventilation system energy performance.

ENERGY BENEFITS

These proposed code changes to multifamily ventilation would result in significant energy savings for high-rise multifamily buildings across multiple California climate zones (CZs). Yearly savings estimates in Figures 6-1-6-3 below are based on a 30-year life cycle, an EnergyPlus model of a six-story multifamily building (described in previous reports for this project) in California's three most populous climate zones. TDV values weight energy savings according to its availability and cost each hour of the year.

NON-ENERGY BENEFITS

The proposed code changes would also yield the indoor air quality benefits of improved reliability and consistency of ventilation rates in apartment/homes in high-rise multifamily buildings. Extending low-rise ventilation requirements to high-rise buildings will ensure reliable mechanical ventilation, and the requirement for compartmentalization of attached multifamily dwellings will limit transfer of polluted indoor air—which often includes tobacco smoke, cooking odors and excess moisture--between homes.

High-rise multifamily buildings with central shaft ventilation systems will also experience improved indoor air quality, occupant comfort and satisfaction as a result of more consistent ventilation rates among homes on different floors. This in turn will translate into reduced occupant turnover rates.

Another invaluable non-energy benefit of adopting these code change proposals is the positive impact on the multifamily building design and construction community as a result of clarifying and unifying ventilation requirements for low- and high-rise multifamily buildings. Designers and contractors will save time by meeting one set of requirements, and compliance with the energy code should also improve.

FIGURE 6-1: ENERGY AND TDV SAVINGS DUE TO ADOPTING CODE CHANGES IN CZ 3 (SAN FRANCISCO BAY AREA)

Climate Zone 3	Electricity Savings (kWh/yr)	Natural Gas Savings (Therms/yr)	TDV Electricity Savings (TDV kBtu)	TDV Gas Savings (TDV kBtu)	TDV Net Savings (TDV kBtu)
Per six-story multifamily building	-689	1,749	-31,981	88,881	56,900
Per square foot	-0.024	0.061	-1.110	3.086	1.976

FIGURE 6-2: ENERGY AND TDV SAVINGS DUE TO ADOPTING PROPOSED CODE CHANGES IN CZ 8 (LOS ANGELES AREA)

Climate Zone 8	Electricity Savings (kWh/yr)	Natural Gas Savings (Therms/yr)	TDV Electricity Savings (TDV kBtu)	TDV Gas Savings (TDV kBtu)	TDV Net Savings (TDV kBtu)
Per six-story multifamily building	-1,050	816	-30,263	42,944	12,681
Per square foot	-0.036	0.028	-1.051	1.491	0.440

FIGURE 6-3: ENERGY AND TDV SAVINGS DUE TO ADOPTING CODE CHANGES IN CZ 12 (SACRAMENTO AREA)

Climate Zone 12	Electricity Savings (kWh/yr)	Natural Gas Savings (Therms/yr)	TDV Electricity Savings (TDV kBtu)	TDV Gas Savings (TDV kBtu)	TDV Net Savings (TDV kBtu)
Per six-story multifamily building	-114	2,048	1,568	106,608	108,176
Per square foot	-0.004	0.071	0.054	3.702	3.756

TECHNOLOGY MEASURES

The technology associated with our proposed changes to multifamily ventilation requirements involve:

- Mechanical ventilation systems in high-rise residential buildings,
- Automatic (as well as manual) duct sealing methods, and
- Self-balancing airflow dampers.

All of these technologies are readily available and already in use in high-rise multifamily buildings.

Standard 62.2-2010 includes a compartmentalization requirement for attached homes. Envelope air sealing requires training and skill but no particular technology. However, the best practice for verifying that envelope leakage does not exceed 0.2 CFM50/ft2 envelope area is to blower door test at least a sample of homes in each multifamily building. While there are several "advanced" blower door testing methods in use for multifamily buildings, there is currently no standard ASTM method for this purpose.

MEASURE AVAILABILITY

Requiring mechanical ventilation of homes in high-rise buildings will not be constrained by a lack of suitable ventilation equipment. Many high-rise multifamily buildings already provide mechanical ventilation to each home, using either individual unit or shared central shaft ventilation systems. If anything, the clarified requirements for mechanical ventilation of homes in high-rise multifamily buildings will spur innovative new strategies for optimizing indoor air quality and energy efficiency. For example, our survey of multifamily building professionals and ventilation experts for this project found an interest in using more effective supply ventilation strategies, as an alternative to exhaust ventilation.

Methods for sealing ductwork to reduce air leakage and energy waste have evolved in recent years. Automated duct sealing technologies have yielded excellent results in both new construction and retrofit projects, and are particularly suited to larger buildings, and whenever manual duct sealing is difficult or impossible because of the inability to physically access ductwork. For the field retrofit component of this research project we used an aerosol duct sealing technology to rapidly seal and monitor the level of sealing existing central shaft ductwork that could not be manually sealed.

"Self-balancing dampers" is a generic term for factory-calibrated devices that are designed to be installed between two sections of ductwork for the purpose of maintaining a consistent airflow through the duct. Depending on the manufacturer, these dampers are either passive devices that require no power or electronic controls, or active devices that electronically control airflow based on feedback from sensors. They are used to control airflow rates at the ventilation grille of apartments connected to a central shaft ventilation system, and have been used successfully to improve the ventilation consistency and energy efficiency of high-rise multifamily buildings in other parts of this country. Those most commonly used in residential buildings are American Aldes passive Constant Airflow Regulators (CAR-II). For higher airflows, Trox makes passive or active Volume Flow Limiters (VFL), and Belimo offers active Pressure Independent Valves (PIV).

PERFORMANCE VERIFICATION

The 2013 residential energy code requires third-party HERS verification that minimum required airflow is delivered by whole-home ventilation systems in low-rise buildings. Adopting these 2016 code change proposals would extend these HERS verification requirements to ventilation systems in high-rise multifamily buildings. This process will be similar to that described in the Reference Residential Appendix section RA3.7—*Field Verification and Diagnostic Testing of Mechanical Ventilation Systems*, with the potential provision that an approved sampling process could be used to verify a portion of systems in the same large multifamily building.

Just as HERS verification is also required for duct leakage in low-rise homes, HERS verification should be required for leakage of central shaft ventilation systems in high-rise residential buildings. The process would be similar to that laid out in the Reference Residential Appendix section RA3.1—*Field Verification and Diagnostic Testing of Air Distribution Systems*. The language may need to be modified slightly for distribution systems in high-rise attached homes.

Standard 62.2-2010 states that one way to verify compliance with its compartmentalization requirement for multifamily homes is to use a blower door to confirm ≤ 0.2 cfm50 per square foot of total envelope area. Blower door testing is currently the only way to measure

These new, clarified requirements for mechanical ventilation of homes in high-rise multifamily buildings will spur innovative new strategies for optimizing indoor air quality and energy efficiency.

envelope leakage, but blower door tests are more challenging in attached multifamily homes than in single-family homes, for several reasons.

HERS verification should be required to confirm the multifamily compartmentalization requirement is met, and a sampling method is appropriate to avoid testing every unit in larger multifamily buildings. The process for demonstrating compliance with envelope tightness requirements is to conduct blower door tests in accordance with ANSI/ASTM-E779-03, *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*, or ANSI/ASTM-E1827 *Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door.*

ESTIMATED COST OF PROPOSED MEASURES

Our survey of current high-rise multifamily building HVAC practices indicated that most of these buildings in California already use mechanical ventilation systems. This is likely the result of the difficulty of adequately and consistently ventilating high-rise apartments without using mechanical ventilation. For that reason, the information in Figure 6-4 is based on the assumption that high-rise residential buildings already include mechanical ventilation, and there is no additional cost for its installation.

FIGURE 6-4: ESTIMATED COST OF APPLYING PROPOSED CODE CHANGES IN HIGH-RISE MULTIFAMILY BUILDINGS.

Proposed Measure	Impact	Estimated Cost		
		Labor and Materials		Testing
Extend low-rise mechanical ventilation and rate requirements to high-rise multifamily buildings	Require mechanical ventilation of high-rise multi-family buildings, and reduce minimum ventilation rates	N/A[5]		HERS verification
Compartmentalize high-rise multifamily dwellings to ≤ 0.2 CFM50/ft² of envelope area	Reduce transfer of indoor air between attached homes in high-rise multifamily buildings	1 bed, 800 ft²	$400[6]	$25[7]
		2 bed 1,100 ft²	$500	$25
		3 bed 1,500 ft²	$600	$25
Require self-balancing dampers in apartments served by central shaft ventilation	Improve consistency of ventilation rates among apartments on different floors of the building	$85 per unit[8]		N/A
Require sealing of central shaft ventilation ducts to 5% or less of total rooftop ventilation fan flow	Reduce HVAC energy use of buildings with central shaft ventilation systems	$35 per unit[9]		$50 per unit[10]

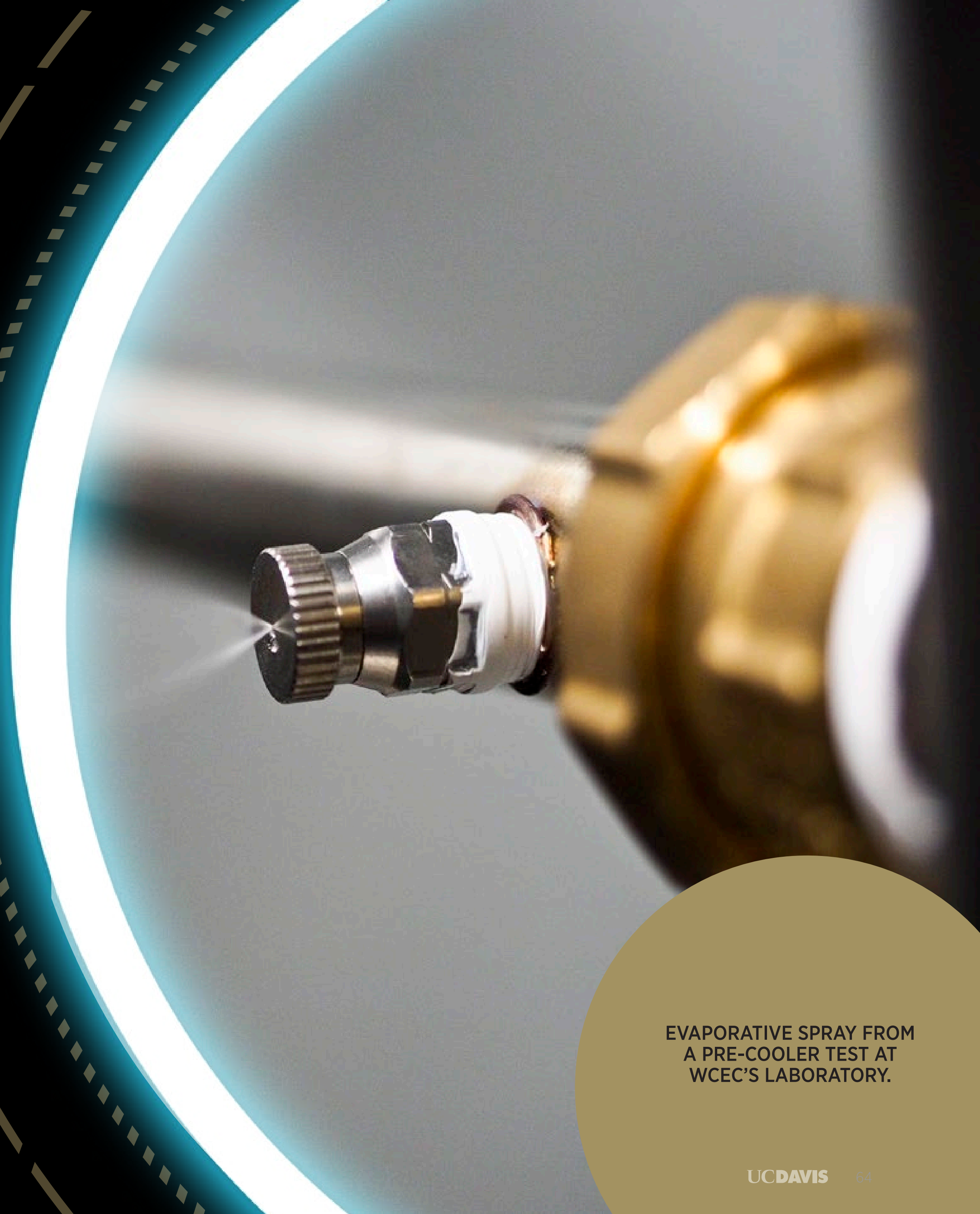
[5] Assuming the incremental cost of installing smaller ventilation fans is negligible.
[6] Assuming a labor rate of $70/hr and a 20% markup on labor and materials, the cost was estimated by the number of hours required to seal penetrations in a typical apartment.
[7] Assuming each apartment contributes 10% of the cost of a blower door envelope leakage test.
[8] Based on the cost of installing one CAR-II damper in an apartment.
[9] Based on the cost to manually seal a duct rise between floors assuming a riser serves one apartment per floor.
[10] Based on the distributed cost for labor required to conduct a blower door leakage test on a 10-story building.

EVAPORATIVE CONDENSER AIR PRE-COOLERS

In air conditioning systems, condensing units reject heat from refrigerant directly into the outside air stream. In these systems, higher outside air temperatures result in higher energy use by the compressors. As the outdoor air temperature rises, the efficiency of the air conditioning system drops and requires more energy to provide the same amount of cooling to the conditioned space. To compound this issue, more space cooling is necessary on days where the outdoor air temperature is higher due to the increased heat load on the building.

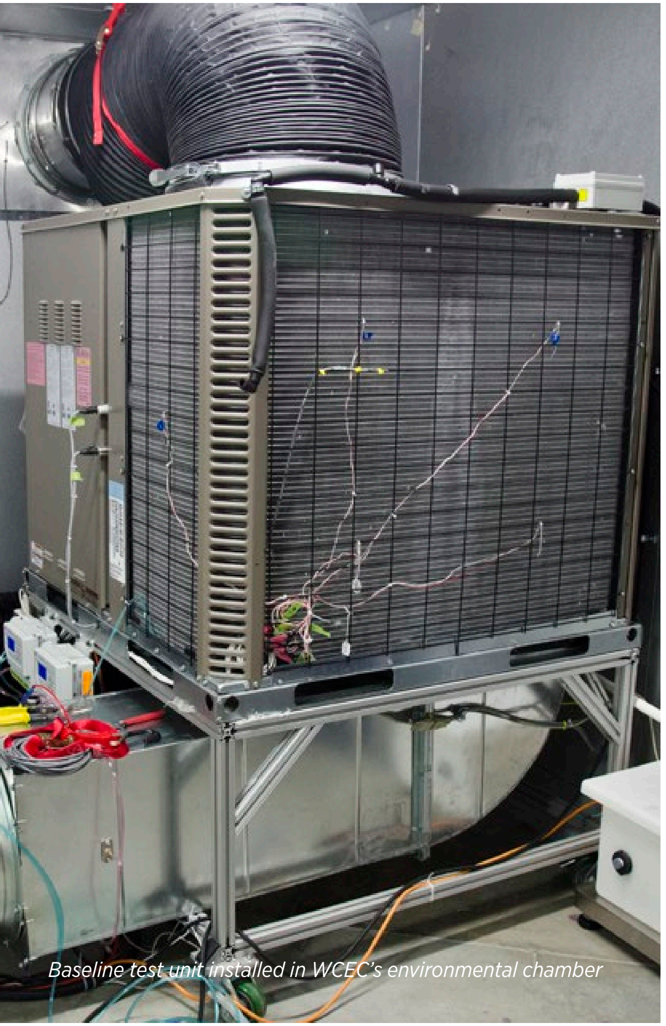
Evaporative cooling takes advantage of the potential of the outside air in dry climates to absorb moisture, which results in a temperature reduction of the air stream. When evaporative cooling is used for pre-cooling condenser inlet air, the condenser operates at a lower temperature than a baseline air-cooled condenser, and therefore less power demand and electricity is consumed to meet the cooling demand.

There are a large number of manufacturers offering evaporative pre-coolers as retrofits to existing RTUs and the methods of pre-cooling air vary greatly. The design of the pre-cooler will impact its performance and the resulting energy savings of the air conditioning system. While various field studies have been conducted, an objective laboratory test protocol is needed to quantify both the energy savings and the associated water use of the pre-cooler at controlled climate conditions.



EVAPORATIVE SPRAY FROM A PRE-COOLER TEST AT WCEC'S LABORATORY.

ESTABLISHING A BASELINE


Baseline test unit installed in WCEC's environmental chamber

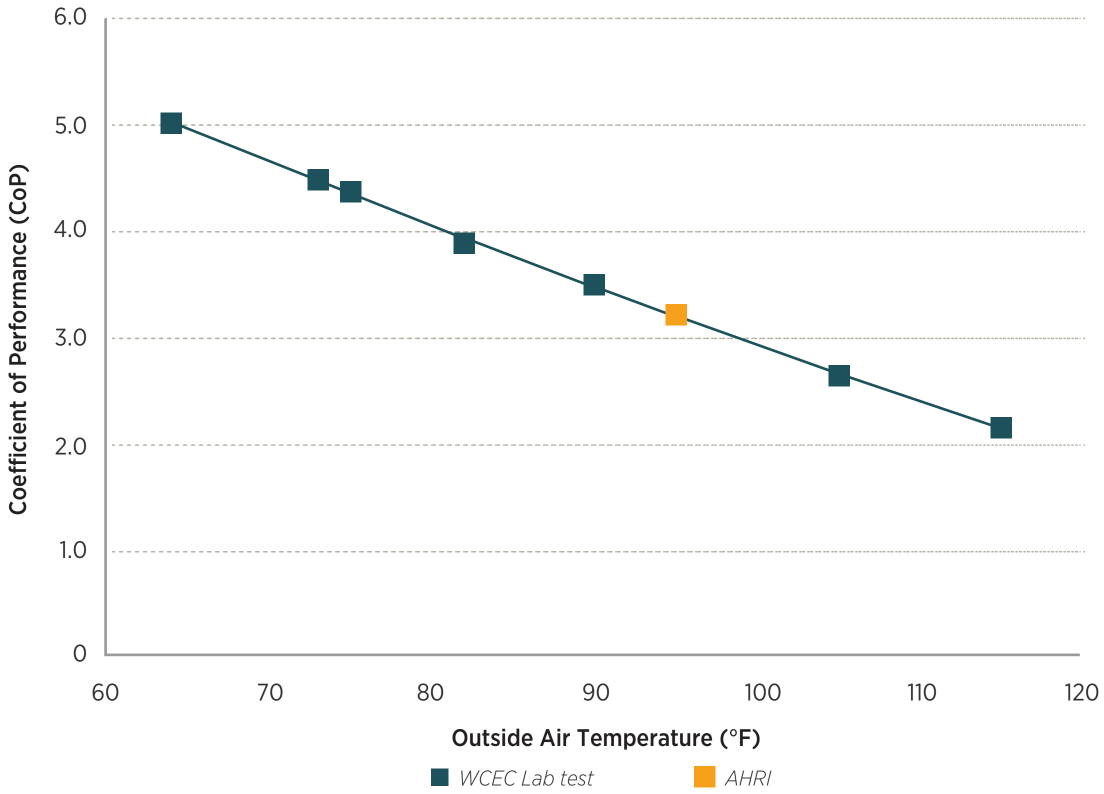


Figure 7-1: CoP trend from baseline unit testing compared to AHRI

Before testing any evaporative condenser air pre-coolers, a set of baseline tests were obtained for a 4-ton York RTU in WCEC's laboratory. The test team ran 8 baseline tests to record system efficiency and performance for a number of outdoor air dry bulb test points and an indoor air condition of 80°F/67°F dry bulb/wet bulb (DB/WB). The coefficient of performance (COP) versus outdoor air dry bulb temperature is plotted in Figure 7-1. For comparison, the COP at 95°F as measured by an Air-Conditioning, Heating, and Refrigeration Institute (AHRI) certified lab is shown in the table and plot.

TESTING THE PRE-COOLERS

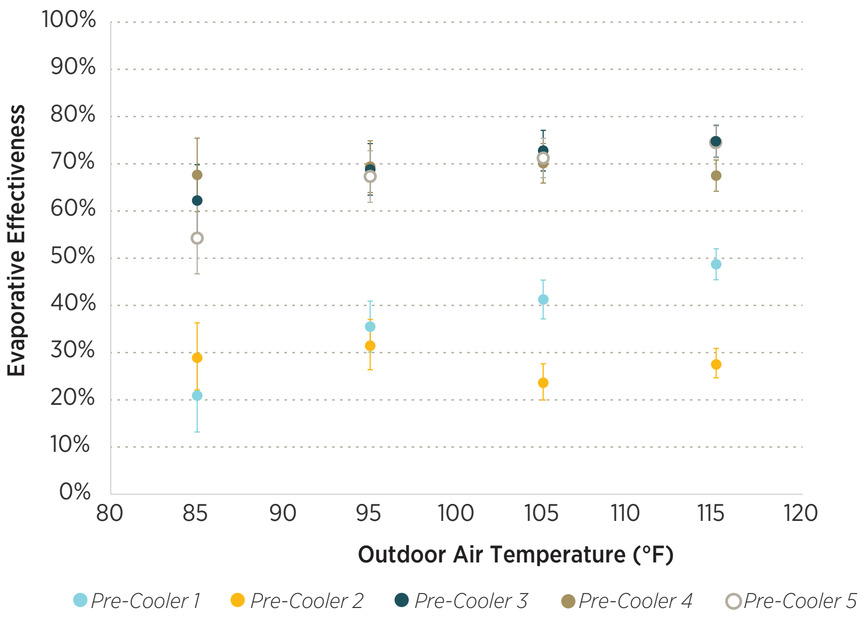


Figure 7-2: Evaporative effectiveness for all 5 tested pre-coolers

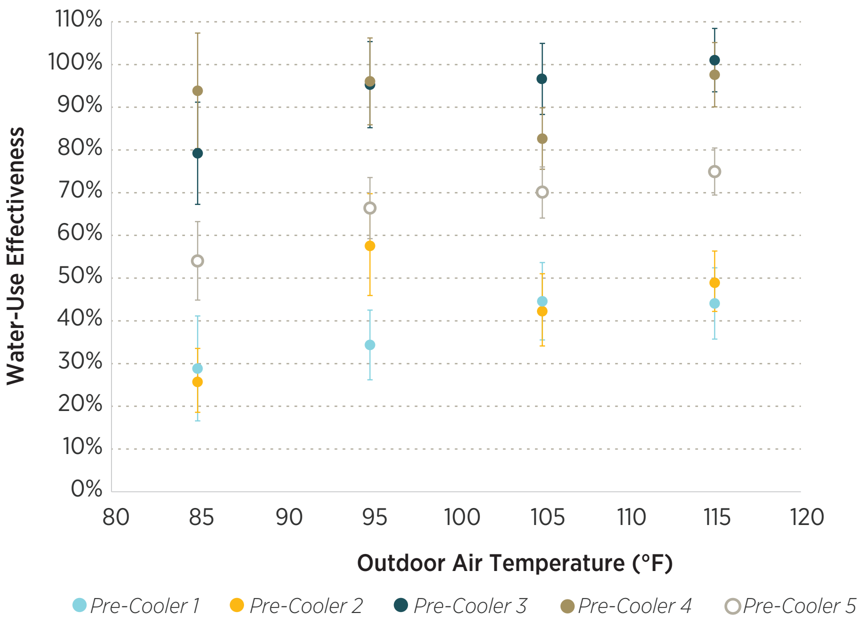


Figure 7-3: Water-use effectiveness for all 5 tested pre-coolers

EVAPORATIVE EFFECTIVENESS

Evaporative effectiveness varied for each pre-cooler technology with results ranging between 20-80% for the four constant dew point tests at outdoor air temperatures of 85-115°F (Figure 7-2). Evaporative effectiveness of pre-coolers 3, 4, and 5 were similar and, in most cases, the results clustered together within the uncertainty limits and between 60-75% evaporative effectiveness. The exceptions were that the performance of pre-cooler 4 was reduced at 115° and the performance of pre-cooler 5 was reduced at 85°F. Generally speaking, the results show that pre-coolers with significant design differences are able to achieve similar results for evaporative effectiveness. The limit for designs tested to date in all tests was 75% evaporative effectiveness.

WATER-USE EFFECTIVENESS

Water-use effectiveness was highest for pre-coolers 3 and 4, measuring between 80-100% in the four constant dew point tests at outdoor air temperatures of 85-115°F (Figure 7-3). However, pre-coolers 4 and 5 are re-circulation technologies and require a constant bleed of sump water to prevent scaling of the pre-cooler. This bleed water is not included here and may increase water use 10-50% based on manufacturer recommendations and the hardness of the water supply. Water-use effectiveness for pre-cooler 5 was in the range of 55-75%, increasing with outdoor air temperature. Pre-cooler 5 does not re-circulate water and requires no maintenance water. Water-use effectiveness measured for pre-coolers 1 and 2 was generally less than 50% and was lacking in comparison to the performance of pre-coolers 3-5.

MEASURING THE RESULTS

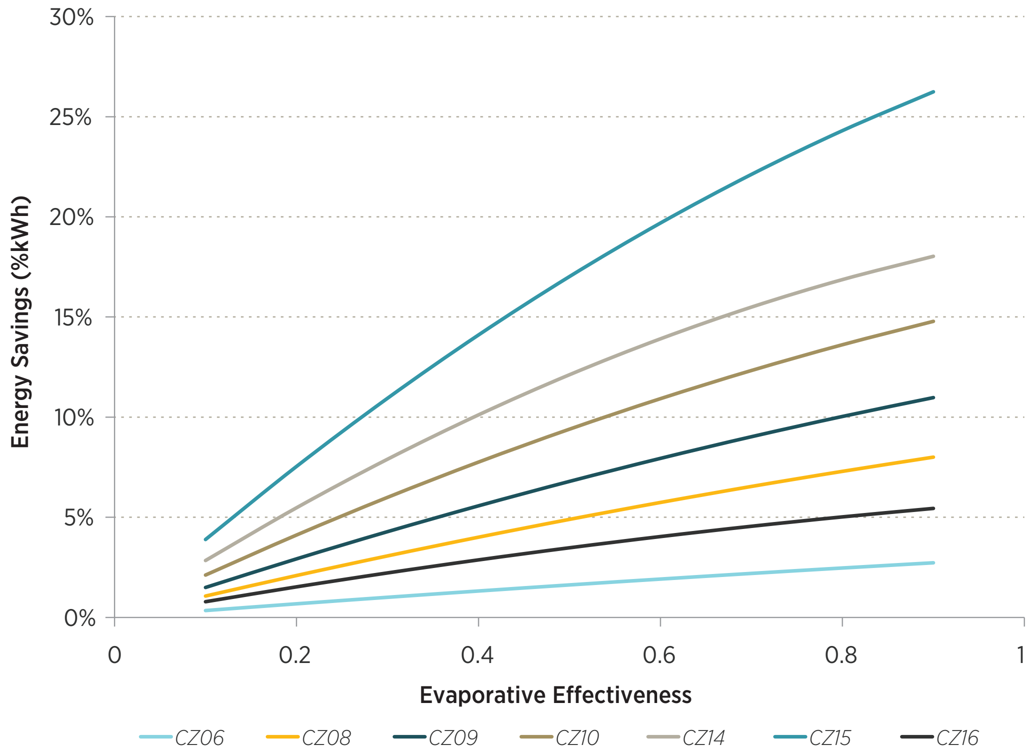


Figure 7-4: Energy savings using evaporative pre-coolers in selected climate zones

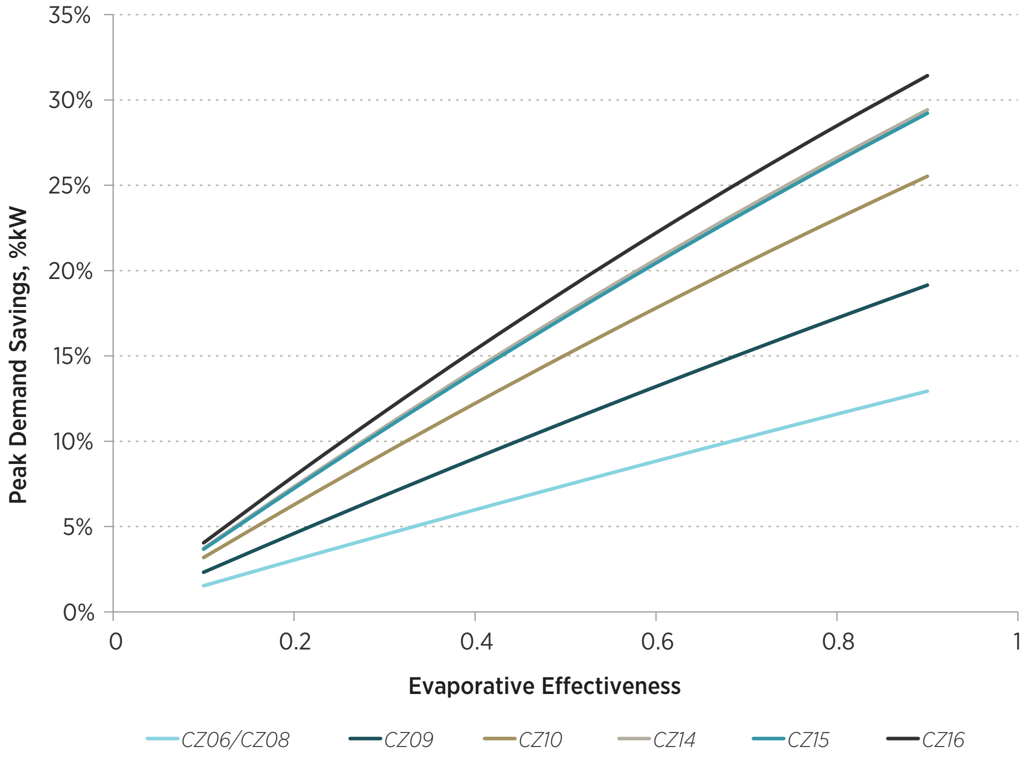


Figure 7-5: Peak demand savings using evaporative pre-coolers in selected climate zones

As shown previously in the laboratory test results, evaporative pre-coolers can consistently achieve evaporative effectiveness between 60-75%. This level of performance has a significant impact on the overall energy and peak demand savings.

The percent savings for both energy and peak demand were determined by calculating the difference between a modeled baseline RTU (using DEER) and the same RTU with pre-cooler installed. The results show that increasing evaporative effectiveness of the pre-cooler increases energy savings and that inland climate zones are expected to have higher savings than coastal climate zones. The greatest savings are expected in Climate Zone 15, with a savings of 280 kWh/ton/year for a pre-cooler will be 25% and 0.30 kW per nominal ton are calculated.

The energy savings described here are for an average RTU based on aggregate load data. An RTU with increased run time would have a greater total energy savings. If the baseline energy use of a particular RTU or building is known, pre-coolers can be strategically installed on units with high run times to increase annual energy savings. Peak demand savings are not a function of the load data and are strictly a function of modeled RTU efficiency and pre-cooler effectiveness. Since all RTUs are assumed to run during a peak event, the savings are expected for any RTU regardless of the load profile of the building.

Download the pre-cooler protocol report » ***http://bit.ly/rturetrofitprotocol***

BEHAVIORAL RESEARCH: CASE STUDIES ON ADVANCED THERMOSTAT FIELD TESTS

The technology for thermostats has changed significantly in the past decade. More advanced features such as programmability offer great potential for energy savings. But with this increased technical complexity has come a corresponding complexity in the user interface. Some manufacturers have attempted to deal with this by adopting a deployment model that transfers to the installing contractor responsibility for the initial setup and user instruction.

This study describes the use of advanced thermostats installed in three non-residential locations. A baseline survey was conducted to measure pre-installation comfort, satisfaction and usability of existing thermostats. The advanced thermostats were installed by contractors, and their usability was assessed by assigning usability tasks to end users and conducting a post-installation survey. Effects on HVAC electricity usage were estimated using SmartMeter and meteorological data collected from comparable pre- and post-installation periods.

In theory, there is great potential for energy savings from thermostats. Even inexpensive programmable ones have the potential to save 30-50% of energy use from heating, ventilation and air conditioning (HVAC) (Nguyen and Aiello, 2013; and Maheshwari et al., 2001). But actual savings falls substantially short of that, ranging from modest savings to negative energy savings (see Meier et al., 2011).

STUDY DESIGN AND OBJECTIVES

Advanced wireless thermostats promise improved programmability and control through a web portal, energy savings through better programming and remote access, and real-time and historical energy use data to facilitate better system management. The aim of the study was to empirically test those claims by field testing the thermostats at three non-residential sites.

Specifically, the primary objectives of the study were to determine whether users can engage with an advanced thermostat's interfaces as desired, and whether or not they use the thermostat features in ways that save energy. As the study progressed, the initial scope was expanded to include a preliminary assessment of the wireless thermostat deployment model and its impact on users.

The study took place in 3 non-residential buildings: a school (CA CZ 04), a restaurant (CA CZ 12) and a clubhouse (CA CZ 12). Each of these buildings had facilities managers, although the level of responsibilities and tasks of these managers differed across sites (as described below in the case studies). Because of the differences in management and use structure in the three sites, the number of study participants per site varied widely. The study initially targeted 14 users in the school (teachers and facilities manager), 1 participant in the restaurant (owner/facilities manager) and 3 participants in the clubhouse (facilities managers and operators).

Users of the advanced thermostats at the school reported a generally negative experience with usability and efficacy. As Figure 8-1 illustrates, respondents were less sure of their ability to perform basic tasks on the advanced thermostat than they were with their previous one, which was already quite low.

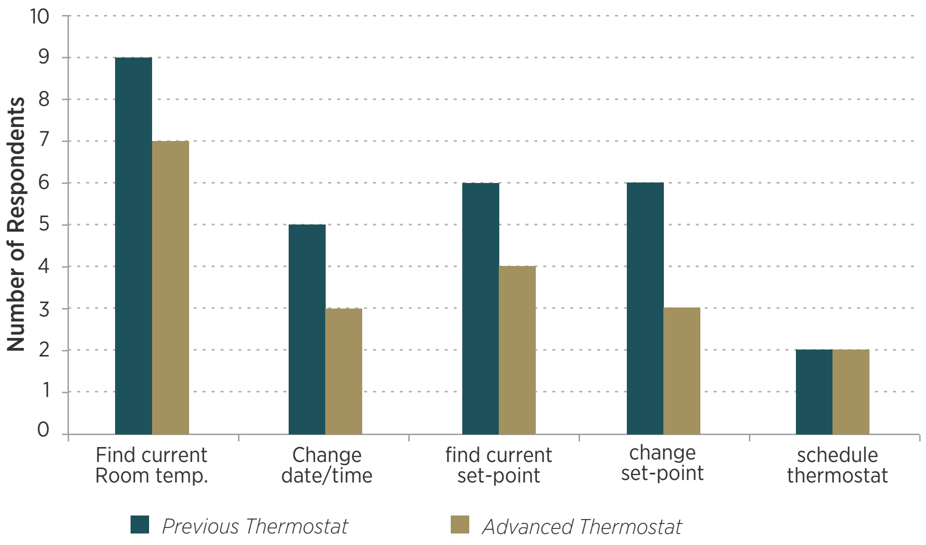


Figure 8-1: Number of respondents who were confident in their ability to perform various thermostat tasks with old versus new thermostat

USABILITY TASKS

In addition to self-reported levels of confidence, respondents were also asked to complete a set of tasks that the researchers could verify using the thermostat log data. The first set of tasks required participants to check the mode the thermostat was in, set it to HEAT (it was winter time, and it had been detected that many thermostats were on COOL mode), and check/modify the date and time. Date and time were correctly displayed in all cases. However, several participants were unsuccessful in reporting and changing the mode.

The second usability task assigned focused on online access, since this had been problematic for some users, and was required for easy access to traditionally difficult tasks, like scheduling. Even with the researchers setting up accounts for respondents, there were usability obstacles at every step of the process: login, access to relevant information, and operation. After trying to program a thermostat schedule, one user reported: “I clicked all over it, and nothing I did changed it…I thought it would be easier.” Overall, participants judged the online portal as frustrating and unappealing, and manifested little interest in accessing it or using it again.

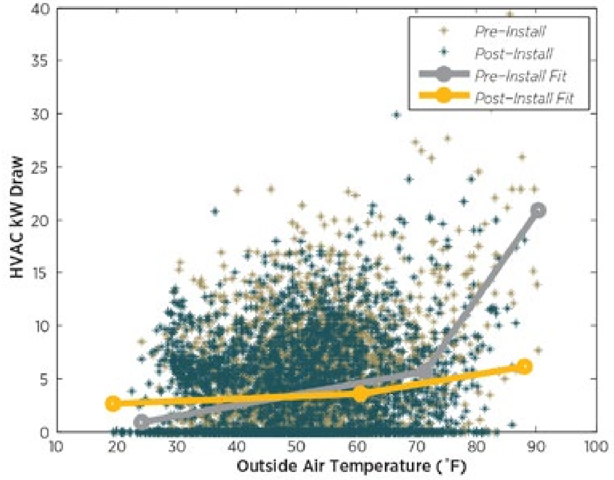
Uncertainty about their ability to accomplish basic tasks with the thermostat may have been due in large part to the fact that very few users received training or instructions on using the new thermostats. Indeed, 9 out of 10 respondents reported that there no information or training had been provided at all (i.e., no general information, personal training, hands-on training, written materials provided, or direction towards online materials). As the thermostat manufacturer designed it, this was the job of the installing contractor. In practice, however, such services were rarely, if ever, provided to the field sites.

The lack of training or instruction translated into a lack of even the most basic understanding of how the thermostat works. In a comment echoed by others, one teacher said: “[I don’t like] having people from the outside deciding what [the] temperature should be in my classroom”. This misunderstanding most likely stemmed from the expectation that the “hold” setting was indefinite, as with the previous thermostat, whereas the new ones had been programmed to either two or four-hour hold settings.

Lack of confidence in and understanding of (and possibly interest in) the new thermostats translated to lack of use of advanced features. By accessing the web portal, the researchers were able to verify that in fact none of the occupants at the school logged in to the system to set a schedule or make a change, even when they are “locked out” of the wall devices.

“How can the [new] thermostat be put back into a mode where it operates like a normal thermostat?”

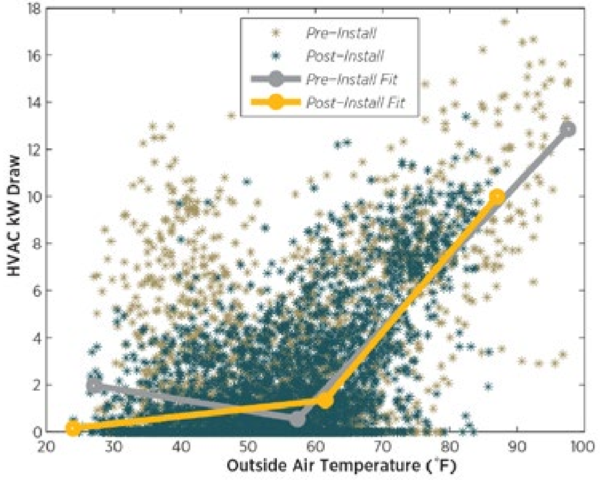
Usability experience quote from a participant after installation of the new, advanced thermostat



SCHOOL RESULTS

The regressions for the school were the worst fit of all three sites, likely attributable to the non-standard operating hours of the church portion of the facility. An attempt was made to correlate the school's event calendar with hourly power usage based on total daily 'event hours'. This appeared to show some correlation but an exact relationship could not be determined and was deemed unsuitable as a predictor of baseload power consumption. This is likely due in part to a combination of: **a)** inconsistencies between scheduled times and actual operating times of a building (i.e. rooms are often booked longer than they may actually be required) and, **b)** large variances in the power use of different types of activities (i.e. due to occupancy, ambient light, indoor vs. outdoor activities, etc.).

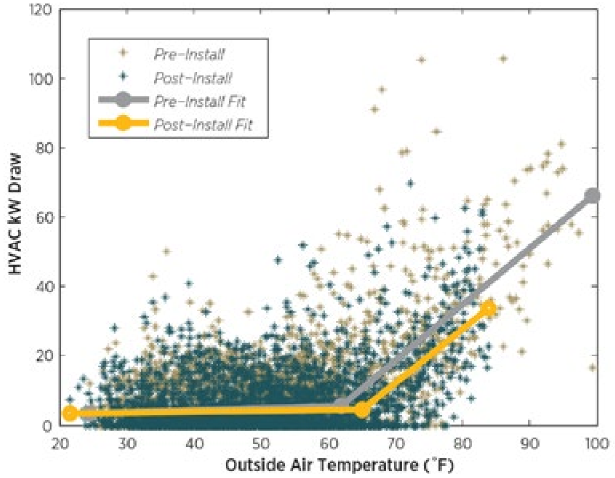
Not surprisingly, then, analysis of school's energy usage in nine classrooms yielded inconclusive results regarding energy savings, since their power consumption could not be disaggregated from that of the less predictable communal spaces.



RESTAURANT RESULTS

The restaurant experienced (negative) energy savings of -6.7% (s.e. 0.43%) of HVAC power draw per degree F (for OAT > 60.6 deg F) with the advanced thermostat.

This result highlights the fact that the energy savings a thermostat may deliver depends in large part on the baseline. In the case of the restaurant, the owner had established an appropriate schedule with his previous programmable thermostat, which had yielded energy savings over his prior system of manual operation. Despite offering remote access and the ability to create a more nuanced program (accounting for holidays, for example), the advanced thermostat performed worse than the previous, well-programmed thermostat, in terms of energy savings.



CLUBHOUSE RESULTS

the clubhouse saved 3.5% (s.e. 1.00%) of HVAC power draw per degree F (for OAT > 65.1 deg F) over the course of the study period (September 2013 to February 2014). This is largely attributable to the programmed setbacks, which eliminated accidental heating and cooling after hours, although that was not empirically proven. The setbacks were scheduled upon installation and were rarely, if ever, overridden.

USABILITY

Evidence from the, admittedly limited, field tests, suggests that the advanced thermostats posed substantial usability issues for many respondents. The interface on the device itself was not user friendly, and the web interface was difficult to access and not intuitive to navigate. The level of frustration that the occupants experienced, especially at the school, was a surprise. The researchers concluded that the design of the thermostat, which did not provide much information to the user about why it was in the mode it was in, was confusing and frustrating. It is likely that some of these issues would have been ameliorated if end users had been given instructions on how to use the thermostats. None of the respondents at the three test sites received training or instruction, indicating a problem with the deployment model which leaves the provision of this essential service entirely up to the installing contractor's discretion.

ENERGY SAVINGS

Energy savings at the three field sites ranged from modestly positive to negative. The small, non-random sample does not allow for generalization of results, but does indicate that there are certainly many non-residential users for whom the advanced thermostat would not save substantial amounts of energy. It depends enormously on the baseline. Furthermore, evidence from the field tests suggests that the one field site that did garner energy savings did so through the initial programming of the thermostat, not the advanced features. Similar results could have been achieved with a much cheaper thermostat programmed properly.

DEPLOYMENT MODEL

The advanced thermostat's deployment, installation and service was full of challenges that highlight the relevance of its service and business model in addition to its technological features. The thermostats were selected by the research team, installed by a contractor selected by the utility, and used by test subjects who had little control over what was happening to them (or at least felt so). Installation did not include troubleshooting of communication issues, and problems in this area did occur when the users attempted to use the web portal. After installation, when the users encountered difficulties, they did not know who to call: their building facilities manager? the contractor? the thermostat manufacturer? The manufacturer had no on-site support capabilities, and was not able to be of much help. Contractors did not have the motivation (or responsibility) to return to the site to address issues such as Wi-Fi malfunctions and missing usernames on the website.

In some cases, the contractor was set up with a "Super User" access to the thermostat, to facilitate support. End user autonomy was not the focus. End users were given no training, instructions, or materials (such as a manual) by their installing contractor. The vast majority of end users never accessed the web portal. End users in the school (a larger organization) were extremely confused about who was controlling their thermostat, and who should be controlling their thermostat. Utilities considering a broader installation of smart thermostats in a program should consider the (significant) support requirements.

ROLE OF CONTRACTOR

The deployment model, in which the thermostat communicates back to the contractor or service provider, implies that this choice of thermostat is made to facilitate use by the contractor. This model worked well when the role of owner and facility manager overlap (small restaurant), moderately well when the facilities management structure was well established, and disastrously in a complex institution with social control issues. In any case, the technician problem remains. Why make a technician's life easier, give him more control, and then no incentive to monitor low-return services such as scheduling, alert annoyances, Wi-Fi issues, etc.?

"Successful use of advanced thermostats require a more sophisticated deployment process that includes training and instruction, documentation, strategy-setting, commissioning, and ongoing support."

MULTI-TENANT LIGHT COMMERCIAL PROJECT

WCEC is working to address the traditionally underserved marked termed Multi-Tenant Light Commercial (MTLC). MTLC buildings are defined as having 2-25 small tenants and are owned by a single landlord. Example of MTLC buildings are strip malls, office parks and mixed use properties. Retrofitting these buildings represent a real challenge for several reasons. Low access to capital, principal-agent problems, short-term leases, and a large variety of end-use types are some of the barriers identified for this market.

Together with CLTC and EEC, WCEC is adopting an integrated approach that tackles lighting, envelope and HVAC in MTLC buildings. Goal of this project is to reduce energy and peak consumption of these buildings by at least 30% in an economically effective way.

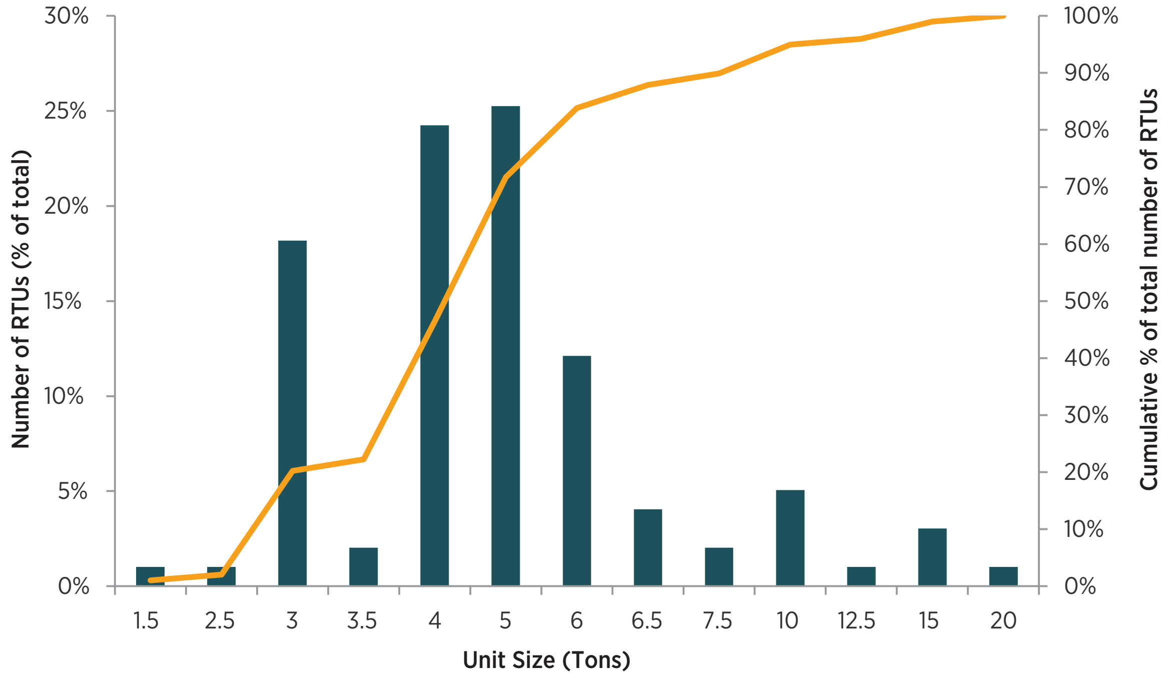


Figure 9-1: RTU Capacity Frequency. Based on a WCEC Conducted field survery of 100 RTUs

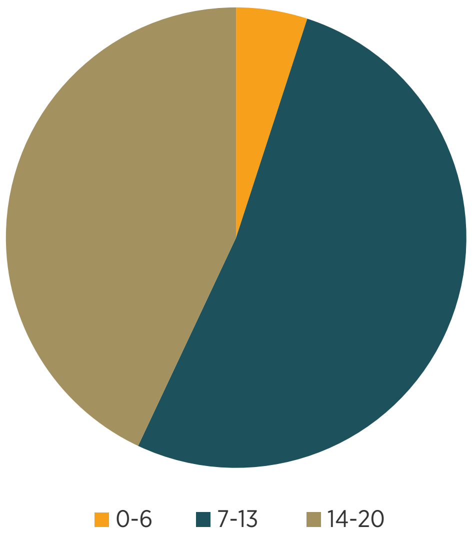


Figure 9-2: RTU Age Distribution. Based on a WCEC Conducted field survery of 100 RTUs

Based on WCEC field surveys in MTLC buildings, we expect most RTUs to be small (2-10 ton, 5-ton on average), with one compressor, a single-speed fan, and usually are not equipped with controllable dampers for economizer operation. The RTU's are on average 12 years old, and are unlikely to have been routinely maintained (WCEC 2013). Thus, there is significant potential to improve operation of these units via the incorporation of modern Load Management technologies.

Recently PGE commissioned HMG to conduct a market and technology feasibility assessment of control technologies for small and medium businesses. WCEC was involved in the selection and review of the technologies. The findings of the report were used as a basis for further investigation into specific load management devices. Of the load management technologies explored in the PGE and HMG report, the following categories were chosen for further consideration in MTLC buildings:

1. **Retrofit kits:** Products in this category are characterized as a deep retrofit of an RTU, replacing parts and adding controls to optimize performance.
2. **Advanced Thermostat:** These are devices that typically involve a one-for-one replacement of a thermostat but offer expanded functionality over a traditional ON-OFF thermostat. Generally, advanced thermostats will offer some form of remote monitoring and control, precise and easily configurable scheduling, and potential for integration with a larger EMS systems and utility DR programs.
3. **Evaporative Cooling:** These technologies provide cooling and ventilation to the building with the exception of pre-coolers, which are used to improve the efficiency of existing vapor-compression equipment.

RTU RETROFIT KITS

Evaluation of currently available retrofit kits has led to the selection of four retrofit technologies that showed potential for providing energy savings in MTLC buildings. The devices selected are similar in nature and all demonstrate both a physical likelihood to reduce energy consumption and an infrastructure and market-model consistent with the needs of SMB.

With the exception of the Jade economizer controller, all of the retrofits considered feature a variable speed drive for the evaporator fan which when coupled with intelligent control algorithms claim to effectively reduce the RTU's power consumption under part-load and fan-only operation. Certain devices also have additional features such as advanced economizers, dampers for split face evaporator coils, and variable speed drives for the compressor.

ENERGY SAVINGS

Although there are slight differences between the Enerfit, CATALYST, and Digi-RTU systems, independent research through both simulations and field studies have demonstrated that all devices have potential to provide energy savings as great as 50%. A simulation study by PNNL which explored both CATALYST style (staged fan controller) and Enerfit/DIGI-RTU style (continuous VFD control) retrofits showed annual energy savings potentials from 22-90%[1]. Furthermore, field testing of an array of advanced retrofit devices including Enerfit, CATALYST, and Digi-RTU by the San Diego Gas and Electric Company has shown RTU energy savings between 24-27%[2]. Other tests also demonstrate savings potential, such as a simulation performed by NREL which demonstrates 29-75% savings in fan energy with Enerfit and a field test of CATALYST by the Snohomish County Public Utility District which demonstrated at least a 20% annual energy savings[3].

Economizer functionality which is provided by all the retrofit options considered has potential to reduce air conditioning power consumption 8-20% when applied to units which currently have no economizers, and savings can be significantly greater for systems with malfunctioning economizers[4].

DEVICE COSTS

Cost of a retrofit solution is largely dependent upon RTU size (since larger units require larger motor drives), and options selected. A typical Enerfit installation would cost between $4,000[5] for a 15 ton unit to $4700 for a 20 ton unit[6]. RTU's greater than 20 tons have not been observed in MTLC buildings throughout the WCEC's market research. CATALYST has been quoted at $4,700 for a 15 ton unit but price can vary based on quantity purchased and options selected. Digi-RTU is in a similar price band with units costing between $3000-$10,000 for sub-20 ton units. Because of the similarity between the designs of Enerfit, CATALYST, and Digi-RTU their prices tend to scale similarly, and on average all devices have a simple payback period of 1 to 4 years[7]. The Jade system provides a lower cost alternative for a light retrofit. A typical Jade installation for a 4-10 ton unit will cost between $200-$300 dollars and in suitable climate conditions can have payback periods as low as two years[4].

SELECTED RETROFIT KITS

Manufacturer	Product
Enerfit	Enerfit
Transformative Wave Technologies	CATALYST
DTL Controls	Digi-RTU
Honeywell	Jade W7220 Economizer Controller

[1] *W. Wang, S. K., H. Ngo, R. Underhill, D. Taasevigen, R. Lutes (2013). Advanced Rooftop Control (ARC) Retrofit: Field-Test Results, Pacific Northwest National Laboratory.*
[2] *Bo White, M. E. (2013). Multi-Vendor RTU Retrofit Controller Field Study Final Report, San Diego Gas and Electric Company.*
[3] *Criscione, P. (2012). Results for RTU Retrofit Technologies Continue to Be Positive. E Source.*
[4] *Criscione, P. (2009). Air-Side Economizers. E Source.*
[5] *PGE and HMG (2012). Advanced Controls Retrofits For Packaged HVAC Systems in Small and Medium Commercial Buildings.*
[6] *Woolley, J. (2013). Advanced HVAC Technologies for Western Climates. E Source Forum. E Source.*
[7] *Criscione, P. (2011). A Dramatic Boost for Existing RTUs. E Source.*

ECONOMICS AND SIMPLE PAYBACK

Evaluating the energy savings of HVAC controls is, by nature, a difficult task. There is no rating metric for the "efficiency" of a controller, and savings depend substantially on how the system is operated before and after the controller is installed.

The goal of this section is to provide a first-order economic analysis for load management retrofits in MTLC buildings in California. Simple payback (SP) is used as the financial metric. Four tenant prototypes are examined: small retail, medium office, medium restaurant and medium grocery store. Characteristics of these tenants are derived from market research and industry experience. Tenant spaces are assumed to have small RTUs nominally sized at 1 ton per 300 ft^2 floor area (rounded up to the next ton). Controls are assumed to impact heating, cooling and ventilation. Rebates are not applied, but are discussed separately.

SIMPLE PAYBACK COST ANALYSIS FOR RTU RETROFIT KITS BASED ON AVERAGE OF CALIFORNIA'S CLIMATE ZONES

	Units	Small Retail	Medium Office	Medium Restaurant	Medium Grocery
Cost of Electricity	$/kWh	0.15	0.15	0.15	0.15
Cost of Gas	$/kBtu	0.01	0.01	0.01	0.01
Square footage	sf	1,500	3,000	3,000	3,000
RTU size	ton	5	5+5	5+5	5+5
EUI Ventilation	kWh/sf per year	1.8	1.3	5.8	2.6
EUI Cooling	kWh/sf per year	2.2	2.6	3.2	2.9
EUI Heating	kBtu/sf per year	3.0	8.6	7.7	7.7
Annual Energy Usage Ventilation	kWh per year	2,708	3,872	17,279	7,737
Annual Energy Usage Cooling	kWh per year	3,318	7,825	9,714	8,633
Annual Energy Usage Heating	kBtu per year	4,533	25,853	23,237	22,978
Annual Energy Savings Ventilation	kWh per year	1,083	1,549	6,911	3,095
Annual Energy Savings Cooling	kWh per year	1,327	3,130	3,886	3,453
Annual Energy Savings Heating	kBtu per year	1,813	10,341	9,295	9,191
Annual Money Savings Ventilation	$ per year	162	232	1,037	464
Annual Money Savings Cooling	$ per year	199	469	583	518
Annual Money Savings Heating	$ per year	18	103	93	92
Annual Money Savings Total	**$ per year**	**380**	**805**	**1,713**	**1,074**
Investment for 5-year payback	**$/RTU**	**1,898**	**4,026**	**8,563**	**5,370**
Investment for 10-year payback	**$/RTU**	**3,797**	**8,052**	**17,125**	**10,741**
Total Cost (all units)		**$4,000-$10,000**	**$8-$20,000**	**$8-$20,000**	**$8-$20,000**

ADVANCED THERMOSTATS

Advanced thermostats promise to provide the energy savings that traditional programmable thermostats could not. Advanced thermostats not only provide the functionality to set operating schedules, but also can provide broader functionality through features such as network access, occupancy detection, automatic learning (self-programming), fault detection and diagnostics, and demand response adjustments. Based on their work both in collaboration with PG&E, HMG, and other laboratory and field studies, the WCEC has identified a list of advanced thermostats which demonstrate potential for MTLC market adoption and energy savings potential. Of the thermostats considered, four were selected as most applicable to the MTLC market and are presented in the table below.

Although specific features and control strategies vary by device, the advanced thermostats considered are similar enough that an approximate energy savings potential for thermostat upgrade within the MTLC market can be developed. In 2014 the WCEC conducted a field study to evaluate both the energy savings and usability from advanced thermostats installed in schools, restaurants, and entertainment businesses.

Energy savings results were obtained by the comparison of pre and post installation site-level power measurement, normalized for temperature and operating hours. A custom disaggregation algorithm was developed and calibrated to each site studied in order to extract HVAC energy usage from other electrical loads and isolate the impact of the thermostat upgrade on site-level energy usage. To evaluate the usability of different thermostats a behavioral research program was conducted which surveyed users, evaluated their interest and understanding of HVAC efficiency, and identified shortcomings of the installed thermostats that hindered usability.

The results obtained indicate that advanced thermostats do have an energy savings potential, but the achievability of these savings depends heavily on both the implementation of the technology and the incentives of the end user to save energy. Specifically, advanced thermostats do not provide more controllability than what is possible with the intelligent use of traditional thermostats; however they often simplify and minimize the amount of user interaction required to establish an energy-efficient control scheme. For end users that do not have a strong interest or workable understanding of energy efficiency, advanced thermostats can offload user's responsibility and provide reasonably efficient control without user intervention.

SELECTED ADVANCED THERMOSTATS

Manufacturer	**Product**
Ecobee	Smart Thermostat
Nest	Nest Learning Thermostat
Honeywell	WiFi Smart Thermostat
Radio Thermostat of America	Various Models

ECONOMICS AND SIMPLE PAYBACK

Evaluating the energy savings of HVAC controls is, by nature, a difficult task. There is no rating metric for the "efficiency" of a controller, and savings depend substantially on how the system is operated before and after the controller is installed.

The goal of this section is to provide a first-order economic analysis for load management retrofits in MTLC buildings in California. Simple payback (SP) is used as the financial metric. Four tenant prototypes are examined: small retail, medium office, medium restaurant and medium grocery store. Characteristics of these tenants are derived from market research and industry experience. Tenant spaces are assumed to have small RTUs nominally sized at 1 ton per 300 ft^2 floor area (rounded up to the next ton). Controls are assumed to impact heating, cooling and ventilation. Rebates are not applied, but are discussed separately.

SIMPLE PAYBACK COST ANALYSIS FOR ADVANCED THERMOSTATS BASED ON AVERAGE OF CALIFORNIA'S CLIMATE ZONES

	Units	Small Retail	Medium Office	Medium Restaurant	Medium Grocery
Cost of Electricity	$/kWh	$0.15	0.15	0.15	0.15
Cost of Gas	$/kBtu	$0.01	0.01	0.01	0.01
Square footage	sf	1,500	3,000	3,000	3,000
RTU size	ton	5	5+5	5+5	5+5
EUI Ventilation	kWh/sf per year	1.8	1.3	5.8	2.6
EUI Cooling	kWh/sf per year	2.2	2.6	3.2	2.9
EUI Heating	kBtu/sf per year	3.0	8.6	7.7	7.7
Annual Energy Usage Ventilation	kWh per year	2,708	3,872	17,279	7,737
Annual Energy Usage Cooling	kWh per year	3,318	7,825	9,714	8,633
Annual Energy Usage Heating	kBtu per year	4,533	25,853	23,237	22,978
Annual Energy Savings Ventilation	kWh per year	271	387	1,728	774
Annual Energy Savings Cooling	kWh per year	332	782	971	863
Annual Energy Savings Heating	kBtu per year	453	2,585	2,324	2,298
Annual Money Savings Ventilation	$ per year	41	58	259	116
Annual Money Savings Cooling	$ per year	50	117	146	129
Annual Money Savings Heating	$ per year	5	26	23	23
Annual Money Savings Total	**$ per year**	**95**	**$201**	**428**	**269**
Investment for 5-year payback	**$/RTU**	**475**	**1,007**	**2,141**	**1,343**
Investment for 10-year payback	**$/RTU**	**949**	**2,013**	**4,281**	**2,685**
Current Cost		**$800-1,000**	**$1,600-$2,000**	**$1,600-$2,000**	**$1,600-$2,000**

EVAPORATIVE COOLING TECHNOLOGIES

Evaporative cooling technologies utilize water to either directly cool supply air including ventilation air or are used to reduce incoming air temperatures for existing vapor compression systems. EC systems are commonly classified into Direct Evaporative Cooling (DEC), Indirect Evaporative Cooling (IEC), Indirect-Direct Evaporative Cooling (IDEC), Hybrid Cooling (HYB) and Condenser Air Precoolers (PRE).

DIRECT EVAPORATIVE COOLING (DEC)

Direct Evaporative Cooling (DEC) systems evaporate water into the supply airstream to cool the space. While this process requires much less energy than traditional air-conditioning systems, DEC systems can reduce thermal comfort in the indoor space because they significantly humidify the supply air. Furthermore, DEC systems also require higher airflow than traditional DX air conditioners, and operate only with 100% outdoor air. Although operating on 100% outside air can help to maintain the air quality, the high airflow can create uncomfortable drafts. Compared to DX systems, DEC systems tend to have lower capital costs. Within the residential sector DEC systems can provide a cost effective alternative to DX systems in certain regions, but their use is often limited in MTLC buildings. Use of DEC systems is best suited for spaces that require high ventilation rates, such as make up air for commercial kitchens and automotive service bays. They could also be used to handle ventilation requirements for big box retail stores.

INDIRECT EVAPORATIVE COOLING (IEC)

Indirect Evaporative Cooling (IEC) systems feature two separate air steams: a supply air stream that is delivered to the space with no humidity added, and a working air stream that passes over a wet medium. The two air streams are connected through a heat exchanger which sensibly cools the supply air without adding humidity. Ventilation capacity of IEC systems is varied with some systems providing 100% outdoor air, and others using a mix of outdoor and return air. IEC systems also operate at lower supply airflow rates than DEC units, and are thus less likely to produce uncomfortable drafts. The supply temperatures of IEC systems are limited by outdoor air conditions and on extremely hot days these units might be unable to provide comfortable temperatures.

INDIRECT-DIRECT EVAPORATIVE COOLING (IDEC)

Indirect-Direct Evaporative Cooling (IDEC) systems combine both direct and indirect evaporative cooling stages to maximize cooling capacity with a minimal humidity addition when compared to DEC systems. As with DEC systems, 100% of the air supplied to the building comes from outside. A test of IDEC in residential application showed energy savings up to 80% over traditional air-cooled DX compressors, during summer peak conditions.

HYBRID EVAPORATIVE COOLING (HYB)

Hybrid Evaporative Cooling Systems combine features of the DX cycle with evaporative cooling technologies. Residential and Commercial (RTU) applications are available in the market. Depending on the model, hybrid units utilize direct, indirect or indirect-direct evaporative cooling when the cooling demand is low, and turn on vapor-compression systems for peak conditions. The three architectures are substantially different, but they all combine evaporative cooling with vapor-compression cycles. At high temperatures when operating with a DX stage these hybrid units tend to perform significantly better than traditional DX-only units. Furthermore, contrary to DX-only units, both efficiency and cooling capacity of hybrid units increase with dry-bulb temperature, and are thus able to provide significant energy savings at peak conditions when they are most needed.

CONDENSER AIR EVAPORATIVE PRE-COOLING (PRE)

Condenser Air Evaporative pre-coolers are an inexpensive way to reduce the temperature of the air that cools the condenser, thus improving the overall efficiency of the cooling system and increasing its capacity. The outdoor air stream passes through a wet medium, reducing its temperature due to evaporation, and comes in contact with the condenser coil. No humidity is added to the space. Evaporative-pre coolers can be added on existing RTUs, making them more attractive for the MTLC market. Condenser air intake in a RTU mounted on a hot roof can reach over 110 °F on summer days in California climate zone 10-15. In areas with 40 °F web bulb depression, a condenser air pre-cooler with evaporative effectiveness of 0.6 could deliver air at 86 °F; increasing capacity by 10% and EER by 30%.

ECONOMICS AND SIMPLE PAYBACK

A thorough economic analysis of an investment in an energy-saving retrofit would require knowing several details about the geographical location, energy use of the facility, existing technology as well as the new technology to be installed. Further, the specific details about the operation of the building and the cost of energy would be needed. With that information a metric such as lifecycle cost or investment net present value would be calculated and used as guidance for the investment.

The goal of this section is to provide a first-order economic estimate analysis for EC retrofits in MTLC buildings in California. Four prototypes of tenants are examined: small retail, medium office, medium restaurant and medium grocery store. Characteristics of these tenants are derived from the market research utilizing CEUS data. Tenant spaces have small RTUs of nominal capacity of 1-ton every 300 sf (rounded up to the next ton).

ECONOMIC ANALYSIS FOR EVAPORATIVE PRE-COOLERS BASED ON AVERAGE OF CALIFORNIA'S CLIMATE ZONES

	Units	Small Retail	Medium Office	Medium Restaurant	Medium Grocery
Cost of Electricity	$/kWh	$0.15	0.15	0.15	0.15
Square footage	sf	1,500	3,000	3,000	3,000
RTU size	ton	5	5+5	5+5	5+5
EUI Ventilation	kWh/sf per year	1.8	1.3	5.8	2.6
EUI Cooling	kWh/sf per year	2.2	2.6	3.2	2.9
Annual Energy Usage Ventilation	kWh per year	2,708	3,872	17,279	7,737
Annual Energy Usage Cooling	kWh per year	3,318	7,825	9,714	8,633
Annual Energy Savings Ventilation	kWh per year	0	0	0	0
Annual Energy Savings Cooling	kWh per year	664	1,565	1,943	1,727
Annual Money Savings Ventilation	$ per year	0	0	0	0
Annual Money Savings Cooling	$ per year	100	235	291	259
Annual Money Savings Total	**$ per year**	**100**	**235**	**291**	**259**

ECONOMIC ANALYSIS FOR EVAPORATIVE PRE-COOLERS+ IDEC BASED ON AVERAGE OF CALIFORNIA'S CLIMATE ZONES

	Units	Small Retail	Medium Office	Medium Restaurant	Medium Grocery
Cost of Electricity	$/kWh	$0.15	0.15	0.15	0.15
Square footage	sf	1,500	3,000	3,000	3,000
RTU size	ton	5	5+5	5+5	5+5
EUI Ventilation	kWh/sf per year	1.8	1.3	5.8	2.6
EUI Cooling	kWh/sf per year	2.2	2.6	3.2	2.9
Annual Energy Usage Ventilation	kWh per year	2,708	3,872	17,279	7,737
Annual Energy Usage Cooling	kWh per year	3,318	7,825	9,714	8,633
Annual Energy Savings Ventilation	kWh per year	542	774	3,456	1,547
Annual Energy Savings Cooling	kWh per year	664	1,565	1,943	1,727
Annual Money Savings Ventilation	$ per year	81	116	518	232
Annual Money Savings Cooling	$ per year	100	235	291	259
Annual Money Savings Total	**$ per year**	**181**	**351**	**810**	**491**

ECONOMIC ANALYSIS FOR 100% OUTDOOR AIR IDEC BASED ON AVERAGE OF CALIFORNIA'S CLIMATE ZONES

	Units	Small Retail	Medium Office	Medium Restaurant	Medium Grocery
Cost of Electricity	$/kWh	$0.15	0.15	0.15	0.15
Square footage	sf	1,500	3,000	3,000	3,000
RTU size	ton	5	5+5	5+5	5+5
EUI Ventilation	kWh/sf per year	1.8	1.3	5.8	2.6
EUI Cooling	kWh/sf per year	2.2	2.6	3.2	2.9
Annual Energy Usage Ventilation	kWh per year	2,708	3,872	17,279	7,737
Annual Energy Usage Cooling	kWh per year	3,318	7,825	9,714	8,633
Annual Energy Savings Ventilation	kWh per year	2,437	3,485	15,551	6,963
Annual Energy Savings Cooling	kWh per year	0	0	0	0
Annual Money Savings Ventilation	$ per year	366	523	2,333	1,044
Annual Money Savings Cooling	$ per year	0	0	0	0
Annual Money Savings Total	**$ per year**	**366**	**523**	**2,333**	**1,044**

ECONOMIC ANALYSIS FOR HYB BASED ON AVERAGE OF CALIFORNIA'S CLIMATE ZONES

	Units	Small Retail	Medium Office	Medium Restaurant	Medium Grocery
Cost of Electricity	$/kWh	$0.15	0.15	0.15	0.15
Square footage	sf	1,500	3,000	3,000	3,000
RTU size	ton	5	5+5	5+5	5+5
EUI Ventilation	kWh/sf per year	1.8	1.3	5.8	2.6
EUI Cooling	kWh/sf per year	2.2	2.6	3.2	2.9
Annual Energy Usage Ventilation	kWh per year	2,708	3,872	17,279	7,737
Annual Energy Usage Cooling	kWh per year	3,318	7,825	9,714	8,633
Annual Energy Savings Ventilation	kWh per year	2,437	3,485	15,551	6,963
Annual Energy Savings Cooling	kWh per year	664	1,565	1,943	1,727
Annual Money Savings Ventilation	$ per year	366	523	2,333	1,0444
Annual Money Savings Cooling	$ per year	100	235	291	259
Annual Money Savings Total	**$ per year**	**465**	**757**	**2,624**	**1,303**

INDIVIDUAL REBATE AND INCENTIVE OFFERINGS FOR RTU OPTIMIZATIONS IN CALIFORNIA

Utility	Measure	Rebate/Incentive	Restrictions
PG&E	Enhanced Ventilation Control	155-190/Ton	
PG&E	Advanced Digital Economizer Control	20/Ton1	
SCE	Variable Speed Drive	$80/HP for fans	Motor <100 HP
SCE	Economizer Retrofit	$35/Ton2	
SDG&E	Variable Speed Drive	$110/HP	Motor <100 HP. Pre-inspection required.
SDG&E	Ventilation Control	$.08-.015 kW/hr. $150/kW3	

UTILITY REBATE OFFERINGS FOR EVAPORATIVE COOLING IN CALIFORNIA

Utility	Efficiency Measure	Rebate Value	Restrictions
SDG&E	Evaporative Cooling Indirect - Packaged System	$65/Ton	Rigid Media Saturation Effectiveness >0.65 Used for space-cooling for human comfort
SCE	Advanced Evaporative Coolers	$123/ton	Rigid Media No Constant Bleed System Located in CZ 9,10,13,14, or 15 Saturation Effectiveness >0.85
SMUD	Advanced Evaporative Coolers	$123/Ton	Rigid Media No Constant Bleed System Minimum flow rate of 1300 CFM and 0.1" Static Pressure Utilize rigid media with a saturation effectiveness >0.85
PG&E	*REBATES CURRENTLY UNAVAILABLE*	N/A	N/A

EXISTING UTILITY INCENTIVES

In addition to the potential savings from reduced energy consumption, California utilities offer incentives and rebates for non-commercial customers who invest in certain technologies or maintainance to reduce their energy consumption below baseline levels when in compliance with federal and state building codes. Statewide, incentives are broadly classified into two categories, 'Basic' and 'Targeted' based on the availability, provableness, and potential savings certain technologies. Targeted incentives apply to new and less-proven technologies which a utility administrator has deemed valuable in and in an effort to increase market penetration are offered at higher rates than basic incentives. Many individual utilities also offer their own incentive and rebate structures, which may offer larger payouts or cover a broader range of efficiency measures than statewide options.

For evaporative cooling systems which do not meet the requirements of the above rebates customized incentives may still be achievable if it can be demonstrated that the project produces significant energy savings or peak reduction. Most utilities offer customized incentive and rebate options to encourage adoption of energy efficient equipment or to defray equipment costs.

UTILITY CUSTOMIZED ENERGY EFFICIENCY IMPROVEMENT OFFERINGS IN CALIFORNIA

Utility	Efficiency Measure	Rebate Value
SDG&E	Air Conditioning and Refrigeration 1	Up to .15/kWh, 100/kW
SMUD	Custom Air Conditioning Incentives	Up to .1/kWh, 200/kW Up to 30% of project cost, not to exceed $150,000
PG&E	Custom Energy Efficiency Offering	Up to .15/kWh, 150/kW
SCE	Custom Energy Efficiency Offering	Up to .15/kWh, 150/kW

WESTERN COOLING CHALLENGE

Cooling and ventilation can account for more than 50% of the summertime peak electrical demand from commercial buildings. Rooftop packaged air conditioners are predominantly responsible for this load. Energy saving features such as variable speed fans and multi-stage compressors promise substantial reductions for annual electricity consumption from rooftop air conditioners, however, since all components must operate at full tilt during peak periods, they do not offer significant savings when electrical demand reduction matters most.

The Western Cooling Challenge advances development and commercialization of climate-appropriate air conditioning systems that capture substantial energy savings at peak. Recognizing the public benefits of reducing sate wide peak electrical demand, The California Public Utilities Commission Energy Efficiency Strategic plan calls for a market shift toward climate appropriate air conditioners. Climate appropriate cooling technologies may take any format that works in concert with local meteorological conditions to achieve savings over code minimum equipment. However, all of the technologies currently advanced through the Western Cooling Challenge utilize some form of indirect evaporative cooling, usually in combination with a vapor compression system.

The Western Cooling Challenge has been in motion since 2008, and quickly expanded the list of entrants that now include Trane, Seeley and Munters.

STAKEHOLDERS VIEWING THE RESULTS FROM A LIVE LAB TEST OF THE MUNTERS EPX5000 AT PG&E'S LABORATORY.

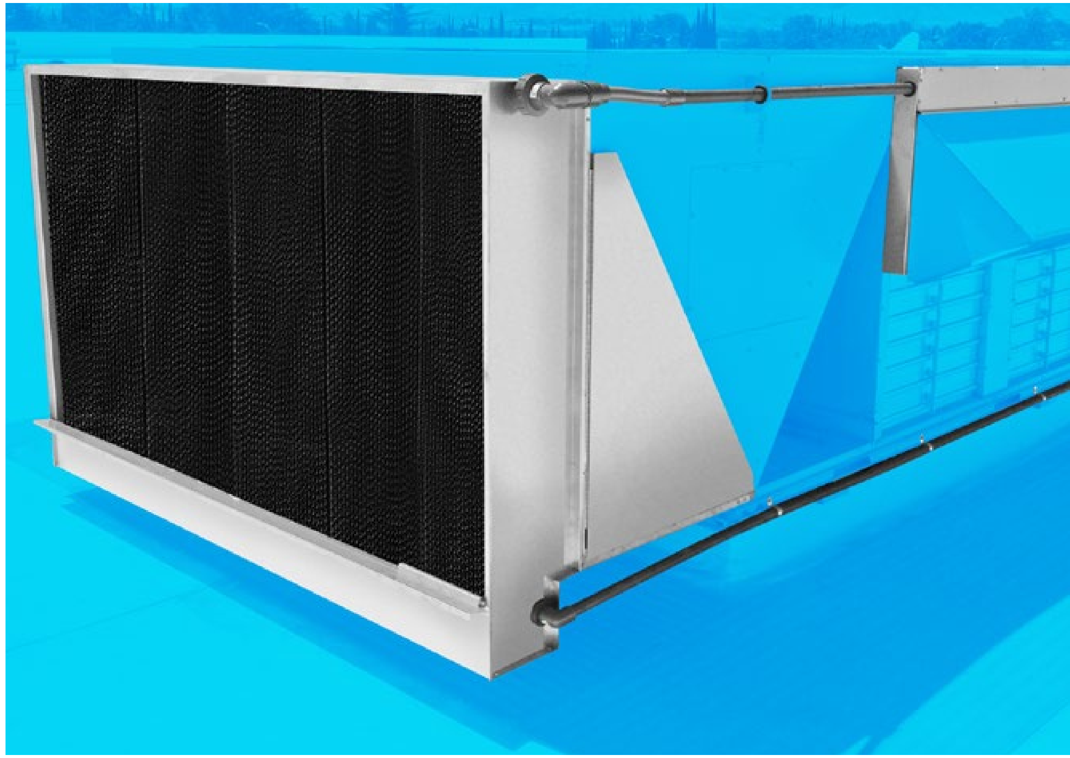
COOLING ENERGY & CO_2 SAVINGS
15%

PEAK COOLING SAVINGS
up to 40%

WATER USE INTENSITY
3.5 gallons
per kWh
energy saved

Rooftop packaged air conditioners server more than 65% of the commercial floor area in California. Unfortunately, these systems are inefficient. The dual-evaporative pre-cooling retrofit studied here increases cooling capacity for conventional rooftop air conditioners while also reducing the electrical power input. At peak, the technology has been measured to reduce peak electrical demand for cooling by more than 40%.

The product tested in this project takes advantage of indirect evaporative cooling to cool the ventilation air stream on a conventional rooftop unit, and uses direct evaporative cooling to cool air at the condenser inlet. This dual design reduces energy by reducing the temperature of incoming ventilation air and by lowering the condensing temperature. Since the dual evaporative pre-cooling technology incorporates with a conventional air conditioner, the combined system still maintains latent cooling capacity for applications where dehumidification is required. These dual processes work together to increase cooling capacity and to improve efficiency for the vapor compression system. The second effect is mainly caused by a lower heat sink temperature for the refrigeration cycle. Laboratory measurements for the dual evaporative pre-cooling technology installed on a similar rooftop air conditioner indicated 43% reduction in power draw at peak.



Download the full case study » **http://bit.ly/WCCCSpalmdale**

COOLING ENERGY & CO_2 SAVINGS
20%

PEAK COOLING SAVINGS
up to 66%

WATER USE INTENSITY
5 gallons
per kWh
energy saved

The product tested in this project takes advantage of indirect evaporative cooling to cool the ventilation air stream on a conventional rooftop unit, and uses direct evaporative cooling to cool air at the condenser inlet. This dual design reduces energy consumption by reducing the temperature of incoming ventilation air and by lowering the condensing temperature. Since the dual evaporative pre-cooling technology can incorporate with any conventional air conditioner, the combined system still maintains latent cooling capacity for applications where dehumidification is required. These two cooling processes work together to increase cooling capacity and to improve efficiency for the vapor compression system. The second effect is mainly caused by a lower heat sink temperature for the refrigeration cycle.

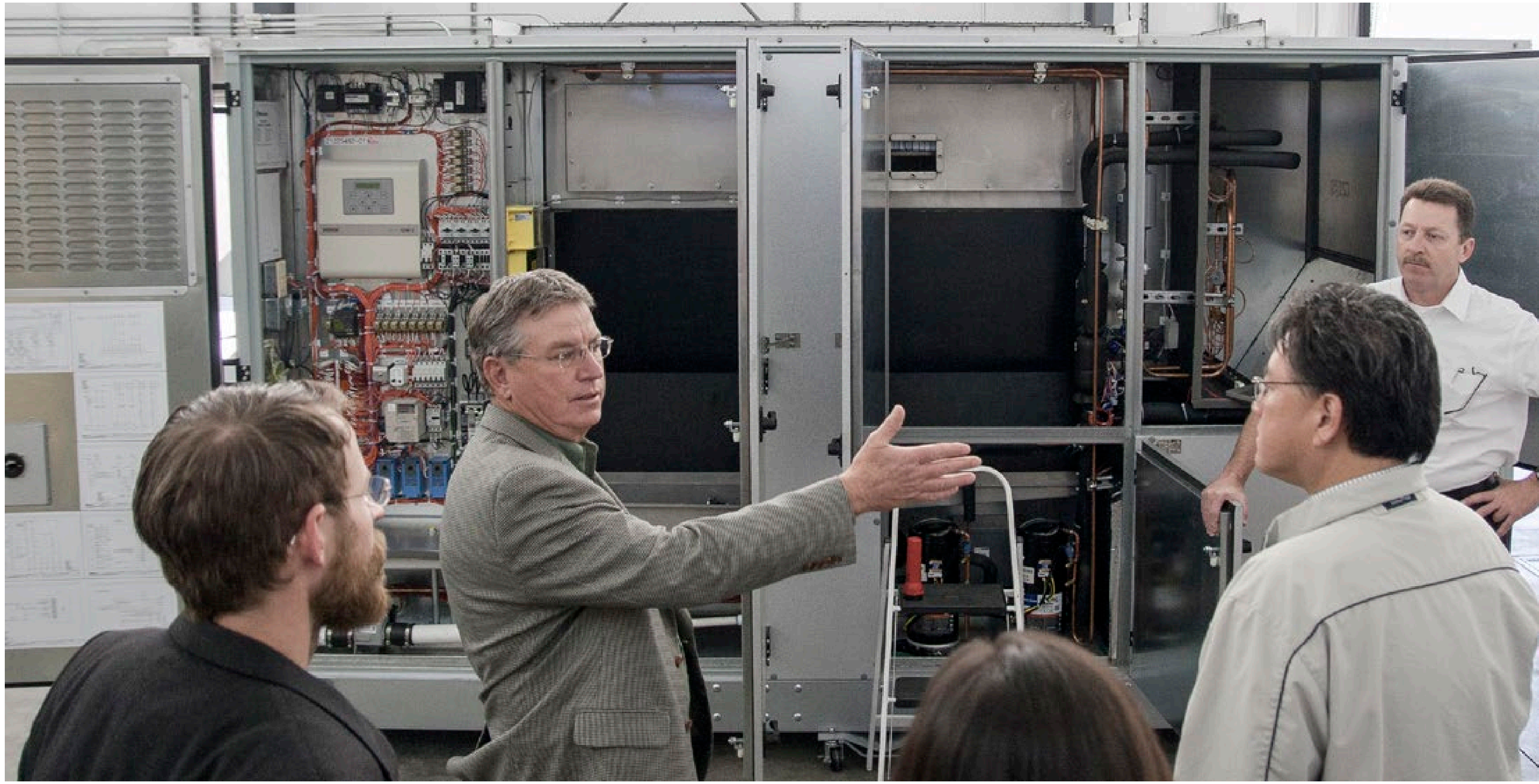
Three variable speed Trane Voyager units with DualCool® were installed in Ontario CA for the purposes of this study. Two were installed on the administrative offices for a mall (M12-14, M15-15), and one was installed to cool the kitchen for a restaurant and bakery (AC7).

Download the full case study » ***http://bit.ly/WCCCSontario***

This report presents analysis of results from laboratory testing of the Munters EPX 5000 - one example of a commercial DOAS product that incorporates indirect evaporative cooling, vapor compression, and heat recovery. The laboratory examination was conducted at PG&E Applied Technology Services in San Ramon, California. Tests were organized in a way to measure the cooling capacity and energy consumption for the system in each mode of operation, and across a range of operating conditions.

RESULTS IN BRIEF

The results from this report indicate a 20% reduction in electrical demand from the whole building HVAC at Western Cooling Challenge peak conditions, and 10% reduction at Western Cooling Challenge annual conditions. Moreover, the analysis indicates that while the baseline scenario requires roughly 42 tons (net nominal) conventional rooftop unit cooling capacity, the EPX 5000 scenario only requires 29 tons (net nominal). This means that an existing building with five conventional rooftop units could downsize to three or four conventional units by shifting the ventilation cooling load over to a new 5000 cfm DOAS.



Up to 20% reduction in electrical demand from the whole building HVAC.

Download the full report » [**http://bit.ly/WCCepx5000lab**](http://bit.ly/WCCepx5000lab)

TITLE 24 CREDIT FOR EFFICIENT EVAPORATIVE COOLING

The commercial buildings sector has an important role to play in helping to reduce California's energy use and associated carbon footprint. A new generation of high efficiency cooling systems has the potential to transform the commercial HVAC industry, and to result in dramatic gains in efficiency. However there are currently no building simulation tools capable of modeling these new systems. Consequently there is not a Title-24 compliance pathway to give appropriate credit to the variety of indirect evaporative and hybrid system architectures. Further, potential customers, engineers, and utility programs are not currently able to project the value of these systems with confidence.

This project seeks to develop a flexible and re-configurable modeling framework for EnergyPlus that will allow EnergyPlus users and HVAC manufacturers to simulate performance of these new systems in a straightforward way. Once Utilities and building owners can be assured of an evaporative product's performance, broader adoption of these technologies will likely follow, leading to significant state-wide energy savings.

NELSON DICHTER, WCEC ASSOCIATE DEVELOPMENT ENGINEER, WAS INTEGRAL IN THE CREATION OF THIS EFFECTIVE MODEL FOR ENERGY PLUS.

NEW, EFFICIENT CLIMATE APPROPRIATE TECHNOLOGIES FOR COMMERCIAL BUILDINGS

A new generation of energy efficient cooling systems is emerging that has the potential to dramatically lower cooling energy use in California buildings. This new category, termed “hybrid” cooling systems, integrates the operation of multiple cooling components in order to leverage the strengths of different cooling strategies at different times, or to enhance the capacity and efficiency of vapor compression cooling. The hybrid systems addressed in this study utilize indirect evaporative cooling in combination with vapor compression cooling. Indirect evaporative is used as the primary cooling system and the secondary vapor compression system is used only to provide supplemental cooling during periods of peak cooling demand.

Several HVAC system manufacturers, including Coolerado, Trane, Munters and Seeley, are actively marketing (or piloting) systems that have potential to capture a significant share in the market for cooling in commercial buildings. The California Energy Efficiency Strategic Plan sets a goal to advance quick market introduction of ‘climate appropriate’ commercial air conditioning equipment (such as these hybrid air conditioners), targeting 15% share of new sales by 2015.

The strategies introduced by manufacturers in this category are diverse. Some systems are packaged rooftop air conditioners (e.g. Coolerado H80) that can be used as direct replacement for conventional rooftop units. Other systems function as Dedicated Outside Air Supply (DOAS) air handlers, or as standalone indirect evaporative precooler, that can be installed to operate in sequence with separate vapor compression equipment.

Future energy savings are anticipated to come from the incremental direct replacement of existing conventional packaged DX cooling units with hybrid units that provide a significant improvement in efficiency. Laboratory and field studies of the Coolerado heat and mass exchanger (HMX) have demonstrated dramatic cooling energy savings with a sensible space cooling COP more than twice that of standard rooftop units under typical Western climate conditions. Given an assumed market penetration of 35% of any newly installed RTUs, projected energy savings (reductions in energy use compared to baseline conventional RTUs) in the first year are estimated to be 1.45E+08 kWh. Savings are expected to increase to a further 1.5E+08 kWh annually until they reach 3.0E+09 kWh savings once peak market penetration is realized.

With a reliable model, hybrid systems can be used within Title-24’s Alternative Calculation Method. Giving building designers and engineers a vital tool to balance building trade-offs between efficiency measures while maintaining an overall energy and monetary budget.

MODEL DEVELOPMENT METHODS

FIRST METHOD

Field data was collected from several hybrid evaporative cooling systems, installed throughout California. This enabled characterization of the functional and operational behavior of the various systems in real world settings. The team used the measured performance data from multiple installations of the Coolerado H80 to develop an empirical model of the performance for each major system component. The performance of each individual component is dependent on fewer variables than the H80 as a whole, thus the field data yields a more complete map of the inputs for each component than it does for the entire system. The team developed individual models for the indirect evaporative cooler and stage 1 and 2 of the direct expansion coils. Stage 1 and stage 2 are levels of performance of the same direct expansion coil. Since the components operate serially, the output of the one component can be used as the inputs to the next component. The team used these models to develop a partially synthetic set of performance data that covered the complete range of operating and environmental conditions the system could be required to operate in. The team then used this partially synthetic data set to develop performance curves that describe how the hybrid system will operate as a whole under a given set of conditions.

SECOND METHOD

Secondly, the team developed a modeling framework (a model that does not represent any specific system but can be tailored to meet the user's requirements) that is flexible enough to allow users with sufficient system performance data to model any currently anticipated hybrid cooling systems within the EnergyPlus software. For the rest of this document, this modeling framework is referred to as the Hybrid-Black-Box model (HBBM).

THIRD METHOD

Finally, the team configured the HBBM model to represent the Coolerado H80 system, and then performed a series of validation exercises to assess the performance of both the HBBM itself and the Coolerado H80 model represented within it.

FIGURE 11-1: FIELD TRIAL LOCATIONS AND START DATES

Technology	Location	Principal Activity	Data Period
Coolerado H80	Davis	Small Office	July 2012
Coolerado H80	Ridgecrest	Small Office	July 2012
DualCool (retrofit) x4	Palmdale	Large Retail	August 2012
DualCool (Trane Voyager) x2	Ontario	Mall	July 2013
DualCool (Trane Voyager)	Ontario	Restaurant	July 2013
DualCool (Trane Voyager)	Fairfield	Mall	June 2013
Coolerado M50 x3	Bakersfield	Large Retail	June 2013
Seeley ClimateWizard x3	Bakersfield	Large Retail	June 2013
Munters Oasis	Temecula	Large Office	July 2012
Munters EPX 5000	San Ramon	Grocery	August 2014
Coolerado C60	Cudahy	Data Center	July 2014
Seeley ClimateWizard	Placentia	Data Center	July 2014

MODEL ACCURACY RESULTS

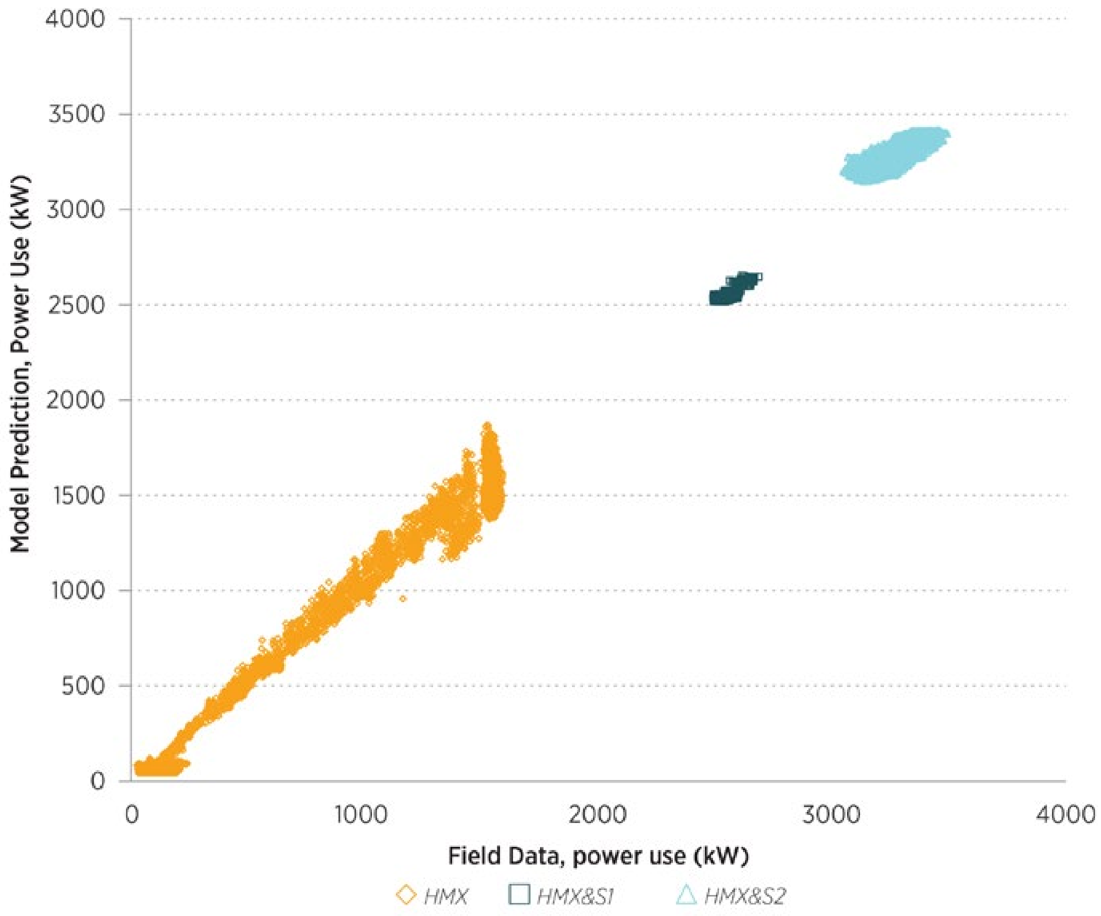


Figure 11-2: Model Prediction of power use vs. actual field data

Figure 11-2 through Figure 11-3 plot the results of the model fitting of the component-by-component empirical model against the recorded field data at identical input conditions. Points that lie on the line passing through the origin with a slope of 1 indicate points where the error in the model when compared to the observed system performance is low. Points that lie far from this line indicate that some system performance characteristic(s) for the real system are not accurately captured by the model. As shown in Figure 11-2 the component level model accurately predicts the system power consumption in all three modes.

Figure 11-3 shows that the empirical component-by-component model predicts the supply air temperature with a high degree of accuracy in HMX&S1 and HMX&S2 operating modes. However, there is some deviation between prediction and data for operation in the "Indirect Evaporative Only" mode. This was unexpected, because the component level approach uses the output of the indirect evaporative heat exchanger as input for the model to predict the input conditions to the Stage 1 and Stage 2 compressor models. Thus, any error inherent in the HMX model should propagate through to the stage 1 and stage 2 compressor models. Further analysis found that these instances are associated with the transient temperature behavior that occurs during mode shifting events. The current version of the HBBM is not intended to capture these transient events; the performance predictions are made according to steady state operating characteristics in each mode. Fortunately, in this instance, these transient periods only account for a very small fraction of the minute-by-minute observations.

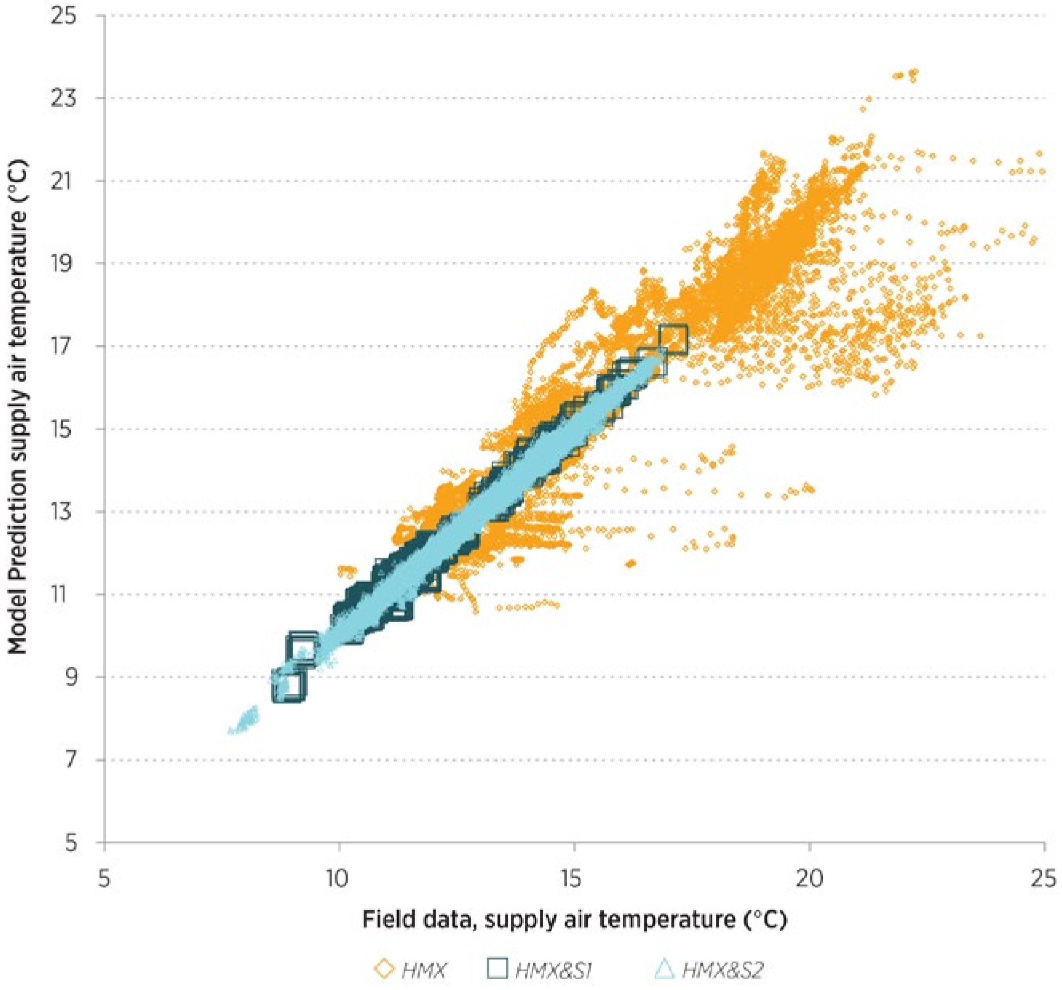


Figure 11-3: Model Prediction of power use vs. actual field data

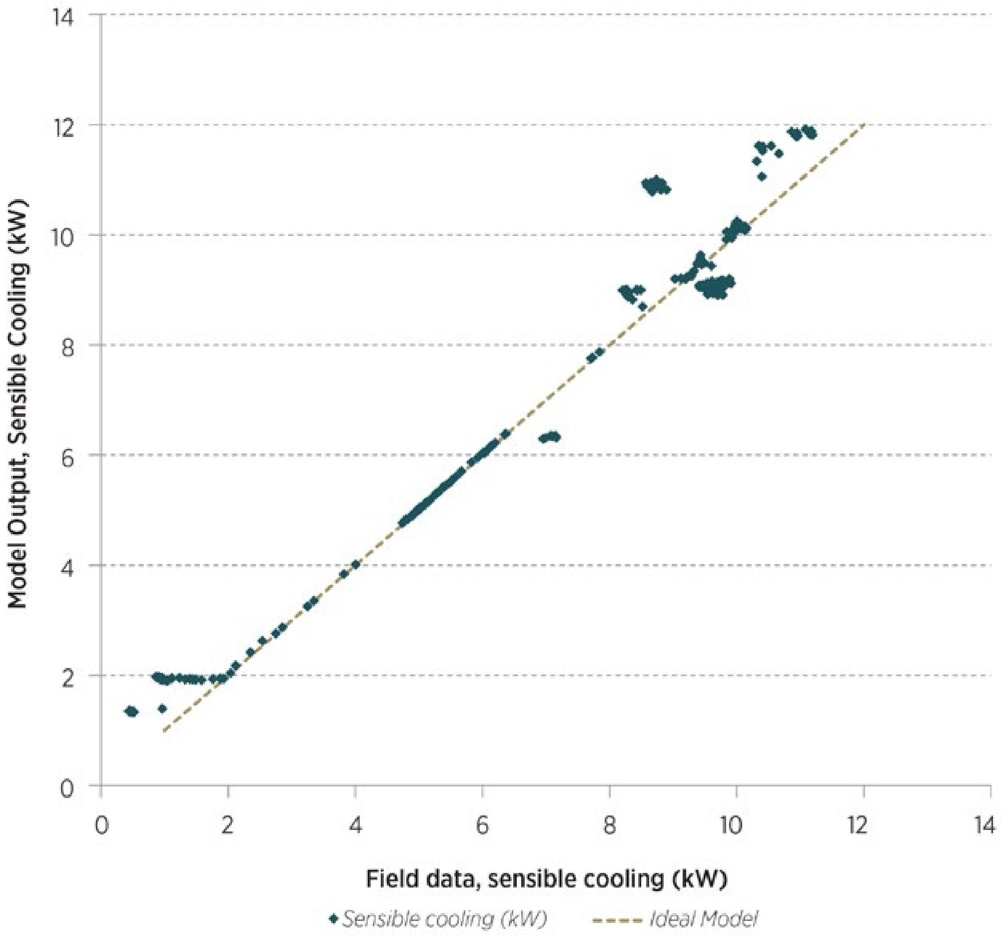


Figure 11-4: Comparison of modeled and predicted sensible capacitydata

For 77% of the time HBBM predicted the same mode of operation that was observed for equipment operation in the field. The modeled sensible cooling and power consumption are highly dependent on which mode of operation the model chooses. On average, the model predicted a 0.3% higher delivered sensible cooling capacity, and 10% higher electricity use than the real system. On average, mass flow rates were predicted to be 0.4% higher than observed.

The assessment demonstrates that the HBBM functions as intended to select the optimal mode and operating conditions, given the performance curves used. The differences between modeled and predicted data occur as a result of inaccuracy in the empirical equations under certain operating conditions. For cases where the test points coincided with actual field conditions the model outputs aligned very well with field observations, resulting in highly accurate predictions of mode, power use and sensible cooling capacity.

CONCLUSION

The research team has developed a new flexible modeling tool that can be used in EnergyPlus to model multi-mode zone HVAC systems that previously could not be accurately represented in EnergyPlus. The approach used is novel, and utilizes several features of EnergyPlus that are not commonly used together. The tool was developed as an EnergyPlus "plug-in" called a Fuctional Mockup Unit. This approach had several advantages over the conventional approach to model development and testing, not least of these being that the model can be trialed by external partners using the current version of EnergyPlus, without requiring the model to be fully integrated into a formal EnergyPlus release.

The team also developed an empirical model of the Coolerado H80 that compared well with the field data. This model was used to populate a 60,000 point table of synthetic performance data, which in turn was used to develop the second order polynomial equations that are used by the HBBM to choose mode and operating conditions and to output performance characteristics to EnergyPlus. This approach to developing performance curves was used out of necessity rather than design. Ideally, a performance data table would be developed by a manufacturer of a cooling system under controlled conditions. Consequently, the performance maps that were derived from our field data are somewhat limited by the operating and environmental conditions observed in the field.

Despite the limitation of this approach, the second order performance curves developed for the Coolerado H80 compared sufficiently well with the field data to proceed with testing of the HBBM. This was based on an acceptability criteria of <20% RMS error in both delivered cooling capacity and electrical power use. A comparison of the predicted and measured performance characteristics found percentage RMS error in the power consumption of 18%, 1% and 1% for the HMX only, HMX plus stage 1 cooling, and HMX plus stage 2 cooling respectively. These figures verify that the second order curves used to define the Coolerado H80 model are sufficiently accurate (<20% RMS error). However, it should be reiterated that the purpose of developing the Coolerado model was for the purpose of testing the HBBM framework, and that the accuracy of this Coolerado model is only significant in that it provides a realistic test model to verify that the HBBM functions as intended.

When these curves are used within the HBBM framework and tested using input data from the field study, the model predicted mode selection and delivery of sensible cooling to an acceptable level of accuracy.

Further testing and validation of the HBBM and the Coolerado model are to continue past the delivery of this report. The model will be released initially for beta testing by industry partners, and then released to the EnergyPlus user community.

Download the full project report » ***http://bit.ly/HybridModelT24***

GAS ENGINE HEAT PUMP: MODELING RESULTS

The gas engine driven heat pump (GEHP) is a relatively new (first produced in 1985) heat pump technology whose purpose is increased energy efficiency in water and space heating/cooling. GEHPs typically contain a "reversible vapor compression heat pump with an open compressor driven by a natural gas fuelled internal combustion engine. Although the efficiency of a gas engine is not very high (about 30 - 45%), the waste heat of fuel combustion can be recovered by approximately 80%. This feature is not present in other heat pumps where the heat released during fuel combustion is simply dissipated into the atmosphere instead of being reutilized. Another benefit to GEHPs is their low fossil fuel consumption; their typical energy sources include natural gas, propane, or LPG, which are also much cheaper alternatives to fossil fuels. GEHPs also help balance electricity demand by reducing the peak electric load.

The results showed wide variations between the systems when comparing site energy, peak power, and cost of operation in a time-of-use pricing structure. The source energy comparison showed much less variation between the systems, with each using roughly the same amount of source energy. WCEC was tasked with modelling the performance of a NextAire GEHP for Climate Zone 12.

NEXTAIRE'S 11-TON GEHP. ONE OF THREE UNITS WCEC MODELLED AND COMPARED.

MODELING PACKAGE AND METHODOLOGY

EnergyPlus was chosen to simulate the annual performance of the gas engine heat pump (GEHP) as well as several conventional heating and cooling systems for comparison. EnergyPlus is a whole building simulation program with an extensive library of features for a wide variety of building constructions and HVAC systems. The release of EnergyPlus V7.2 included modules for Variable Refrigerant Flow (VRF) air conditioners. These modules can be used to simulate heat pumps, heat recovery and water-cooled VRF systems. The addition of the VRF modules to EnergyPlus makes it a convenient and powerful package for simulating the GEHP.

SYSTEM MODEL DESIGN

Three different HVAC systems were simulated, a conventional air conditioner and gas furnace, an electric heat pump, and a gas engine heat pump. The same building geometry and construction was used for each simulation. The results from these simulations were used to compare the annual energy use of each HVAC system in each of California's climate zones. The plots in this report represent California Climate Zone 12.

BUILDING MODEL

A DOE reference model of a small office building was chosen to provide the geometry, materials, construction and internal gains for the simulations.

The office building is 5,505 square feet and is broken up into 6 thermal zones. There is one zone in the core of the building and one zone along each of the external walls. Each of these conditioned zones has it's own thermostat. The sixth thermal zone is the unconditioned space above the ceiling.

The total capacities of both the heating and cooling systems that service the building are set at 35.2 kW (120 kBtu/h). The model includes no mechanical ventilation but has a natural infiltration rate set at 0.223 CFM per square foot of floor area.

Internal gains that are simulated in the model include lights, electrical equipment and people. The internal lighting levels in the building were set at 1.8 W/SF producing a total of 10 kW (34.2 kBtu/h) of heat. The electric equipment load was set at 1 W/SF resulting in a contribution of 5.5 kW (18.8 kBtu/h) of heat to the building load. The occupancy for the small office building was set at one person per 200 square feet and the activity level of the occupants was set at 120 Watts per person. Thus, during full occupancy, 3.3 kW (11.3 kBtu/h) of heat is generated as a result of human activity. The weekday schedule for the fraction of each internal gain is shown in Figure 12-1. Figure 12-2 shows the building load resulting from the internal gains.

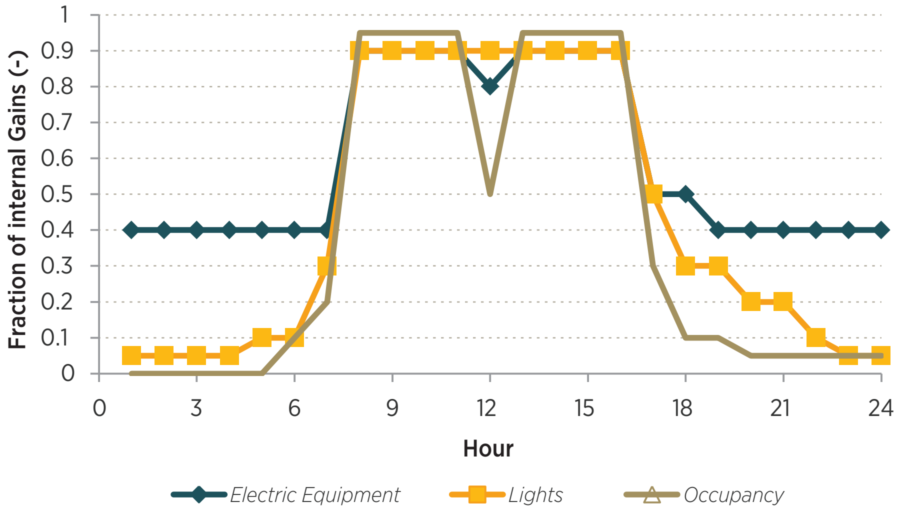


Figure 12-1: Weekday schedule of internal gains fractions

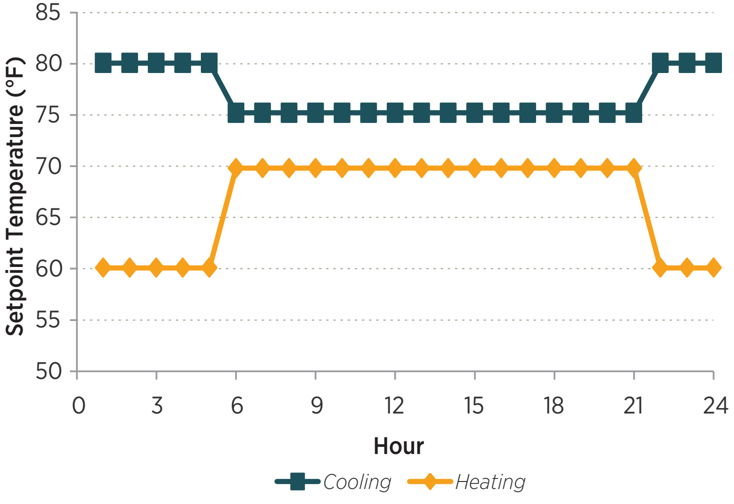


Figure 12-3: Weekday heating and cooling setpoint schedules

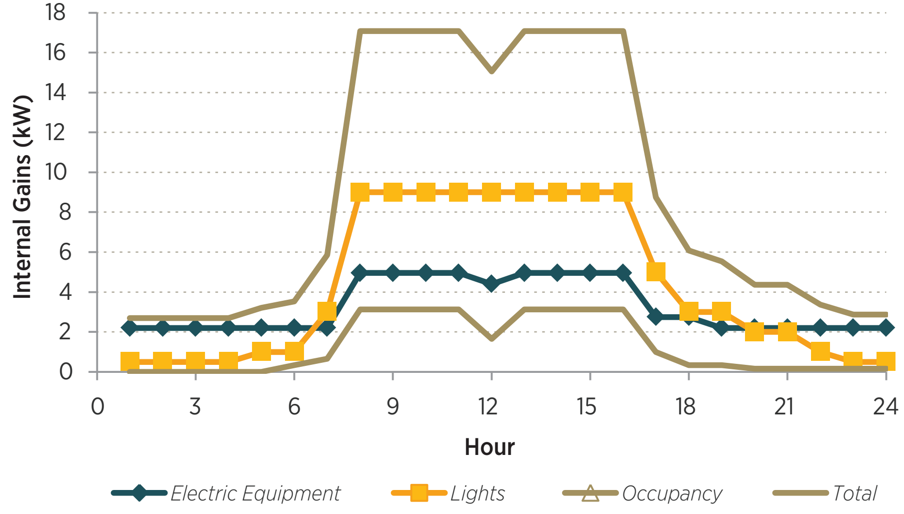


Figure 12-2: Schedule of internal gains

AIR CONDITIONER AND GAS FURNACE MODEL

The conventional system included an air conditioner and gas furnace that was simulated using EnergyPlus air loops. Each conditioned thermal zone was served by its own air loop for a total of five air loops. Each air loop operates independently and individual air loops can heat and cool simultaneously. The capacity of each heating and cooling coil is set at 7.0 kW (24 kBtuh) for a total building heating and cooling capacity of 35.2 kW (120 kBtuh). This configuration would be typical of a building served by individual RTUs for each building zone.

ELECTRIC HEAT PUMP

The electric heat pump was simulated using the variable refrigerant flow (VRF) objects in energy plus utilizing a single heat pump utilizing terminal units in each zone. Performance curves for the electric heat pump were taken from an EnergyPlus example file. The system is configured such that the heat pump cannot provide heating and cooling simultaneously to different thermal zones. The mode of operation is dictated by the type of conditioning (heating or cooling) requested by the zone with the largest load. For consistency, the total building capacity of the heat pump system was set the same as for the baseline unit, namely 35.2 kW (120 kBtuh) in both heating and cooling modes. The coils in the terminal units serving each zone were given a capacity of 7.0 kW (24 kBtuh).

GAS ENGINE HEAT PUMP

The performance of the gas engine heat pump (GEHP) was simulated in the same way as the electric heat pump, using the VRF objects in energy plus with a single heat pump utilizing terminal units in each zone. The VRF objects use a set of curves to define the performance of the GEHP for simulation. The set of cubic and biquadratic curves define the capacity and energy input ratio (EIR) as functions of indoor and outdoor air conditions and the part load ratio (PLR) of the system. The method of least squares was used to fit the curves that define the performance of the VRF system to tabular data provided by the manufacturer that characterizes the performance of the GEHP. For consistency, the total building capacity of the heat pump system was set the same as for the baseline unit, namely 35.2 kW (120 kBtuh) in both heating and cooling modes. The coils in the terminal units serving each zone were given a capacity of 7.0 kW (24 kBtu/h).

MODEL RESULTS

The model presented is based on reference standards from DOE and other sources. As such the absolute results indicating total energy used are not as important as the relative differences that can be seen between the different technology alternatives. As laboratory and field testing are completed the model will be refined.

The modeling results are presented in terms of energy use, peak power demand, and cost within a time-of-use (TOU) billing structure. The energy results are shown in terms of site energy and source energy usage. Source energy is a good basis for comparison because this metric takes into account the amount of energy used at the point of production and transmission losses associated with each energy source.

Figure 12-4 shows the amount of energy used onsite, broken down into heating and cooling from both gas and electric energy sources. Although California CZ 12 typically has two to three times more heating degree days (HDD) than cooling degree days (CDD), all three systems use significantly more energy annually for cooling than they do for heating. This is because internal loads offset the heating load and increase the cooling load. The thermostat scheduling for the office space also tends to increase cooling load by tending to operate the system during the hottest parts of each day, and subsequently decrease heating load by tending to operate the system during the hottest parts of the day.

Figure 12-5 shows the amount of energy used at the source, broken down into heating and cooling from both gas and electric energy sources. When compared on a source energy basis, it can be seen that the heating energy is roughly the same for a conventional furnace and electric heat pump system and the GEHP uses slightly more energy than the other two systems. This should not be the case because heat recovery from the gas engine should allow the GEHP to operate much more efficiently when in heating mode. Thus further investigation is merited. The electric heat pump and the GEHP uses less cooling energy than the conventional system because they are a variable speed system which does not have to cycle itself on and off as frequently as the conventional system. This results in a smaller magnitude of part load losses.

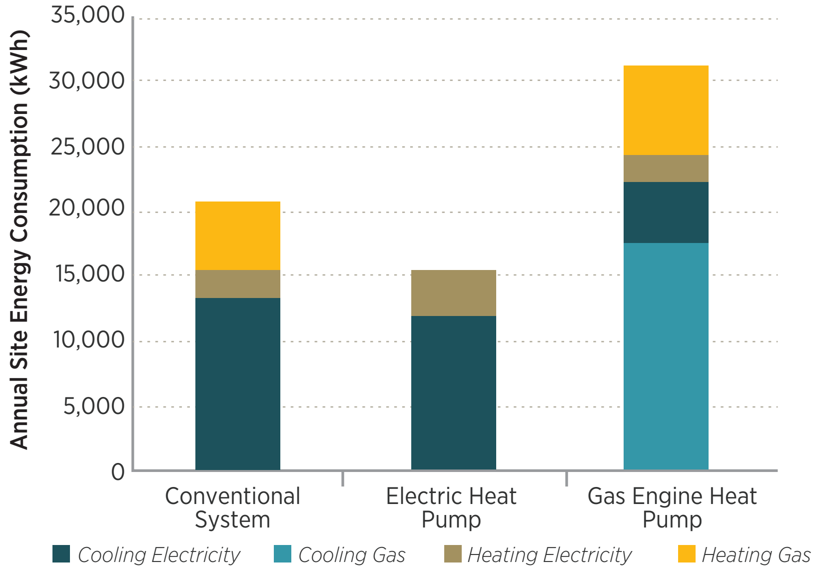


Figure 12-4: Site Energy Consumption

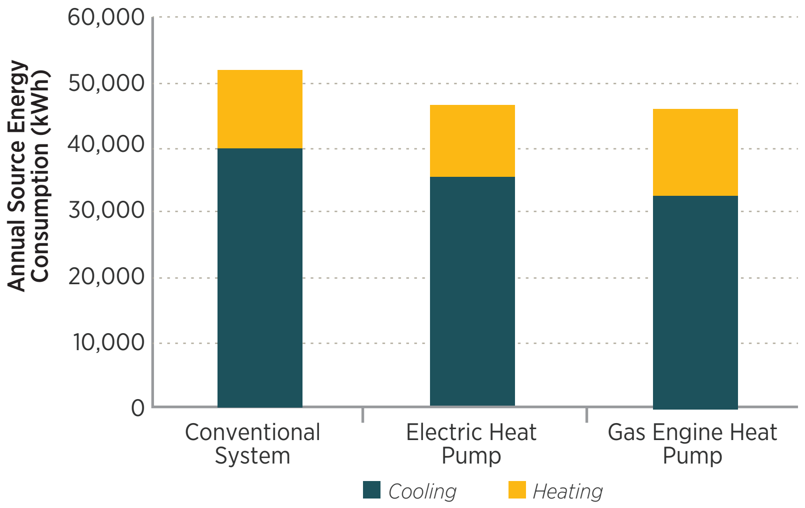


Figure 12-5: Source Energy Consumption

The peak electrical draw of each system is shown in Figure 12-6. In commercial buildings peak electricity draw is an important factor to consider. As Figure 12-6 shows, the peak electricity draw of systems that are powered by gas, are only due to fan power and thus is very small when compared to systems the utilize electric compressors. The peak cooling electricity draw of the electric heat pump is larger than that of the conventional system because as a variable speed system it is capable of operating at a higher capacity than its rated capacity, thus drawing more power during its peak operating conditions.

The annual operating costs of each system within the PGE E-6 time-of-use billing structure are shown in Figure 12-7. Comparing operating costs shows that the cost of electricity is much greater than that of natural gas. The figure also shows that the annual cost for heating energy is roughly the same for the three systems with the GEHP using slightly more than the other two. This should not be the case because the heat recovery from the gas engine should allow the GEHP to operate more efficiently than the other two systems. Despite the higher cost of electricity, the electric heat pump is less expensive to operate than the conventional system. This may be due to many reasons including that as a variable speed system it incurs less losses due to cycling the system on and off than a conventional single speed compressor or slight differences in system efficiencies.

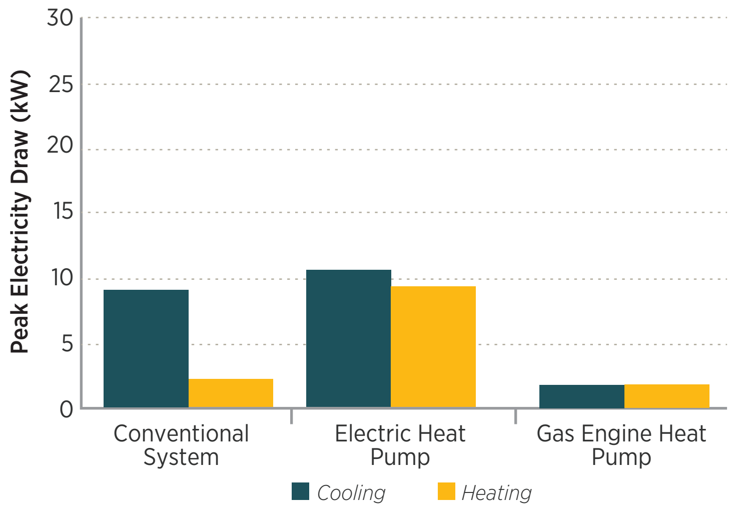


Figure 12-6: Peak Electricity Draw

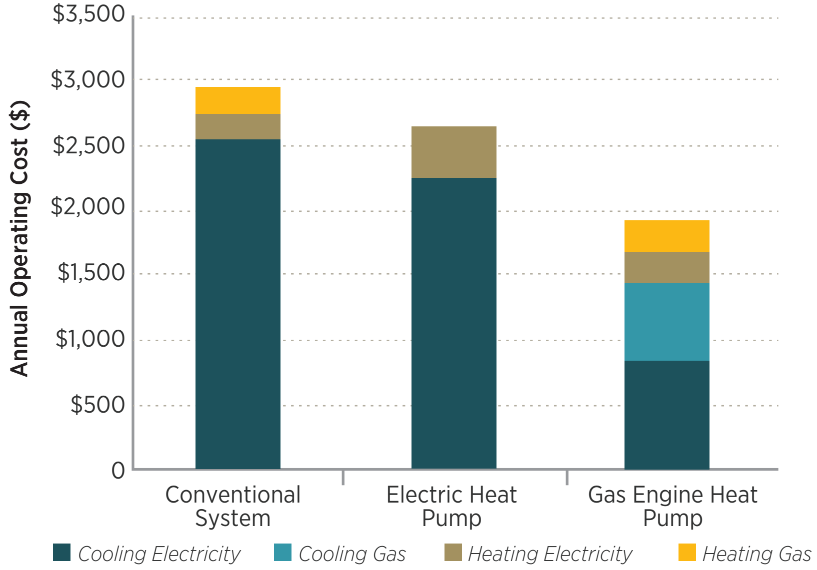


Figure 12-7: Annual Operating Cost in TOU Billing

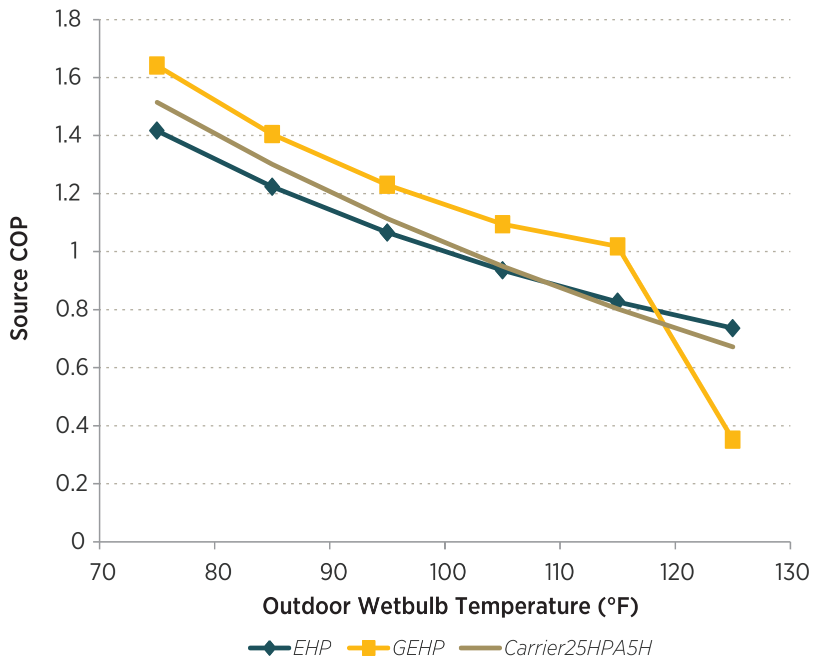


Figure 12-8: Source cooling COP for the EHP, GEHP and a standard Carrier 15 SEER heat pump at 100% PLR and a 67 °F indoor wet-bulb

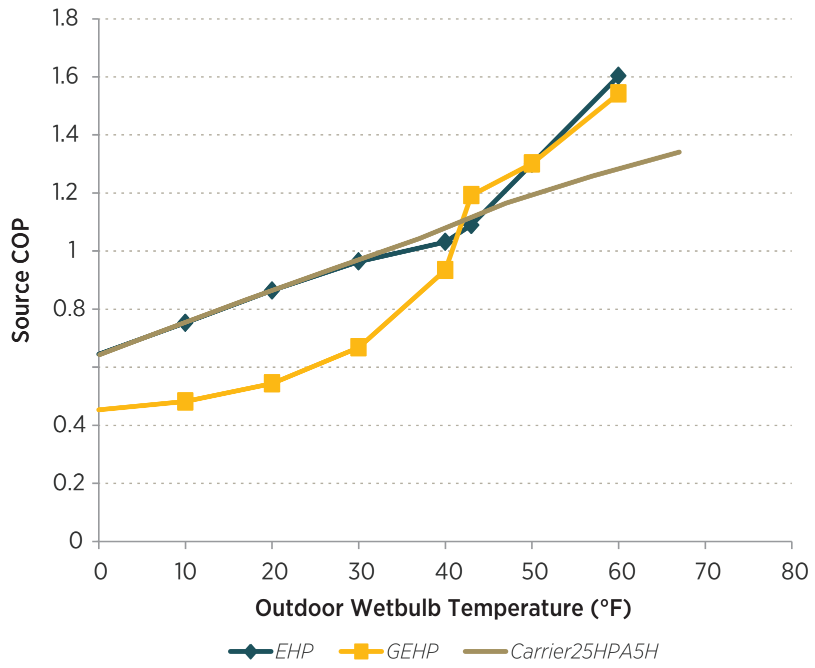


Figure 12-9: Source heating COP for the EHP, GEHP and a standard Carrier 15 SEER heat pump at 100% PLR and a 67 °F indoor wet-bulb

Figure 12-8 shows the GEHP performs slightly better than the EHP and Carrier unit for all but the hottest outdoor drybulb temperatures at which point the performance of the GEHP quickly decreases. Note that each system is compared on a source energy basis. Therefore COP is defined as thermal energy delivered / source energy used.

Figure 12-9 shows that when heating, the GEHP, EHP and the Carrier unit perform similarly at high outdoor wetbulb temperatures but the GEHP performance falls below the EHP performance at lower temperatures. The lower performance of the GEHP explains why the simulations show that the GEHP uses more source energy and is more costly to operate annually for heating than the EHP. However, this seems to be counter-intuitive; the GEHP should be able to take advantage of waste heat recovery during these operating conditions and should outperform the EHP. This suggests that the tabular data used to generate the performance curves for the GEHP may not adequately characterize the performance of the entire system in heating mode. This will be the subject of further investigation and refinement.

CONCLUSION AND CONTINUING WORK

This report represents the results of a model that still requires more refinement and calibration. Of primary importance will be to integrate the results of the laboratory testing into the modeling framework created here to increase the confidence in the results and to construct a tool that will be useful for making accurate comparisons between the selected technologies. As such, the results presented should be viewed as preliminary results and no firm conclusions should be drawn from the data presented at this point of model completion. Multiple areas of further improvement are outlined below that will be investigated and implemented over the remainder of the contract period. The results of these investigations and validated results will be integrated into the final report.

Based on the preliminary results presented, it is seen that there are wide variations between the systems when comparing site energy, peak power, and cost of operation in a time-of-use pricing structure. The source energy comparison showed much less variation between the systems, with each using roughly the same amount of source energy.

The results show that the electric heat pump is less costly to operate and more efficient in both heating and cooling than the conventional air conditioner and gas furnace. The improved performance of the electric heat pump over the conventional system is likely due to its variable speed operation. When the load on the building is small, the electric heat pump is able to operate at low and efficient speeds while the conventional system, which is single speed, must cycle itself on and off and incurs losses while doing so.

Due to the low cost of natural gas, the results show that the gas engine heat pump is less costly to operate in cooling than both the conventional system and the electric heat pump. However, the results indicate that the gas engine heat pump performs less efficiently in heating than the other two systems. By comparing the performance curves it is apparent that this is because the data that was used to model the gas engine heat pump shows that its efficiency drops below that of the electric heat pump at low outdoor wetbulb temperatures. The opposite should be true because the gas engine heat pump is capable of recovering the waste heat from the gas engine and thus should operate much more efficiently when heating. Further investigation into the performance data for the gas engine heat pump will be conducted

CONTINUING WORK

The model has shown some areas of unexpected behavior the merits further study. In general continuing work will focus on refining the accuracy of the model and preparing it for calibration with the laboratory test data that will be gathered as part of future tasks on this project.

The present results show that the GEHP performed marginally worse for heating than both of the comparison systems. This is unexpected as the gas engine heat pump should have the advantage of waste engine heat that it can use to improve its heating performance.

A comparison of CO2 emission from each system is expected to closely match the source energy usage results. There will however be slight variations due the different amount of electrical energy used on site, and the amount of natural gas used on site.

Continuing work will also explore the possible advantages that could be gained if the waste heat during the cooling season was used to supply domestic water heating loads. With proper integration the GEHP can take advantage of both space cooling and domestic hot water heating. This will also be explored.

The gas engine heat pump is capable of recovering waste heat, but that capability has not shown to increase heating efficiency over the electric heat pump model or the conventional Carrier unit.

PHASE-CHANGE MATERIALS FOR HYDRONIC SYSTEMS

This project is investigating the feasibility of adding micro-encapsulated phase change materials (mPCMs) into hydronic cooling and heating systems to reduce the energy needed to circulate the fluid in the system. The capacity of a hydronic system is primarily a function of the fluid flow rate, the heat capacity, and the temperature differential across the heat exchanger. Adding mPCMs will increase the effective heat capacity of the water, allowing for a reduction in water flow rate while providing the same amount of heat transfer. Since the pumping power is roughly proportional to the cube of the flow rate, reducing the flow rate leads to significant power savings.

There has long been interest in using PCMs for thermal storage with the current primary focus being on load shifting for peak load reduction. While the only widely available commercial system uses ice as the phase change material, this work has resulted in a significant body of literature on the properties of bulk (or macroencapsulated) PCMs, much of which is relevant to our work here.

KRIS KARAS, GRADUATE STUDENT RESEARCHER, TESTING THE SIZE DISTRIBUTION OF PCMS WITH A LISST INSTRUMENT

PREVIOUS RESEARCH: LABORATORY TESTING

FURTHER MECHANICAL CYCLING TESTS WITH DIFFERENT MPCM SIZES

Analysis of the mechanical cycling data suggests low rupturing rates for small diameter mPCMs in the centrifugal pump and suggests that large diameter mPCMs withstand cycling in a diaphragm-type pump. In particular, no dramatic "fall off" in diameter concentration is observed in either test after many thousands of cycles. However, whether rupturing is entirely eliminated in either case has not been determined. The number of cycles used with the diaphragm pump was only around 6% of the number tested in the centrifugal pump due to lower flow rates associated with this pump, which necessitated long run times to accumulate a large number of cycles.

Preliminary studies on energy savings have been conducted in the lab using the results from the tests of the 64ºF, 20 micron MPCMs. Generally, it was found that slightly greater RPMs were required to pump MPCM slurries at the same flow rates as clear water due presumably to the increased viscosity of the slurries. Thermal transfer improvements due to MPCMs must therefore be above a threshold corresponding to a slightly higher RPM and flow rate for clear water before the MPCMs provide an energy benefit. Since improvements in thermal transfer appear to increase with increasing flow rate, and only about half the MPCMs actually change phase, this suggests that a threshold flow rate- or heat transfer rate- exists below which energy savings cannot be realized.

Figure 13-1 shows data from a run in which a 16% concentration of 62ºF MPCMs was pumped through the heat exchanger at several flow rates. The heat transfer rates associated with the MPCMs were then matched to clear water runs. The plot shows that greater energy savings occurred at higher heat transfer rates, with savings as high as 30% at the highest flow rates tested. Energy savings appear to disappear below 15,800 BTUs/hr, corresponding to flow rates of ~3 gpm.

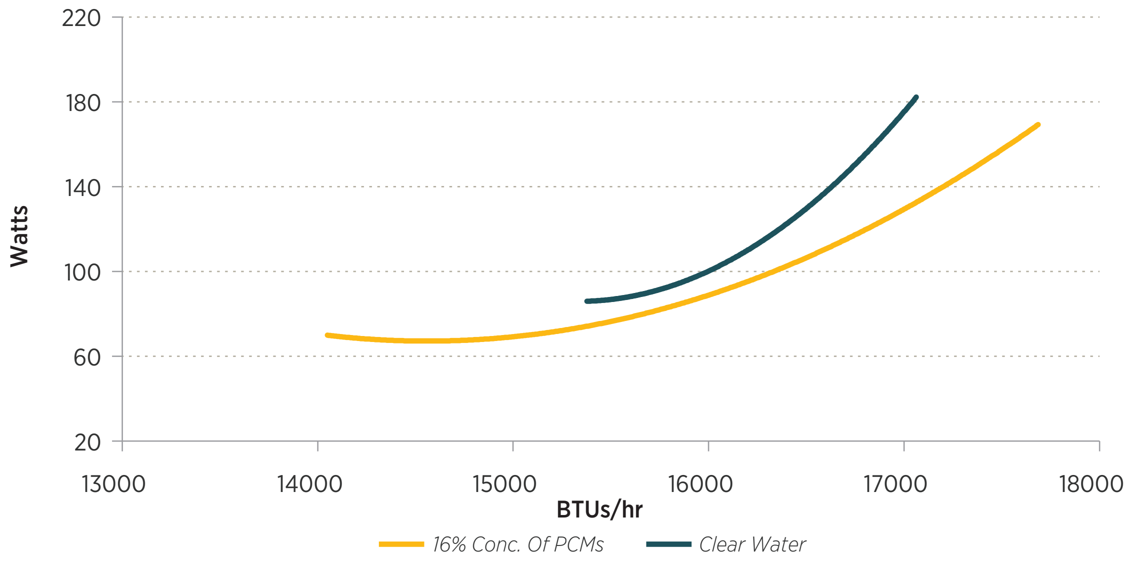


Figure 13-1: Pumping power measured against heat transfer rate for 62°F MPCM slurry and clear water. Slurry entry temperature is 56°F and air entry temperature is 110°F.

Only 30%-50% of the mPCM material actually changed phase during cycles through the heat exchanger.

A thermal performance test was conducted at an unoccupied demonstration building to determine the performance of the mPCMs in a field test. The building is located south of the UC Davis campus. It is approximately 200 ft2 with an average ceiling height of 10.5 ft. The walls are concrete ~5" thick. Its air handling unit consists of a single coil and fan which draws outside air without recirculation. The air coil was originally linked via copper pipe to a 3 ton chiller.

Experimental retrofitting began in late December. Winter time conditions led to the decision to rebuild the system as a heating system rather than testing the MPCMs in the original cooling system. For this purpose, a tankless Argo "AT" series electric boiler rated at 34,120 BTUs/hr (10 kW) was selected and purchased.

SETUP & INSTRUMENTATION

The boiler was mounted on an outdoor wall in order to avoid boring holes through the building's 5" concrete walls for piping and wiring. The system's original copper piping was cut at the entry and exit points to the air handling unit and flow was rerouted to the boiler using 1" PEX piping and Sharkbite fittings. Fittings for valves, gauges, and spigots were of galvanized steel. The piping was insulated with fiberglass pipe wrap insulation which had a nominal R value of 3.3.

A single horse power Taco centrifugal pump mated to a 3-phase motor was installed to circulate the water/slurry. The pump's motor was connected to a single-phase-to-three-phase variable frequency drive (VFD) manufactured by Eaton. A relay was installed across the boiler's pump terminals to provide on/off control of the pump through the VFD, allowing the boiler to automatically shut down and start up the pump in response to a heating demand.

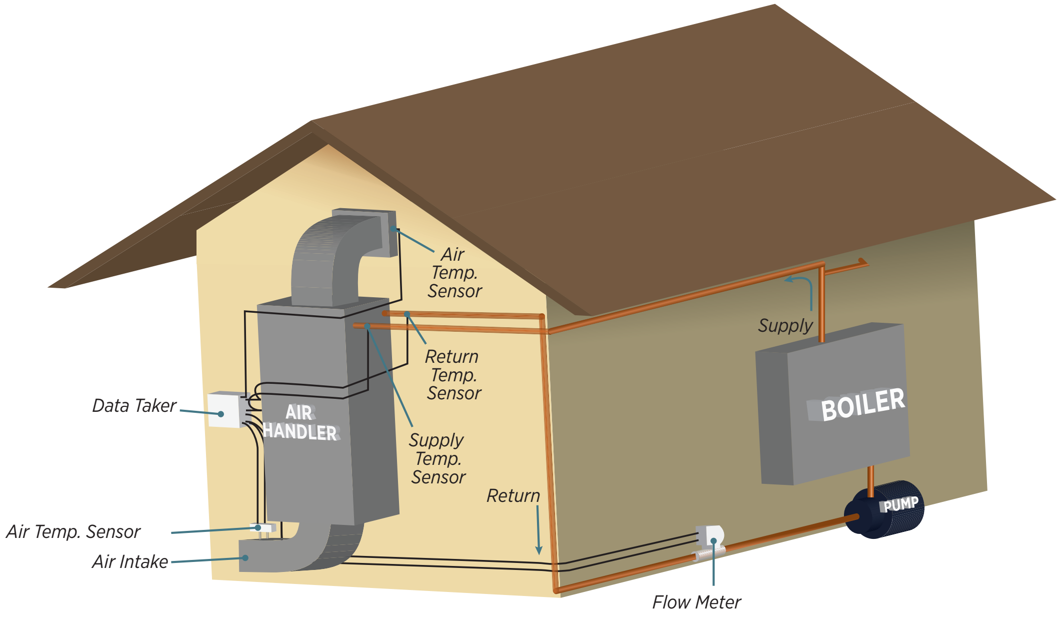


Figure 13-2: Diagram for the PCM demonstration building

The building's air-handling coil and fan were left unmodified. No manufacturer data could be found on either unit. Powerscout readings over multi-hour runs showed the fan's speed to be non-varying. Rough performance measurements of the air coil showed that its heat transfer coefficient was higher than that of the laboratory coil for similar air and water flow rates. In order to safeguard against unexpected startup/ shut down of the fan, the fan's original thermostat control was disabled and control was rerouted to the boiler pump relay. A resistance heating element which originally provided heating for the building was also disabled. Ducting and an air damper were added to the entry point of the air handling unit in order to allow control air flow into the unit.

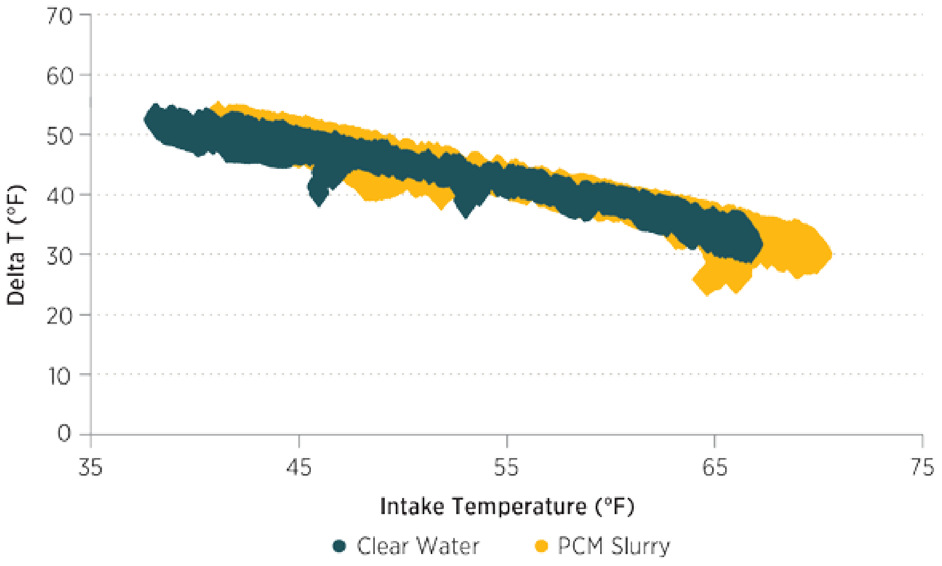


Figure 13-3: Temperature rise of air between intake and outflow of both clear water and mPCMs

Figure 13-3 is plotted from data obtained respectively for a clear water baseline run and the run in which a 14% concentration of MPCM slurry was used. The clear water run was made on the day prior to the slurry run. All parameters including liquid supply temperature set-point, liquid flow rate, and damper valve angle were kept constant between the two runs. Pumping speed was adjusted on the slurry run in order to maintain the same flow rate as the clear water run. The parameters used were a fluid supply temperature of 112°F, a 5 gpm water/slurry flow rate, and a 45° damper valve angle. Each test ran for roughly 20 hours, covering both night time lows and day time highs. The thermostat terminals in the boiler were linked together with a jumper wire in order to produce a continuous heating demand and insure that the boiler and pump would not shut off. Data on all temperatures and on liquid flow rate was taken every 5 seconds by the Datataker.

When the trend lines for the resulting plots are plotted against each other over the range of intake temperatures observed, discrepancy between the trend lines is on the order of 0.1°F, suggesting that virtually no change in air flow has occurred.

In Figure 14-4, supply and return temperatures have been plotted over the course of a single night for an early test in which a fixed speed pump was used to circulate water at ~5 gpm. The heavy oscillations of both the supply and return temperatures are immediately apparent and have amplitudes > = 8°F. This is roughly 4-5 times as wide as the bulk melting range for the 110°F MPCMs. Laboratory testing has shown that effectiveness of the MPCMs is highly dependent on the slurry supply temperature. This temperature must remain close to the upper or lower end of the MPCMs' melting range, with tolerances of only 1°F – 2°F, or else the ratio of latent to sensible heat absorption rapidly falls off. Thus, it is imperative that a method of "tightening" boiler control of the water/slurry temperature be developed.

PATH FORWARD

Upcoming work will focus on improving boiler control of fluid temperature set-points. It is expected that once a temperature set-point can be maintained to within a 1-2° tolerance, observable effects from the MPCMs will be realized. Once these effects have been demonstrated, subsequent runs with clear water will be made in an attempt to match thermal transfer rates observed with the MPCMs. Once the clear water flow rate is found at which thermal transfer rate matches that observed with the MPCMs, it will be possible to gauge energy savings from comparisons of pump, boiler, and fan power consumption between the slurry and clear water runs.

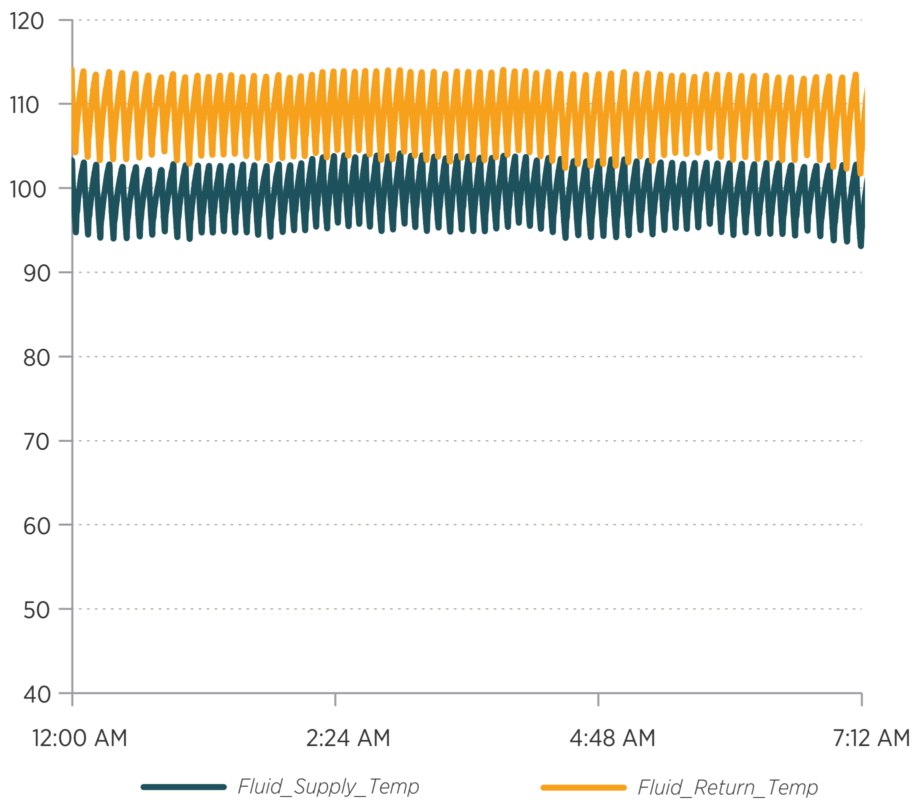


Figure 14-4: Fluid supply and return temperatures for clear water measured over the course of a single night. Boiler set-point temperature is 114°F and flow rate is 5gpm

TRACER GAS AIRFLOW MEASUREMENT SYSTEM

The current status-quo methods for measurement of airflow in HVAC systems are inaccurate and time consuming. It is especially difficult to measure airflow rates through air handlers and rooftop units. In many instances, physical limitations prohibit the proper use of conventional tools such as anemometers, pilot tubes, and capture hoods. Tracer gas airflow measurement is an alternate method for measurement of airflow rates. The tracer gas airflow measurement has provided an alternate method for many years. It is even covered by ASTM E2029 - Standard Test Method for Volumetric and Mass Flow Rate Measurement in a Duct Using Tracer Gas Dilution. However, it is not used widely, except by researchers, in part because there has been no viable product. Our project was funded by the UC Office of the President to improve upon and commercialize a tracer gas airflow measurement system based on intellectual property initially developed by Lawrence Berkeley National Laboratory. LBNL's innovation focused mainly on a new method to ensure good mixing of the tracer gas into the air flow stream.

TRACER GAS AIRFLOW MEASUREMENT SYSTEM.

A major innovation developed as part of this project is a method to allow operation over a wide dynamic range of airflow. This technology is capable of measuring between 50-20,000 cfm with better than 2% uncertainty, and up to 50,000 cfm with better than 5% uncertainty. For comparison, the status quo method of flow measurement in ducted systems only reaches 5% uncertainty in controlled laboratory environments. In real world scenarios, uncertainty of those methods is actually much higher. Being able to measure 50-50,000 cfm with such high accuracy using a single tool will be a boon to researchers and contractors alike. The exact same tool can be used to accurately determine the mixture ratio of multiple air streams, and to measure the in-situ air change rates for buildings.

The potential applications include: measurement of airflow rates in ductwork, measurement of air change rates in rooms, measurement of air mixture fractions (such as for accurate determination of airflow rates). Potential users include HVAC contractors, technicians, test and balance contractors, engineers, researchers, building energy auditors, commissioning engineers, codes officials. Due to the comprehensive nature of this technology, even RTUs with no outside air dampers are found to bring in outside air through leaks. Typical modelling protocols would not count the leaks present as a form of outside air and would incorrectly assume an outside air fraction of 0, when in reality, after testing using the Tracer Gas system, the outside air fraction due to leaks was on the order of 20% in one real world test. This has a profound impact on predicting performance of adding technologies to buildings and can help ensure proper load balancing and troubleshooting.

PATH FORWARD

In the effort to commercialize this technology, WCEC is refining the software/interface design to streamline its usability with a heavy focus on automation. Therefore, we are focusing the majority of our effort in developing a clean 'plug-and-play' system that is both simple for contractors to use and offers greater flexibility controls demanded by researchers. To that end, WCEC will continue to develop the software side of the technology and will validate its usability through a series of tests in WCEC's laboratory.

The current completed tracer gas system (laptop not included)

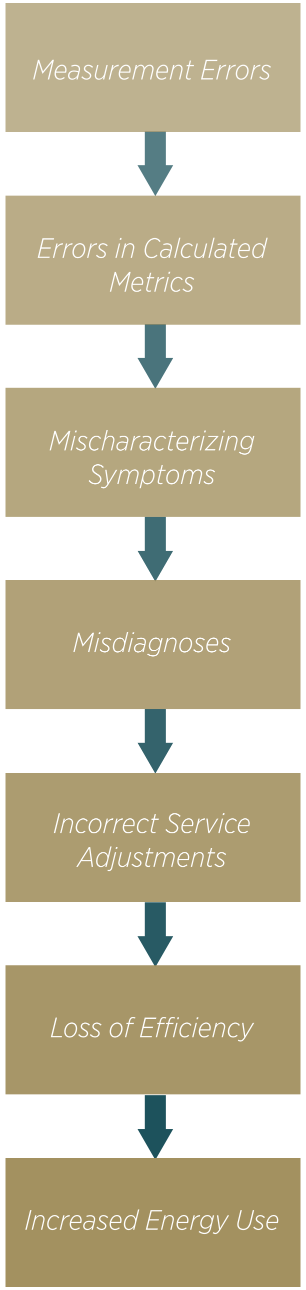
HVAC TECHNICIAN INSTRUMENT LABORATORY

HVAC (Heating, Ventilation, and Air Conditioning) systems are fundamental to the comfort of people inside buildings. Consequently, a significant amount of electricity consumption in buildings comes from maintaining this comfort. Some of that energy consumption has less to do with the initial equipment's efficiency, and more to do with how well it's maintained over the useful life of the machine. These systems need to be installed correctly and maintained to operate at optimal performance and efficiency.

It has been suggested that the instrumentation available to technicians in the field is not accurate enough in predicting refrigerant properties, and thus leads to improper adjustments in the field, which makes the full expected savings difficult to achieve. The HVAC Energy Efficiency Maintenance Study ("HEMS", Hunt et al, 2010) suggested that uncertainties in instrumentation accuracy could account for at least some of the failure to produce the expected savings.

The HEMS study identified the need for research into instrumentation performance, to identify whether or not instruments are as accurate as their manufacturers promise and called for the study that is described here. If we do find gaps between promised and actual measurement accuracy, though, does this necessarily mean that there is a significant problem? Or is the current level of accuracy "good enough"? Would spending more on more accurate instruments be cost-justified through improved energy performance?

INSTRUMENT TESTING APPARATUS AT WCEC'S LABORATORY IN DAVIS, CA



With funding from CEC's PIER program, WCEC developed a lab to evaluate the accuracy of HVAC service instruments. After testing 69 refrigerant temperature, refrigerant pressure, and air temperature instruments (Figure 16-1), we found that on average, accuracy was satisfactory, although there were many individual "outlier" instruments in each category.

In addition to testing the accuracy of these new instruments, we also invited technicians into the lab and tested the gauges that they typically use in their service, so that we could observe a wider range of accuracies that might be found in the field. We tested a total of thirty-eight instruments from six contractors (note that some instruments were used for multiple purposes, such as pressure gauges that also had line temperature sensors: these were counted twice).

FIGURE 16-1: INSTRUMENTS TESTED IN THE LAB

Category of Instrument	Type of Instrument	Quantity Tested	
		New	*Technician owned*
Refrigerant Line Pressure	Analog Instruments	3	13
	Digital Instruments	6	
Refrigerant Line Temperature	Stand-alone Instruments	4	13
	"Dual" Temperature and Pressure Instruments	6	
Air Temperature	RTDs: Immersion Probes	1	12
	Thermocouples: Bead Probes	5	
	Thermocouples: Immersion Probes	3	
	Thermistors: Bead Probes	2	
	Thermistors: Immersion Probes	1	

The goal is to increase energy savings from utility programs and building codes, by facilitating the adoption of more suitable instrumentation for HVAC installation and maintenance, and identify suitable methods of using these instruments.

The experimental apparatus for this project consists of a HVAC system operating as if it were installed in a residence or a small business, where technicians from companies and private practices can use their instruments as they would if they were in the field. The accuracy of their measurements will be tested by comparing the values they find to the values acquired by the calibrated instrumentation installed in the system.

This system makes use of a water-to-refrigerant heat exchanger that provides the same heat to the refrigerant line and is an appropriate substitute to a standard residential A/C system that does not take as much space as a conventional air conditioning system would.

The system is provided with several electronic controls that will be used to maintain the desired conditions (95°F condenser inlet air temperature, 80°F evaporator inlet water temperature). Resistance Temperature Detectors (RTDs) are used to monitor water, refrigerant, and air temperatures throughout the system and to control hot water flows.

The condensing unit of the HTIL Lab houses the compressor where the refrigerant is converted from vapor to liquid and is charged with 5 pounds of R-22. A fan blows out air to remove the heat from this conversion to outside. A flexible duct is connected the top of the condensing unit to the air outlet. This duct was removed for this picture so it would be possible to see the fan.

LABORATORY TESTING INSTRUMENTS AND RESULTS

The results of the tests utilizing the new instruments to measure refrigerant properties are detailed in this section. For each instrument type, we provide the individual test results for each instrument, at the four test conditions (ambient temperatures of 85, 95, 105, and 115). Actually, each individual result shown is the average of about ten readings taken a minute apart. Each of the reported individual test results is the average "error" for each test: that is, the average of 10 one-minute readings from the instrument, subtracted from the average of 10 one-minute readings from the reference instrument at the same time. Hence, the readings of the reference instruments is assumed to be the "true" value, which the tested instruments are attempting to match.

For the each of the refrigerant pressure and temperature tests, we report three different error values:

» The Manufacturer's Stated Error, which is the stated accuracy in the instrument literature (top set of results).

» The Total Measured Error, which is the difference between the reference instrument and the tested instrument (described above…in the bottom set of results).

» "Field Factors" which we define to be the difference between the Manufacturer's Stated Error and the Total Measured Error, and is thus somehow capturing a range of factors that might lead one instrument to read differently than another. The numbers shown are the average differences, and negative numbers are shown as zero (-).

		High Pressure	Low Pressure	Line Temp	Air Temp
Title 24 2013		± 7.0 psi	± 3.5 psi	± 2°F	± 2°F
Higher Accuracy: • *Digital P* • *Dual Line T* • *RTD/Thermistor*	Median	± 3.1 psi	± 0.4 psi	± 0.5°F	± 0.7°F
	Extreme	± 6.9 psi	± 1.6 psi	± 5.5°F	± 2.8°F
Lower Accuracy: • *Analog P* • *Standalone Line T* • *Thermocouple*	Median	± 3.0 psi	± 0.4 psi	± 1.2°F	± 0.2°F
	Extreme	± 10.9 psi	± 6.9 psi	± 6.6°F	± 8.6°F

Figure 16-2: Comparison of Instrument Errors Found in the Lab and Title 24 Requirements, for the Higher and Lower Accuracy Instrument Types (as indicated), for both Median and Extreme Errors (highest absolute value error)

	P (hi-psi)		T (deg F)		P (lo-psi)		T (deg F)	
	Digital	Analog	Stand-alone	Dual	Digital	Analog	Stand-alone	Dual
Total Measured Error (RMS)	3.4	6.1	3.5	3.0	0.8	3.3	3.5	3.0
Manufacturers's Stated Error	4.2	1.0	2.6	1.1	3.1	1.0	2.6	1.1
"Field Factors" that Affect Error	1.2	5.2	2.2	2.2	0.1	2.7	2.2	2.2

Figure 16-3: Total Measured Errors (RMS) for New Instruments, Divided into Manufacturers' Stated Error and "Field Factors"

Figure 16-2 shows the errors for different instrument types. It indicates that:

- Median values of the errors are quite low: less than Title 24 requirements in all cases.
- Extreme values of the errors in most cases, however, are higher than Title 24 requirements.
- The median values for the "higher accuracy" and "lower accuracy" instruments are not far apart (eg, not much difference between digital and analog gauges).
- However the extreme values for the "higher accuracy" and "lower accuracy" are quite different.

Figure 16-3 shows the central tendencies of the errors in measurements (this time, they are root-mean-squared errors), split into total measured error, manufacturers' stated error, and "field factors" (essentially the RMS of all non-negative differences between measured and stated errors…note that it is therefore not the arithmetic difference between the two values). This indicates that the field factors for the analog pressure gauges are particularly high, suggesting that these instruments are particularly prone to errors in the field.

Findings from Figure 16-4 on impacts on efficiency and energy use include:

- Median values of the impacts on efficiency and energy are extremely low: generally much less than ± 1%.
- Extreme values of the efficiency impacts, however, are somewhat higher: ranging from less than 1% impact on EER to about 3%, with the exception of the impact of technicians' line temperature instruments which was more than 8% EER impact for TXV's.
- Extreme values of the energy impacts, however, are somewhat higher: ranging from less than 1% impact on annual energy use for nonTXVs (except, again, for technicians' line temperature sensors which is much higher) to about 1 to 5% for TXVs.

		TXV						NonTXV					
		Pressure (psi)			Line Temp (deg F)			Pressure (psi)			Line Temp (deg F)		
		New		Tech	New		Tech	New		Tech	New		Tech
		Digital	Analog		Stand-alone	Dual		Digital	Analog		Stand-alone	Dual	
Median	Inst. Err.	-3.1	-3.0	-2.9	-1.2	0.5	-1.3	-0.4	-0.4	-0.6	-1.2	0.5	-1.3
	SC/SH	-0.6	-0.6	-0.5	-1.2	0.5	-1.3	-0.2	-0.2	-0.3	-1.2	0.5	-1.3
	EER	-0.7%	-0.7%	-0.8%	-0.7%	-0.9%	-0.7%	0.1%	0.1%	0.0%	-0.8%	0.6%	-0.8%
	kWh	0.5%	0.5%	0.4%	0.4%	-0.8%	0.4%	-0.1%	-0.1%	-0.1%	0.2%	-0.2%	0.2%
Extreme	Inst. Err.	6.9	10.9	12.3	6.6	5.5	15.8	1.6	6.9	3.6	6.6	5.5	15.8
	SC/SH	1.3	2.1	2.4	6.6	5.5	15.8	0.7	3.2	1.6	6.6	5.5	15.8
	EER	-1.1%	-1.3%	-1.4%	-2.8%	-2.4%	-8.5%	0.8%	2.3%	1.4%	3.5%	3.2%	2.4%
	kWh	-1.9%	-2.3%	-2.4%	-1.9%	-2.0%	4.7%	-0.2%	-0.3%	-0.2%	-0.1%	-0.2%	4.4%

Figure 16-4: Implications of Measured Errors for Metrics, Efficiency and Energy Use, for both the Median Errors and the Extreme Errors (highest absolute value error)

CONCLUSION AND RECOMMENDATIONS

The findings from the laboratory measurements of technician instrument accuracy were somewhat surprising. The central tendencies (median values) of the errors showed very satisfactory performance. However, the errors in the outliers—that is, the instruments with the highest measured errors—are much higher, for the most part, exceeding Title 24 requirements.

We considered the potential impact of these errors on the performance of HVAC systems. The results suggest that only very large errors will significantly affect performance. We concluded that attempting to "fine-tune" every system to get the last ounce of savings may be less impactful than using simple screening tools that focus on detecting these egregious problems and administering methodical "differential diagnoses." For code compliance, making and verifying fine-adjustments may be challenging, so other less expensive and more reliable and repeatable methods to verify quality workmanship and use of best practices are needed.

The results of this study will lead to more effective practices for HVAC adjustment in Title 24, as well as in rate-payer funded quality installation and maintenance programs.

We also recommend that further research go into the "field factors" that can cause one instrument to be an outlier while on average the accuracy is acceptable. Also, ways to make the instruments more rugged so that their accuracy does not degrade after being in use for several years.

WCEC DIRECTOR MARK MODERA GIVING A TOUR TO THE NETHERLANDS STATE SECRETARY FOR INFRASTRUCTURE & ENVIRONMENT, WILMA MANSVELD

INDUSTRY SUPPORT & OUTREACH

WCEC has been involved in numerous activities to support industry in advancing energy-efficient HVAC technologies. WCEC was able to participate and influence the progress on a number of efficiency measures through a host of technical meetings, conference and other outreach speaking engagements. WCEC participated and chaired technical committees at ASHRAE to help shape Title 24 policy with regards to Fault Detection & Diagnostics; wrote the standard protocol for properly evaluating evaporative cooling retrofits; as well as involvement with numerous committees involved in HVAC efficiency including (but not limited to) ACCA QH Standard 12 Advisory Committee, ASHRAE SPC 207P, TC 6.3 and TC 7.5.

Also of note, WCEC has met with and consulted on energy efficiency strategies for a large number of prominent businesses in California including (but not limited to) Wal-Mart, Target, and Wells Fargo. WCEC also met with many representatives from HVAC manufacturing, contractors and a diverse group of policymakers from Jordan, the United Arab Emirates, Australia, and even with Wilma Mansveld, State Secretary for Infrastructure & Environment for the Netherlands.

THANK YOU TO OUR VALUED AFFILIATES & PARTNERS FOR ANOTHER SUCCESSFUL YEAR

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