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FINAL PROJECT REPORT

Energy Efficient Heating, Ventilation, and Air Conditioning Packages for Existing Residential Buildings

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Energy Efficient Heating, Ventilation, and Air Conditioning Packages for Existing Residential Buildings is the final report for Contract Number: EPC-16-005 conducted by the University of California, Davis Western Cooling Efficiency Center. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

This project demonstrated and evaluated two residential retrofit packages that use advanced technologies to improve single-family building envelopes, indoor air quality, and cooling efficiency. These technologies included a sub wet-bulb evaporative chiller, supply ventilation systems, and building-envelope sealing. Occupant comfort and indoor air quality were also assessed to study the potential benefits of adopting these retrofit packages.

The project team evaluated each technology independently. The evaluation showed mixed results. The sub wet-bulb evaporative chiller performed worse in the field installation than earlier laboratory and modeling studies suggested. The capacity was significantly limited by the air-side performance of the hydronic fan coil systems. Energy modeling indicated that the optimized sub wet-bulb evaporative chiller design showed substantial savings potential for California residential customers, with average cooling savings of 57 percent. With further development, the sub wet-bulb evaporative chiller has potential in the residential market.

The ventilation systems showed improvement in indoor air quality with average carbon dioxide and particulate matter decreasing 2.5 levels to within acceptable ranges relative to the baseline. Advanced controls were most effective in the cooling season when over-ventilating during cooler nighttime periods and avoiding or minimizing ventilation during hot daytime periods.

The aerosol sealing process successfully reduced home air leakage by 64 percent, and in the other case by 37 percent. This result was very impressive considering these were some of the first applications of retrofit sealing using an aerosol-based process.

Keywords: Residential retrofits, evaporative chiller, supply ventilation, envelope sealing, hydronic fan-coil

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Cooling loads constitute approximately 13 percent of the total electricity demand for the United States, and in the western states, the hot dry summers drive cooling loads and peak demand throughout the season. Currently, the market is driven by compressor based systems, which are inherently limited in efficiency and constrain the electric infrastructure. In California, because the climate is hot and dry, there is potential to expand the market to incorporate evaporative cooling. Cooling of single-family homes will account for more than 5,700 gigawatt-hours (GWh) annually by 2024.

This project demonstrated and evaluated two residential retrofit packages of advanced technologies capable of improving single-family building envelopes, indoor-air quality, and cooling efficiency. The first package featured a sub wet-bulb evaporative chiller with distributed fan coils, combined with a smart residential-ventilation system and a new aerosol-sealing technology that tightens building envelopes. The second package included the same sub wet-bulb evaporative chiller, connected to a central-system fan coil paired with a NightBreeze whole-house ventilation and precooling system and an aerosol-sealed building envelope.

Preliminary estimates show that these forward-looking technologies, that can improve single family building envelopes, indoor-air quality and cooling efficiency are reasonably cost effective. With estimated preliminary market pricing of various retrofits these retrofit packages cost under $10,000 for a 1,500 square-foot home. Key benefits to homeowners include lower electricity costs for cooling and better health through improved indoor-air quality. Key benefits to the state and utilities are reductions in overall and peak electricity loads and lower greenhouse-gas emissions from reduced or eliminated conventional refrigerants.

The central technologies in these retrofits proved very effective in laboratory and limited field evaluations, but without actual field demonstrations they are unlikely to win the essential outside support critical to long-term evaluations of their potential. For example, slow adoption of the previous generation of residential aerosol duct sealing revealed the urgent need for publicly funded research to move beyond current, less efficient practices. The interaction and synergies between the technologies in a retrofit package have additionally never been investigated, so the scale and potential of this opportunity are still far too uncertain to attract competitive market funding. Market barriers to adoption also extend beyond the basic concerns of cost, performance, and return on investment. A broad effort is required to not only prove the technical merits of the retrofit package, but also to demonstrate occupant satisfaction and market acceptance.

Project Purpose

This project evaluated the performance of two residential retrofit packages that incorporate advanced technologies for improving building-envelope sealing, indoor air quality, and cooling efficiency in California homes. The retrofit packages meet or exceed the goals that California has set forth in the "big bold energy efficiency strategies" described in the state's *Long-Term Energy Efficiency Strategic Plan*. The project's focus was to combine several cutting-edge technologies to create a cost-effective approach for bringing existing buildings up to current

California energy-efficiency standards and developing opportunities to encourage widespread market adoption.

Project Approach

The project's research team was led by the University of California at Davis Western Cooling Efficiency Center. Subcontractors included the Electric Power Research Institute, which provided the smart residential-ventilation system; Frontier Energy, which provided and installed the NightBreeze ventilation system; and Integrated Comfort, which provided the project's two cooling units.

The baseline equipment's performance was monitored in two participating homes for approximately one year. Data collection included monitoring the performance of the cooling systems, the ventilation systems, and indoor air quality. The residents of both houses were additionally surveyed throughout the project to gather feedback on the retrofit packages. After baseline monitoring, it was determined that the sub wet-bulb evaporative chiller would probably fail to meet peak cooling demands, and that the design required modification to add a small compressor for additional capacity. The retrofit technologies were then installed in the houses and the performance of the retrofit equipment was monitored for a second year. This allowed comparison of the baseline retrofit across a broad range of outdoor conditions.

Laboratory testing was also performed for the sub wet-bulb evaporative chiller. A sub wet-bulb evaporative chiller has the ability to cool below the ambient wet-bulb. This testing produced additional data that could not be collected in the field. The lab tests evaluated the sub wet-bulb evaporative chiller for operating in Stage 1 and Stage 2 cooling. This data also modeled the cooling unit. The model was created to develop effective design strategies and simulate the chiller's performance in different California climate zones.

The technologies evaluated in this project are not yet commercially available (the NightBreeze ventilation system was previously but is no longer available). In an effort to better evaluate their market value, an extensive market study was performed to determine their future market potential. This study examined both barriers and opportunities for the cooling system, ventilation systems, and building-envelope sealing.

Project Results

Energy-efficient retrofit packages like those evaluated in this project improve indoor air quality and reduce cooling energy consumption. Project results show that building-envelope sealing and mechanical ventilation can substantially improve indoor air quality. Results also reveal the potential for evaporative cooling to reduce energy use. The evaporative chiller evaluated in this project does require further development, but this research helped refine information for the design and controls for residential applications.

The sub wet-bulb evaporative chiller performed worse than expected in the field, but lab testing and performance modeling showed its potential for achieving, with some design changes, both greater cooling capacity and efficiency. Lab results showed that with a variable speed pump the sub wet-bulb evaporative chiller can provide cooling capacities near 1.5 tons, with a performance coefficient of 12 during peak conditions at an outdoor dry-bulb temperature of 105°F. Dry-bulb temperatures are shielded from radiation and moisture. A model of the chiller was combined with the lab results to perfect the design for residential applications, and further explored the implications of delivering cooling using a central or distributed (mini-split) fan coil system. The research team used the model to further improve the design and operation of the hybrid chiller by integrating a compressor. In some cases, the capacity for the sub wet-bulb evaporative chiller was more than double what was observed in field trials. Furthermore, the reconfigured chiller in Stage 1 cooling achieved similar capacities to the original design that operated in Stage 2 (with the compressor). Energy modeling with the redesigned sub wet-bulb evaporative chiller in a similarly sized home (as in the field test) showed substantial energy-savings potential, with average savings of 57 percent across all climate zones simulated. The distributed fan coil system showed a similarly promising performance as the central system in California's Climate Zone 12 but did not consider the implications of duct thermal losses and additional fan power related to duct air-flow resistance.

Building-envelope sealing and mechanical ventilation both substantially improved indoor air quality. Field results showed that CO_2 and particulate-matter levels decreased after the retrofit packages were installed. The NightBreeze ventilation system was fully developed but is no longer commercially available. The NightBreeze was originally developed in Davis, CA by energy engineers with the Davis Energy Group. Earlier versions were not connected to the internet and required a custom thermostat. NightBreeze has since been spun off, redesigned and patented as an Internet of Things device. The smart residential ventilation system was a prototype designed for this project, so this project will aid in its further design development.

Overall, this project concluded that with additional development, energy-efficient retrofit packages can potentially improve both energy efficiency and indoor air quality in existing homes in California. Given increasing wildfires statewide and events such as COVID-19, mechanical ventilation and building envelope sealing are two effective mitigation measures. The ventilation systems evaluated in this project both improved air quality and meet California building code standards. But the sub wet-bulb evaporative chiller requires additional development before it will be ready for implementation of the strategies recommended in this project, including the size of its components and its water- and air-flow rates. Model results show that with necessary reconfiguring, the sub wet-bulb evaporative chiller can potentially reduce cooling energy use by 43 percent to 75 percent in California. Furthermore, this chiller, in evaporative-only mode (Stage 1), met the load for a smaller, 872 square-foot home in all but one (Climate Zone 15) of California's climate zones. The chiller, in hybrid mode (Stage 2), was additionally able to meet the load for a larger, 2,400-square-foot home in all but three of the state's hottest climate zones (climate zones 11, 13, and 15). Future warming trends may require a more effective heat exchanger and associated fan, a cooler inlet water temperature or both.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The results from this project will be widely shared with a broad spectrum of stakeholders since the technologies evaluated were pre-commercial and the results are essential to further their development and create a path to market. This development is unique to each technology, so outreach and dissemination will likely focus on each individual technology rather than on the package as a whole.

Throughout this project, the University of California, Davis, Western Cooling Efficiency Center worked with the sub wet-bulb evaporative chiller patent owner to find a suitable manufacturing partner. Integrated Comfort, Inc., agreed to manufacture the cooling unit for the project demonstrations. The hybrid design for the chiller was the first design type for this unit. The team worked with Seeley Corporation, which purchased Integrated Comfort, Inc., during the course of the project and provided the field and modeling results that will determine the next steps for this technology. Seeley manufactures other evaporative coolers and develops similar hybrid systems; however, in communications with Seeley, the research team emphasized that the difficulty with a product like the chiller is that the consumer market values cool air for comfort (as opposed to cool water) and underscored the challenge of adding an additional heat-exchange process between the water and the air. The modeling results from the chiller will be submitted to a journal for publication.

The results from the two ventilation systems will be shared with NightBreeze Corporation and the Electric Power Research Institute, which together are responsible for developing these systems for commercialization. Field results from the smart residential ventilation system will help the Electric Power Research Institute further develop controls and finalize its optimization algorithm. The Electric Power Research Institute is also seeking funding to further develop the smart residential ventilation system based on the promising results from this project. While NightBreeze Corporation is closest to commercialization, it still needs support to clear the path to market. The NightBreeze chief executive officer expressed specific interest in the publication of these results. Project results will also help the NightBreeze Corporation market its product and effectively communicate with heating, ventilation, and air-conditioning manufacturers.

This project demonstrated the first application of aerosol sealing in occupied homes and provided a foundation for further research. The results show a significant reduction in building envelope leakage and no major issues with sealant deposition on finished surfaces. While removing the contents from homes during installation was intrusive for occupants and substantially increased the cost, this necessity similarly applies to other situations such as moving or home renovation. This project also led to a subsequent project with the United States Department of Energy's *Building America* program, which is investigating the use of aerosol sealing in about 35 existing residences in California and Minnesota.

Benefits to California

This project presents a valuable opportunity for reducing operational costs for existing single-family homes in California while also providing increased occupant comfort and safety through improved ventilation. The sub wet-bulb evaporative chiller performed worse than expected in the field, but lab testing and performance modeling showed its potential for achieving, with some design changes, both greater cooling capacity and efficiency. Additionally, the mini-split coil, that worked in conjunction with the sub wet-bulb evaporative cooler was undersized and did not have enough capacity to keep occupants cool. . With further development of the sub wet-bulb evaporative chiller, cooling-energy use could be halved. Replacing just 10 percent of standard air conditioners by 2024 with this chiller system would save an estimated 285 gigawatt-hours of electricity across California, reducing greenhouse gas emissions by 96,000 metric tons. Envelope air sealing, together with smart ventilation systems, would additionally provide cooling-energy reductions by reducing cooling loads. This would further reduce home cooling-energy use.

Indoor air quality can be improved through better filtration, better sealing of building shells, and increased ventilation rates of filtered air. Indoor pollutants can harm respiratory health and include particulate matter, oxides of nitrogen, volatile organic compounds, and ozone.

While aerosol sealing a building envelope decreases unwanted outdoor pollutants in a home, ventilation is also required to bring in fresh outside air. By combining building-envelope sealing with mechanical ventilation that meets Title 24 requirements, air quality in existing homes across California could be improved. Once the houses in this project were retrofitted with both sealing and ventilation systems, indoor CO_2 and particulate matter levels were substantially reduced.

CHAPTER 1: Introduction

More than half of California homes were built before the state's energy standards were enacted. These ambitious standards have opened up opportunities for energy-saving retrofits and equipment such as those evaluated for this research project. The goal of this project was to assess the performance of two retrofit packages for improving the energy efficiency and indoor air quality of existing homes. Specific objectives of this project were to: 1) combine several cutting-edge technologies to create a cost-effective package for reducing residential energy use; 2) assess the installed performance (electricity use, indoor air quality, and occupant satisfaction) of two retrofit packages that feature envelope sealing, smart mechanical ventilation, and compressor-less air conditioning technologies; and 3) identify market barriers for adoption of these retrofit packages through engagement with multiple market players (e.g., real estate agents and property managers).

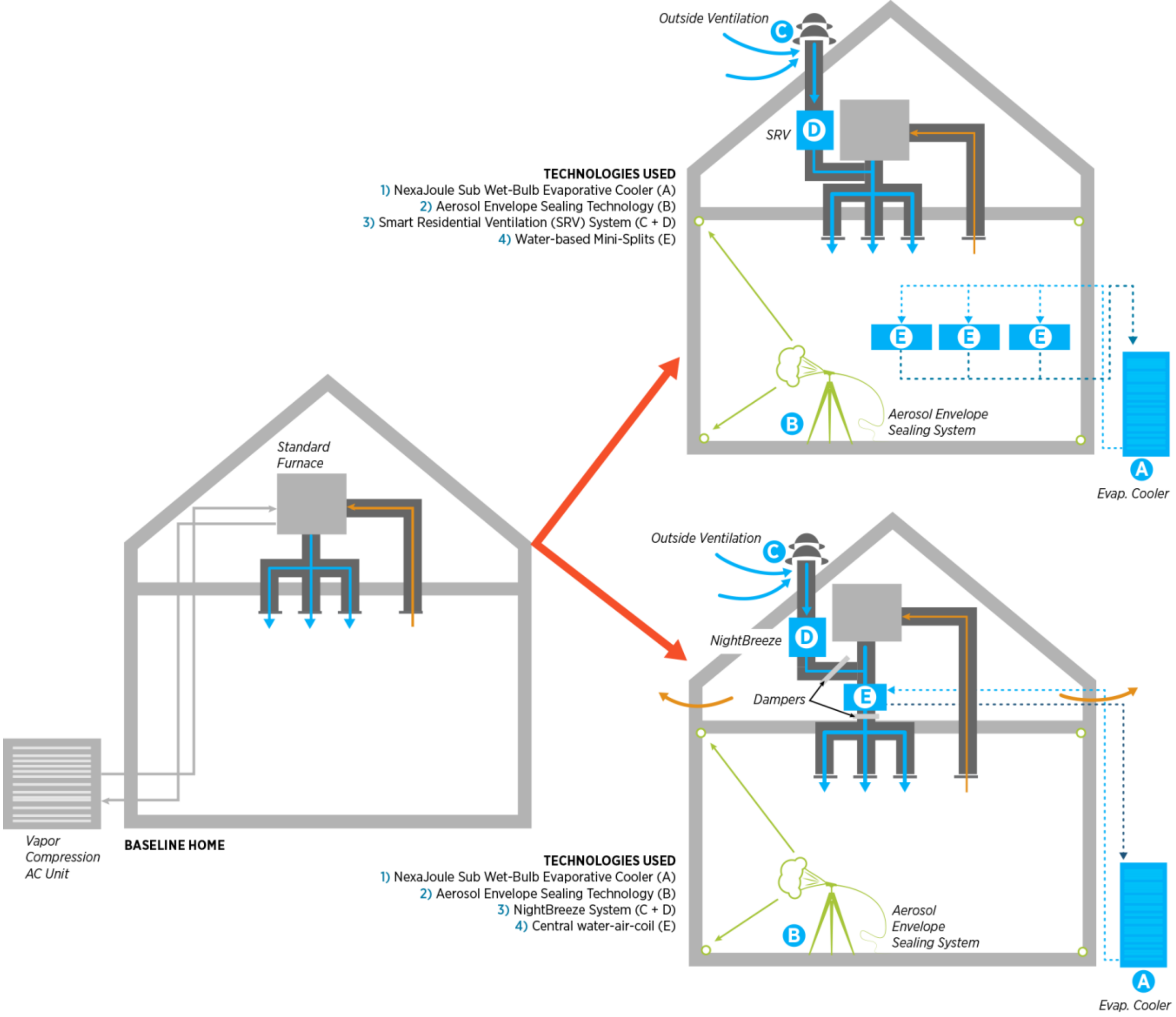
Retrofit Packages

Figure 1 shows a generic schematic of the existing heating, ventilation, and air conditioning (HVAC) system of the homes retrofitted for this project. The system illustrated consists of a furnace for heating and compressor-based air conditioning for cooling, as well as schematics of the two retrofit packages evaluated in this project. Following are brief descriptions of retrofit packages A and B.

The building envelope was sealed using automated aerosol sealing technology, and ventilation was provided by a smart residential ventilation (SRV) system. The SRV provides ventilation through the supply side of the existing ductwork through a secondary air handling unit and a variable speed fan (Unit D in Figure 1). The unit communicates wirelessly with a ventilation controller that determines the most efficient air-flow rate, based on ventilation requirements and weather conditions. The cooling system was replaced by a sub wet-bulb evaporative chiller (SWEC), which provided chilled water to terminal units in multiple zones of the house.

In the second retrofit package, the envelope was also sealed with an automated aerosol sealing technology, but ventilation was provided by a NightBreeze, Inc., (NightBreeze) whole-house ventilation system. While the NightBreeze controls were designed to use the furnace fan for heating, air conditioning, and ventilation cooling, the existing furnace in the participating home could not be converted to variable speed and had insufficient air-flow capacity. A second fan manufactured by Airscape was therefore installed in-line with the supply ductwork in the attic. Dampers were also installed in the supply and ventilation ducts. Both dampers were actuated when the NightBreeze control called for ventilation cooling, allowing the Airscape fan to deliver outside air through the supply registers without back-drafting the furnace. A third damper in the ceiling with insulated shutters also opened during fan operation to allow indoor air to be exhausted into the attic. A filter in the ventilation duct filtered incoming outside air. As in Retrofit A, the cooling system was replaced by a SWEC that provided chilled water to a water coil; however, in this retrofit, there was only one coil located in the attic. Ideally this coil would have been placed at the central air handler. However, due to limited space, the coil had to be installed in the attic, at the main supply duct.

Figure 1: Diagram of the Two Retrofit Packages Installed in Each House

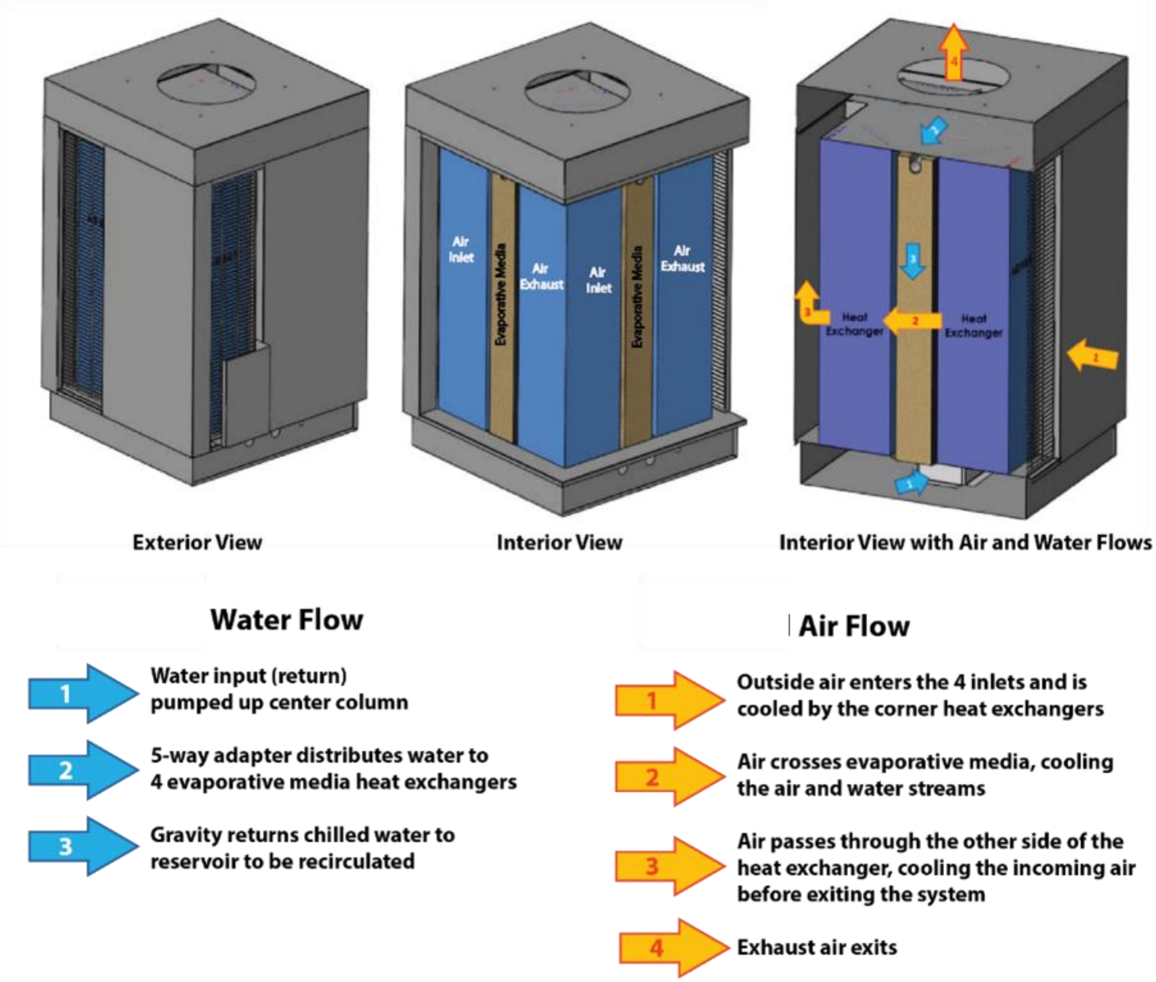


Source: University of California, Davis

Cooling Technology

The SWEC was manufactured by Integrated Comfort, Inc., (ICI) based on a design developed by Nexajoule, Inc. (Nexajoule), and uses an evaporative cooling process to chill water for building cooling systems. The patent-pending design (Application Number US2013/0333407) utilizes a two-stage system to chill water below the wet-bulb temperature of the outdoor air. As shown in Figure 2, The SWEC uses an evaporative cooling process to chill water in cooling systems. The patented design chills water below the wet-bulb temperature of the outdoor air. The design integrates four horizontal-plate heat exchangers and four sections of evaporative media in a daisy-chain configuration so that the exhaust from one section is used to precool the incoming air stream of the adjacent section. This reduces the wet-bulb temperature before it contacts the wet media. The theoretical limit for the supply water temperature becomes the dew point of the outdoor air, and less water is consumed than in a standard cooling tower. Laboratory testing has demonstrated the ability of the Nexajoule SWEC design to chill water with an energy efficiency ratio (EER) of between 29 and 110.[1] While this EER does not include the power needed for pumps that distribute the chilled water, or for indoor-fan energy use, the performance far surpasses even the highest-efficiency vapor-compression equipment on the market (which only approaches 21 without using chemical refrigerants). Because the water is a higher temperature than the refrigerant in traditional air conditioner coils, the coils have to be larger and the air-flow duration recirculating through the central system has to increase. While this would increase fan power when compared with conventional vapor-compression air-conditioners, the longer duration of recirculating air flow would improve indoor air quality. Unlike traditional evaporative cooling systems, no added humidity or contaminants are introduced to the indoor space.

Figure 2: Schematic of NexaJoule Sub Wet-Bulb Evaporative Chiller



Source: University of California, Davis

Nexajoule's early work on the SWEC system was funded through the California Energy Commission's (Energy Commission) Public Interest Energy Research Energy Innovations Small Grant program. ICI was acquired by Seeley International, which has a portfolio and expertise in evaporative-cooling methods and technologies. This partnership will potentially broaden the market for the Nexajoule system by providing a larger manufacturing base.

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[1] T. Pistochini and J. Garcia, *"Sub Wet-Bulb Evaporative Chiller".* Southern California Edison. Dec 2014. ET13SCE1260

During initial mechanical design efforts for the retrofit package, it was determined that the SWEC system alone would probably not meet peak-demand requirements at the demonstration sites. To avoid creating adverse comfort issues for the participants, it was therefore decided to integrate a small vapor-compression cooling cycle into the SWEC system as a second cooling stage for peak periods. This allowed the SWEC system to be evaluated both with and without the refrigerant-based cooling system. This modification would also extend the viability of the SWEC systems to other, more humid climate zones.

The refrigerant system was designed to take advantage of the evaporative cooling process to improve performance. The condenser was cooled by the exhaust air of the system, which is warm, humid air below the ambient dry-bulb temperature. This design reduced the condensing temperature, thus reducing the work required by the compressor.

Ventilation

California's Title 24 requires that new and rehabbed homes meet the American Society for Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) requirements for Standard 62.2.[2] Standard ventilation practice in both new and existing homes is to either introduce a damper-modulated outside air duct into the return air stream or run a bathroom exhaust fan 24 hours a day. In contrast, the two ventilation technologies selected for demonstration in this research project adopted an intermittent ventilation strategy (in compliance with ASHRAE 62.2), which provided cooling-load reductions through smart ventilation controls.

One of the project objectives was to evaluate and quantify the effectiveness of two residential ventilation retrofit solutions that fulfill ASHRAE 62.2-2016 requirements: EPRI's smart residential ventilation (SRV) and NightBreeze's cooling ventilation system, installed by Frontier Energy. Details of each ventilation system's installation and functionality are provided in Appendix A.

Both systems were installed in adjoining duplexes of the same size in Davis, California. Installations were completed by April 2019. The specification of the homes used as demonstration sites are shown in Table 1.

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[2] California Energy Commission, "2013 Residential Compliance Manual- 2013 Building Energy Efficiency Standards," Chapter 4: Building HVAC Requirements. Sept 21, 2015. http://www.energy.ca.gov/2013publications/CEC-400-2013-001/chapters/04_Building_HVAC_Requirements.pdf

Table 1: House Characteristics at Demonstration Sites

Characteristic	Value
Conditioned Area [ft^2]	900
Conditioned Volume [ft^3]	8500
# of bedrooms	3
Occupancy	4
ACH50* pre-seal – West House (SRV install)	5.54
ACH50 post-seal – West House (SRV install)	3.47
ACH50 pre-seal – East House (NB install)	6.64
ACH50 post-seal – East House (NB install)	2.42

*** ACH50: air changes per hour at 50 pascals**

Source: University of California, Davis

An important metric in assessing ventilation systems is the total ventilation provided: air volume delivered over time (expressed in cubic feet per minute [CFM]), expressed in imperial units (IPs). Based on the house characteristics (three bedrooms with a floor area of 900 square feet [ft2]), ASHRAE 62.2, Table 4.1 (Figure 3) shows a ventilation requirement of 60 CFM.

Figure 3: Table 4.1 Reprinted From ASHRAE 62.2 for Ventilation Air Requirements

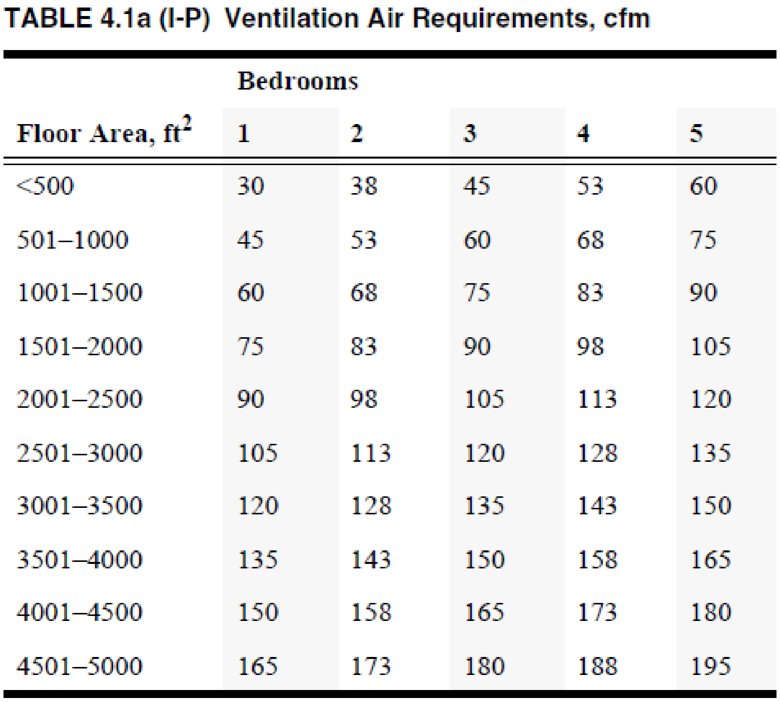

TABLE 4.1a (I-P) Ventilation Air Requirements, cfm

	Bedrooms				
Floor Area, ft^2	1	2	3	4	5
<500	30	38	45	53	60
501–1000	45	53	60	68	75
1001–1500	60	68	75	83	90
1501–2000	75	83	90	98	105
2001–2500	90	98	105	113	120
2501–3000	105	113	120	128	135
3001–3500	120	128	135	143	150
3501–4000	135	143	150	158	165
4001–4500	150	158	165	173	180
4501–5000	165	173	180	188	195

Source: University of California, Davis

Smart Residential Ventilation System

The Electric Power Research Institute (EPRI) team installed the SRV system in the West House and implemented time-varying controls, which were invented by EPRI co-principal investigator Ram Narayanamurthy.[3] The fan must overcome the static pressure in the supply air duct while providing energy-efficient ventilation. Therefore, a high-static pressure, in-line, backward curved fan was selected. During installation, it was decided to increase the size of the duct that connected the fan to the main-supply air duct. A fan box was fabricated to house the fan, with a filter sleeve upstream of the fan.

The time-varying controls were based on equations from ASHRAE 62.2, Normative Appendix C2, which are summarized in this section.

The total ventilation delivered can be a combination of infiltration and mechanical ventilation, as shown in this equation.

$$Q_{total,k} = Q_{fan,k} + \varphi Q_{inf,k}$$

$$\varphi = \frac{Q_{inf,k}}{Q_{inf,k} + Q_{fan,k}}$$

> Where φ is the additivity coefficient, k is the time step and Q_{inf} is the effective annual average infiltration rate, expressed in CFM.

To determine Q_{inf}, the infiltration rate was measured before and after the aerosol envelope sealing technology, summarized in Table 1. For the West Home, where the SRV was installed, the air-changes-per-hour (at 50 pascals [Pa]) pressure differential (ACH50), pre-seal, was 5.54, which gives a total air change of $Q_{tot,ACH50}$ = 47,090 ft3/hr. In setting up the algorithm, the post-seal ACH50 was assumed to be 2, with total air change of 17,000 ft3/hr, a conservative estimate compared with the measured post-seal ACH50 of 3.47. This shows how a tighter seal of the conditioned space requires higher ventilation requirements since the rate of air changes is greatly reduced.

To determine $Q_{total,k}$, the total air change is related to the referenced pressure of the ASHRAE standard of 4 Pa, using the following equation.

$$\frac{50}{Q_{tot,ACH50}{}^{2}} = \frac{4}{Q_{tot,ASHRAE}{}^{2}}$$

The subscript ACH50 represents the actual ACH50 readings, and subscript ASHRAE represents the infiltration, according to the standard's referenced pressure. This shows a rate of 80 CFM for infiltration post sealing in the West House.

ASHRAE 62.2 also provides a relative exposure procedure (in Normative Appendix C3), which is a requirement for time-varying total ventilation. This procedure requires a peak exposure limit of 5, which must not be exceeded, as shown here.

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[3] Narayanamurthy, R., et. al., Sept 15, 2011, "Method and system of ventilation for healthy home configured for efficient energy usage and conservation of energy resources," US Patent 0223850A1

$$R_k = \begin{cases} 1, if\ k = 1 \\ R_{k-1} + \dfrac{Q_{tot}\Delta t}{V_{space}}, if\ Q_{fan,k} = 0 \\ \dfrac{Q_{tot}}{Q_{total,k}} + \left(R_{k-1} - \dfrac{Q_{tot}}{Q_{total,k}}\right) e^{-\frac{Q_{total,k}\Delta t}{V_{space}}}, if\ Q_{fan,k} > 0 \end{cases}$$

R is the relative exposure and must not exceed 5, k is the time step, V_{space} is the volume of the house, and t is the duration of each stage.

The SRV algorithm was set up so that it would operate in optimized mode for one week, followed by a non-optimized mode for an additional week. The non-optimized mode served as the baseline for comparing the effectiveness of the smart version of the time-varying controls. During the non-optimized mode, the algorithm was programmed so that the fan would deliver a constant air-flow rate every hour for each 24-hour period, based on the total ASHRAE-required ventilation of 60 CFM. Instead, 75 CFM was set as the target value (as a safety factor) during the cooling season, and set to 30 CFM for the heating season.

For 75 CFM target, the daily ventilation delivered would therefore be 108,000 CFM for a 24-hour period.

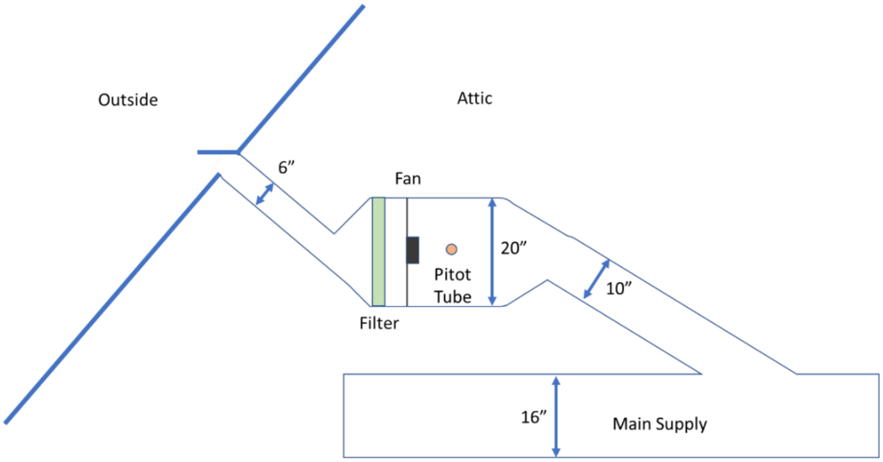
In the optimized mode, the algorithm would solve for a target CFM each hour, based on weekly outdoor air temperature forecast data as the input for the optimization code. The optimization code is described in detail in Appendix A.

Components:

The SRV system (shown in Figure 4) consists of a:

- Fan Box, with a variable-speed backward curved fan connecting to ducts with air filters.
- One-way damper or Y-connection ducts to prevent back-flow.
- Power connection of 120 volts of AC electricity (120 VAC).
- Controller (Raspberry Pi board) that executes the SRV optimization algorithm and connects to the pressure transducer as well as the fan. It was powered by the power strip and required either an ethernet or wireless fidelity (Wi-Fi) cable.
- For SRV, the ebm-Papst fan motor, with nominal power consumption of 75 watts (W), with a 1.2 amps (A) current draw at 2,450 revolutions per minute (rpm).

Figure 4: Schematic of Smart Residential Ventilation System Installed at the West House



Source: Electric Power Research Institute

Functionality:

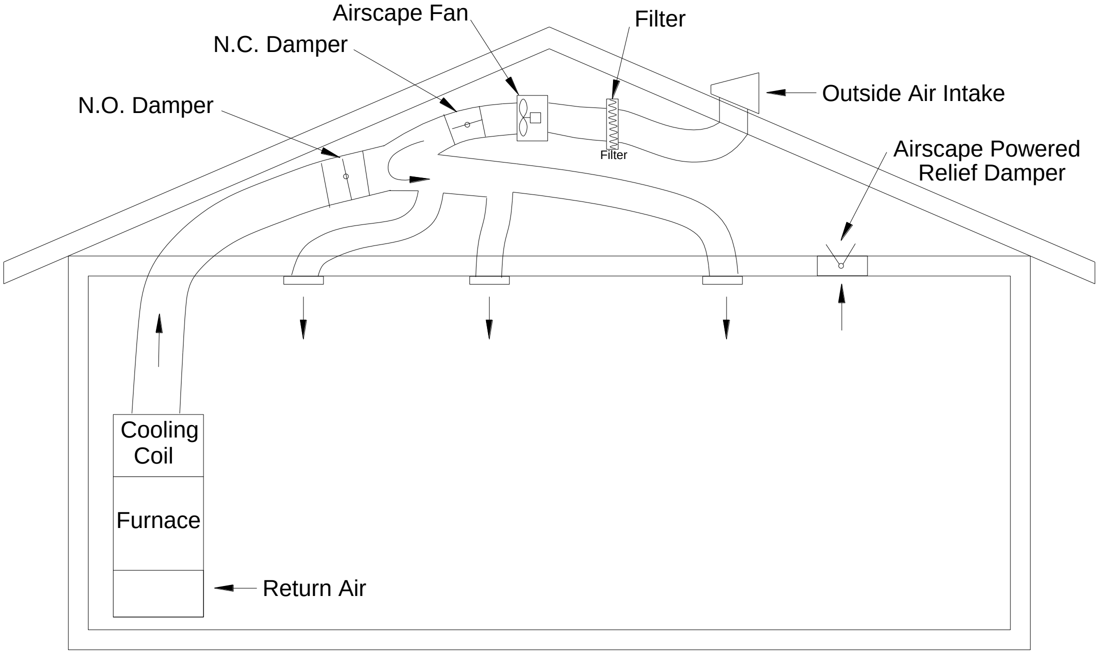
- The SRV system is a low-flow ventilation strategy utilizing ASHRAE 62.2 ventilation requirements (of Section 4) and the relative exposure procedure in Normative Appendix C for variable ventilation. The SRV system installed for this Energy Commission Electric Program Investment Charge (EPIC) project is the first prototype developed that fulfills ASHRAE 62.2 requirements.
- The SRV is a secondary air-handling unit with a variable-speed, low-flow, high-efficiency backward-curved fan that is ducted into the main supply duct. The fan speed depends on the optimization algorithm, which uses outdoor ambient conditions as its input. The algorithm tracks the total fresh-air flow rate to satisfy the total volume of ventilation required over a 24-hour period.
- The optimization algorithm provides the ventilation schedule based on ambient weather conditions in a given climate. It calculates hourly cooling or heating loads based on outdoor temperature and an assumed indoor temperature of 75°F and also minimizes each day’s total load by adjusting the ventilation rate. The controller can “over ventilate” during periods with low cooling or heating loads to avoid ventilating during peak-load periods. This prevents the ventilation system from increasing heating and cooling loads during peak periods, which could strain heating and cooling equipment and jeopardize occupant comfort. Since the SRV minimizes load based on the temperature profile, locations with larger daily temperature fluctuations may result in greater savings.

NightBreeze System

NightBreeze was manufactured for about 10 years by Advanced Energy Products a spin-off of Davis Energy Group, which was acquired by Frontier Energy, Inc. The product has been out of production since 2014, when the controls manufacturer stopped making it. NightBreeze was developed as part of the Energy Commission’s *Alternatives to Compressor Cooling* project. The goal of the project was to slow the growing increase in air-conditioner use in cooler climates where the units may be used for only a few hours per year, impacting utility peak loads. This product is suitable for any cooling climate where summer nighttime temperatures typically fall below 70°F. Since it is capable of using a furnace or heat pump to warm ventilation air, it is also suitable for climates with very low wintertime temperatures.

While NightBreeze controls were designed to use the furnace fan for heating, air conditioning, and ventilation cooling, the existing furnace in the participating home could not be converted to variable speed, nor did it have enough air-flow capacity, so a second fan manufactured by Airscape was installed. The NightBreeze ventilation cooling system was installed by Frontier Energy and uses the schematic shown in Figure 5**Error! Reference source not found.**.

Figure 5: Schematic of NightBreeze Ventilation System Connected to Existing Main-Supply Duct



Source: Frontier Energy

Components:

- The in-line Airscape fan used an electronically commutated motor compatible with NightBreeze controls.
- A wye-branch was installed in the main-supply duct from the furnace, and the branch was connected to the whole-house fan.
- Dampers were installed in the supply and ventilation ducts. The main-supply duct damper is normally open while the ventilation duct is normally closed. Both dampers were activated when the NightBreeze control called for ventilation cooling, allowing the Airscape fan to deliver outside air through the supply registers without back-drafting the furnace. A third damper in the ceiling with insulated shutters also opened during fan operation to allow indoor air to be exhausted into the attic. A filter in the ventilation duct filtered outside air.
- For NightBreeze, the fan motor specification was *321W ultra-high efficiency electronically commutated motor*, by AirScape. The motor was manufactured by Regal-Beloit.

Functionality:

- NightBreeze can be programmed to meet ASHRAE 62.2 ventilation requirements in winter, but summer ventilation compliance must be verified using the relative-exposure procedure in Normative Appendix C.
- In cooling mode, the emphasis was not on fresh air ventilation but rather on ventilation cooling. The operational objective was to eliminate or minimize air-conditioner use using ventilation cooling while incidentally meeting fresh-air ventilation requirements. The controller minimizes fan energy use and ensures occupant comfort by varying the fan speed according to how much cooling is required.
- In heating mode, ventilation occurs regardless of outdoor temperatures. NightBreeze operated the fan at the minimum speed of around 200 CFM for a fraction of each hour to deliver the hourly average volume of filtered outdoor air required by ASHRAE 62.2 and in accordance with Title 24 Part 6 code Section 150.0 meters (m), which also requires MERV 13 filtration of outdoor air.

Aerosol Envelope Sealing

Achieving a tighter building envelope reduces the energy required for heating or cooling a building. A tighter building envelope can also improve indoor air quality by reducing the penetration of both particles and ozone from outside. Both of these substances are regulated under the 1970 federal *Clean Air Act* because they are known to impact respiratory and cardiovascular health. By reducing uncontrolled infiltration by sealing leaks, outdoor air for ventilation can be controlled to minimize the thermal loads introduced and treated to remove unwanted pollutants.

Sealing building envelopes using traditional methods can be highly labor intensive and has variable success rates, especially for retrofits. The automated-envelope sealing process developed by WCEC involves pressurizing a home while introducing an aerosolized sealant inside the building. As air escapes through leaks in the building shell, sealant particles are transported to the leaks, where they form seals. Field testing efforts so far have returned excellent results in single and multifamily residential buildings, sealing up to 90 percent of leaks in less than two hours. However, the technology has yet to be rigorously tested as a retrofit. With the ability to achieve very tight enclosures, it is advisable to simultaneously address the home's ventilation system. Mechanical ventilation in existing homes is typically limited to exhaust fans that rely on leaks in the envelope to allow make-up air to enter the home.

Behavioral

Assessing occupant behavior included collecting data on thermal comfort, acceptability, usability, and overall user satisfaction with the installed technologies. Periodic data collections were conducted to account for seasonal variability and occupant familiarity with the new technologies. Data was collected in the pre- and post-retrofit periods on household size and composition, occupancy patterns, household activities related to cooling and indoor air quality, and other energy-use habits. With these indicators, the team was able to interpret and double-check results of the energy-use analysis and assess their generalizability (G theory).

CHAPTER 2: Project Approach

Field Testing

As part of the project, the team gathered field data to evaluate the new cooling and ventilation technologies. First, baseline data on the performance of existing systems in the homes were collected by monitoring both the cooling systems and indoor air quality for approximately one year beginning in December 2017. Next, the retrofit technologies were installed before summer 2019 and monitoring of the newly installed cooling and ventilation systems continued through July 2020. The approach to the field evaluations follows.

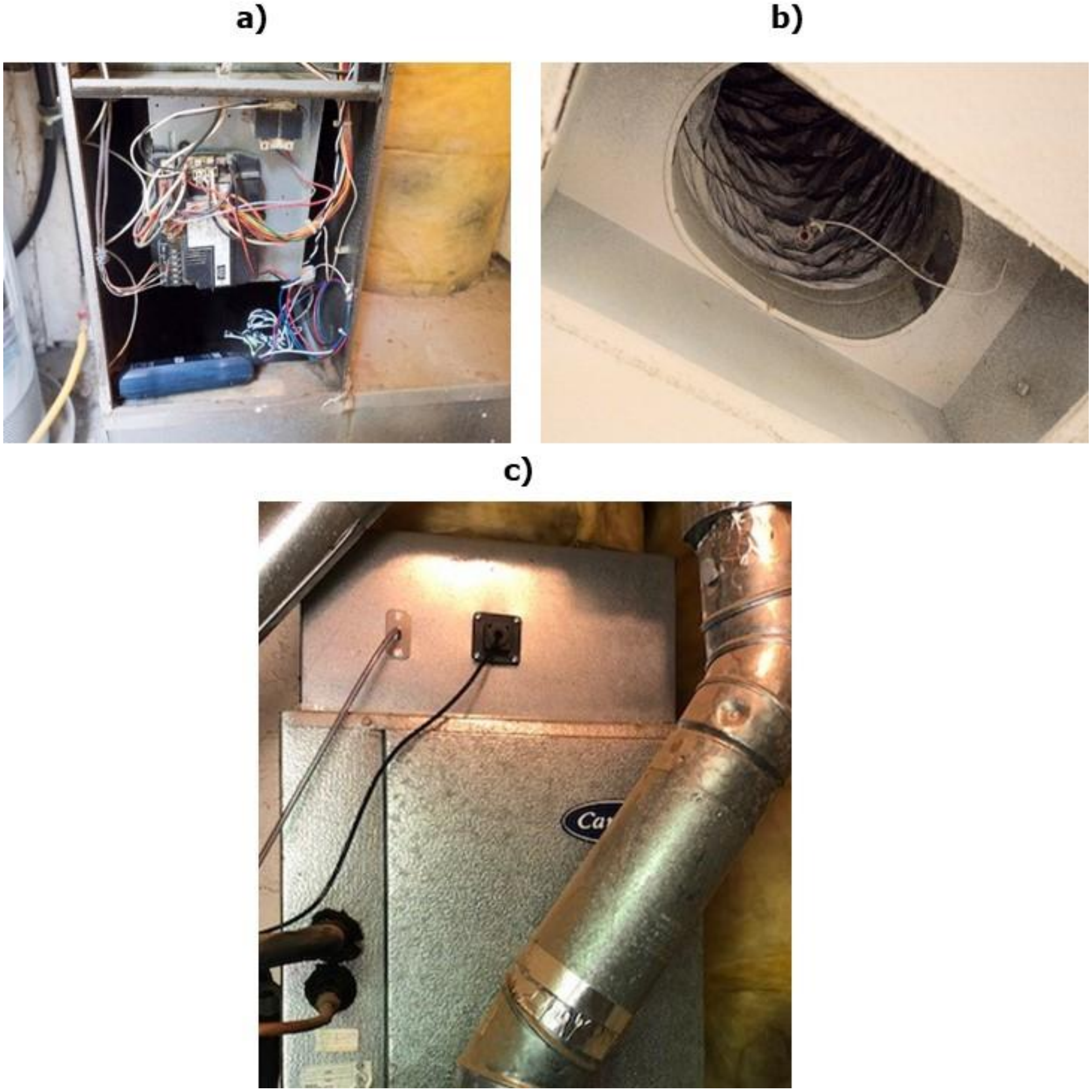
Baseline

The baseline monitoring for both homes was similar since both homes had identical installed equipment. The following describes monitoring efforts for these baseline systems.

Cooling

The performance of the existing cooling system was monitored during baseline testing. Measurements included supply-air temperature measurements at each supply grille in the houses, and return-air temperatures were measured at the return grille (Figure 6). Temperature and relative humidity measurements were monitored before and after air entered and exited the central air handler. A one-time flow measurement at each supply grille was taken using a power-flow hood and then combined with the grille temperature to determine the distribution of thermal loads. The temperature of the attic space was also monitored, which allowed duct losses to be calculated as a function of attic temperature. Cooling system power was monitored, including the outside condenser and indoor air-handler unit. Outdoor air conditions were additionally monitored to map performance of the cooling system to outdoor air-temperature conditions. The capacity and efficiency of the entire cooling system were determined with these measurements.

Figure 6: Monitoring of Performance of Existing Cooling Systems



a) Power measurement sensors on the air handler in one of the homes, b) resistance temperature detector (RTD) sensor inside one of the supply ducts in the home, c) pressure and temperature/relative humidity sensors inside the ductwork attached to the air handler.

Source: University of California, Davis

Ventilation

Many existing homes in California do not have installed mechanical ventilation systems since the Title 24 code did not require whole-building mechanical ventilation in residential buildings until 2013. Exhaust systems are generally installed in bathrooms and kitchens to remove pollutants from cooking fumes and humidity. Neither home monitored in this study had bathroom fans. Both homes did have kitchen exhaust; however, both were unvented recirculating systems that were poorly maintained and residents did not use them while they were cooking. Window operation is another method used to ventilate homes. Window operation was not directly monitored as part of this study, but occupant surveys were conducted to collect qualitative data on window-operation habits. Building leakage is measured as a rate of cubic feet per minute at 50 Pa, written as CFM50. The significance of the measured leakage depends on the volume of air in the building and is converted to the number of air changes per hour at 50 Pa, or ACH50. This is the number of times the volume of air in the building is exchanged hourly when subjected to a 50 pascal pressure difference and is the usual way to report home air leakage. Prior to aerosol envelope-sealing technology the West Home had an air leakage of 5.54 ACH50 and the East Home had a leakage of 6.64 ACH50.

Indoor Air Quality

Particles from the outdoor environment enter buildings through open windows and doors, cracks in the building shell, forced-air ductwork, and mechanical ventilation systems where there is an outdoor-air intake. Indoor particle levels are also affected by various indoor sources including cooking, smoking, burning processes such as fires or candles, unvented natural-gas pilot lights, and resuspension. A portion of the outdoor particles is removed when air passes into the home. Particles are also removed through deposition and filtration when air passes through a heating, ventilation, and air-conditioning (HVAC) system. Indoor air quality can be improved through better filtration, better sealing of the building shell, and increased ventilation rates of filtered air. Indoor pollutants that adversely affect respiratory health include particulate matter, oxides of nitrogen, volatile organic compounds, and ozone. The indoor air quality for the homes was monitored by taking measurements of $PM_{2.5}$, CO_2, and formaldehyde. $PM_{2.5}$, CO_2, temperature, and relative-humidity sensors were continuously measured throughout the study. The sensors were contained within a box mounted on the living room wall in each home. These sensors were also located outside one of the homes, protected from the elements. Formaldehyde sensors were installed in the homes for one three-day period during the baseline period. An additional PM2.5 sensor was placed in the homes as a quality-assurance, quality-control (QA/QC) measure for three one-week periods during the baseline period.

Behavioral

The pre- and post-retrofit behavioral audits from the home residents assessed occupant responses to the two retrofit packages. Questions on occupant behavior and comfort helped evaluate barriers to the adoption of study upgrades and provided recommended strategies to overcome those barriers.

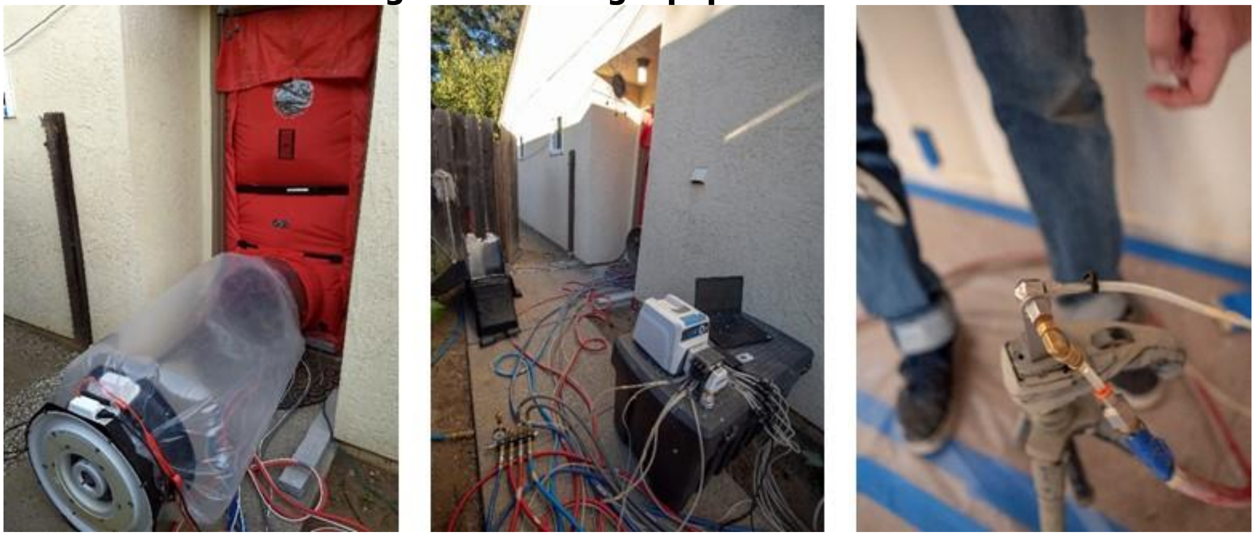
Retrofit

The following describes the monitoring approach to the retrofit phase of this project, which monitored the performance of the new cooling and ventilation equipment, indoor air quality, and resident behavior. Retrofit monitoring for each home was slightly different since each had a tailored retrofit package. The following describes monitoring efforts for each package.

Aerosol Sealing

The retrofit package for this project paired a new ventilation system with building envelope sealing, which improved energy efficiency by reducing uncontrolled infiltration and thermal loads. Because these homes were occupied, all resident belongings had to be removed before sealing. A moving company was hired to pack, move, and store their belongings during the sealing process, and to move everything back in afterwards. Residents vacated their homes during the moving, preparation, and sealing processes. This was similar to processes undertaken during occupant turnovers. The sealing equipment used is shown in Figure 7.

Figure 7: Sealing Equipment Used



Blower door fan installed at front door for pressurization (left). Liquid sealant injection pump and compressed air for sealant delivery (center). Spray nozzle (right).

Source: University of California, Davis

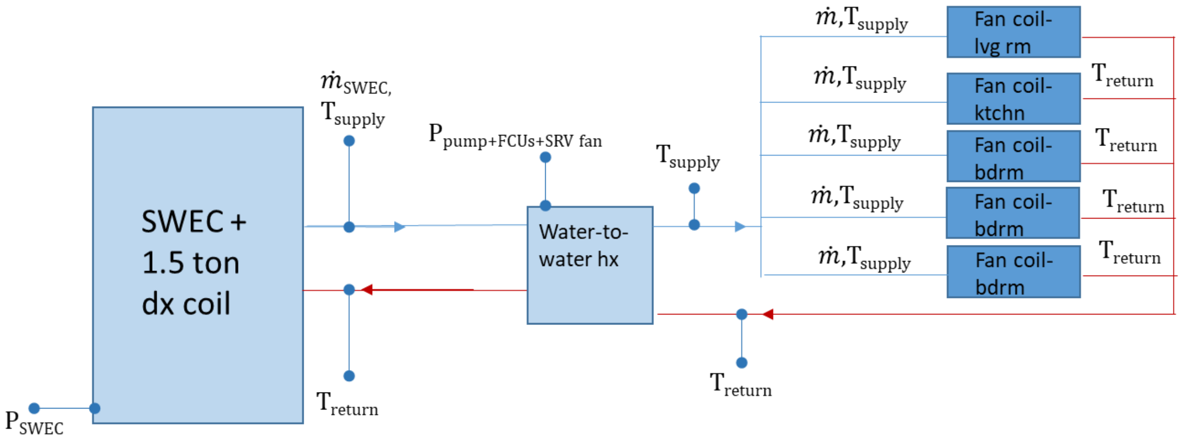
Western Cooling Efficiency Center (WCEC) staff performed pre- and post-aerosol sealing air-leakage tests. Staff also performed required prep work for sealing both homes. During new construction only HVAC systems, windows, plumbing fixtures, and exterior doors must be prepped for sealing. Sealant deposits are not as much of a concern for new construction since many features such as doors, cabinets, electrical outlets, lighting fixtures, flooring, and appliances have not been installed yet. When retrofitting existing homes, all of these features are already in place and must be protected to prevent lengthy clean-ups or damage.

Cooling

The performance of the SWEC cooling system was monitored during the retrofit testing period. The monitoring for each home is described here.

- **West House**: The cooling system for this house was installed as a mini-split system. A total of five water-to-air fan-coil units was installed throughout the home. There was also a water-to-water plate heat exchanger installed in the outside utility closet, where cooled water produced from the SWEC exchanged heat with the water supplied to the fan-coil units in the house. Measurements included supply-and-return water temperatures at each fan-coil unit in the house. Supply-and-return water temperatures were also measured before and after the plate heat exchanger on both the SWEC and the house side of the heat exchanger. A flow measurement was additionally measured for the SWEC and at each fan-coil unit in the house. The power of the overall cooling system was monitored including power supplied to the SWEC, the power of the pump circulating water to the fan coils, and the fan coils themselves. Figure 8 shows a diagram with measurement details for the West House.

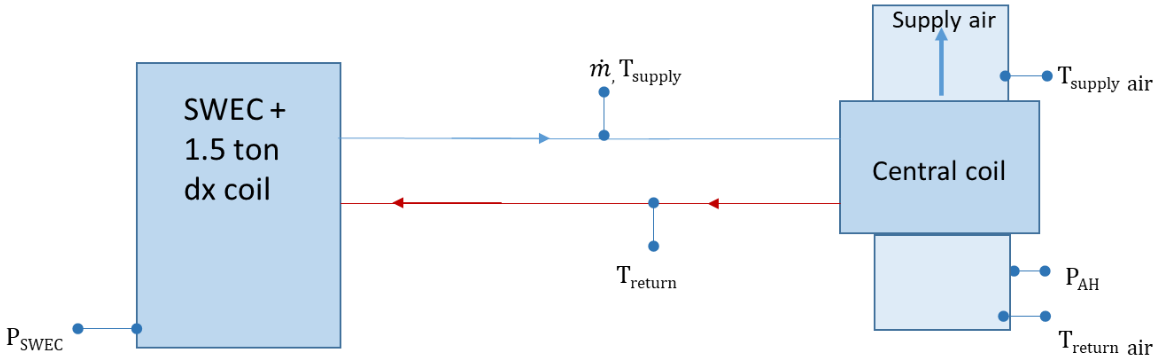
Figure 8: Monitoring Details for the West House With a Mini-Split Configuration



Source: University of California, Davis

- **East House**: For this house the existing evaporator coil was replaced with a central hydronic coil so that the existing furnace fan and ductwork could still be used with the new cooling system. All monitoring equipment was left in place from the baseline including temperature sensors in each of the supply grilles, as well as one in the return grille. Temperature sensors measured the supply and return air before and after the central coil at the air handler. Since the central coil was too large to fit in the space where the existing evaporator coil had been, the water coil was placed in the attic and the supply air-temperature sensor was moved to be after the coil in the attic. In addition to the air-temperature sensors, there were water-temperature sensors that measured the supply- and return-water temperature to and from the SWEC to the central coil. A flow sensor also measured the flow of the SWEC and central-coil loop. The power of the system was monitored to include the SWEC power and air-handler fan. Figure 9 shows a diagram of the measurement details for the East House.

Figure 9: Monitoring Details for East House for the Central System Configuration



Monitoring shown in this figure does not include air-temperature measurements at the supply grilles or at the return grille.

Source: University of California, Davis

With these measurements for the cooling systems in both homes, the capacity and efficiency of the entire system could be determined. Outdoor air conditions were monitored to map cooling-system performance to outdoor air temperature.

Ventilation

Both the SRV and NightBreeze systems' control algorithms were adjusted independently throughout the testing period. Selected dates and operating conditions were therefore not always the same for side-to-side system analysis and comparison. The project team instead focused on evaluating the efficacy of each system and assessing their respective benefits and opportunities for future development and implementation.

Metrics

For each system, the primary numerical metrics measured and computed for performance evaluations were:

1. Ventilation system net power (watts): sensor measurement.
2. Static-pressure differences in the fan ducts and water column: sensor measurement.
3. Volumetric air flow (CFM): based on power and pressure differences: flow-map correlation.
   - For SRV: The SRV controller logs the fan RPM and CFM based on the flow map from lab testing (CFM as a function of RPM and static pressure measurement).
   - For NightBreeze: Frontier Energy measured air flow using a TrueFlow grid. The calibration curve was determined with CurveExpert software using "logged watts" and cfm.
4. Fan efficacy (watts/CFM): calculated from sensor measurements
5. Ventilation load: British thermal units per hour (BTU/h): calculated as an approximation based on ventilation system CFM, supply, and indoor temperatures. Supply temperatures were calculated based on outdoor air conditions plus the ventilation fan heat, and indoor temperature was measured in a central location in the home.

$$Q_v = \dot{V}\rho c_p(T_{amb} + dT_{fan} - T_{indoor})$$

$$dT_{fan} = \frac{W_{fan}}{\dot{V}\rho c_p}$$

6. Outdoor air temperature (°F): sensor measurement
7. Indoor air quality: indoor versus outdoor CO_2 ppm (data provided by the indoor air-quality team)

Assumptions/Adjustments

1. Ventilation system net power, in watts: The sensor measurement SRV used forecasted weather data for optimizer algorithm input. The SRV algorithm was alternated each week: one full week in the optimized mode, followed by a week in a non-optimized mode so performance could be compared on comparable seasonal days.
2. For NightBreeze power data, stand-by power of 32 W was subtracted to plot net fan power.
3. For fan heat, since both the SRV and NightBreeze fans were variable speed, the fan heat and power consumption varied with fan speed and air flow. All the fan motor electrical energy was assumed to be transferred into heat energy in the supply airstream.

4. COVID-19 Impacts: Due to the shelter-in-place executive order that started in mid-March 2020 through the end of this project, there was some delay in accessing each of the host sites for sensor troubleshooting and power cycling the SRV controller box; these delays are reflected in data interruptions in the collection periods.
5. The August 2020 Bay Area Lightning Complex fires, starting on August 22, 2020, led to the request to switch off ventilation systems in both homes due to poor and unhealthy outdoor-air quality from smoke.

Indoor Air Quality

The indoor air quality for the homes was monitored by measuring $PM_{2.5}$, CO_2, and formaldehyde levels. $PM_{2.5}$, CO_2, temperature, and relative-humidity sensors took continuous measurements throughout the study. The sensors were contained in a box mounted on the living room wall in each home. These sensors were located outside one of the homes as well, well protected from the elements.

Behavioral

The pre- and post-retrofit behavioral audits from residents in the homes assessed occupant responses to the two retrofit packages. Questions on occupant behavior and comfort will help evaluate barriers to the adoption of study upgrades and assist in providing strategies to overcome those barriers.

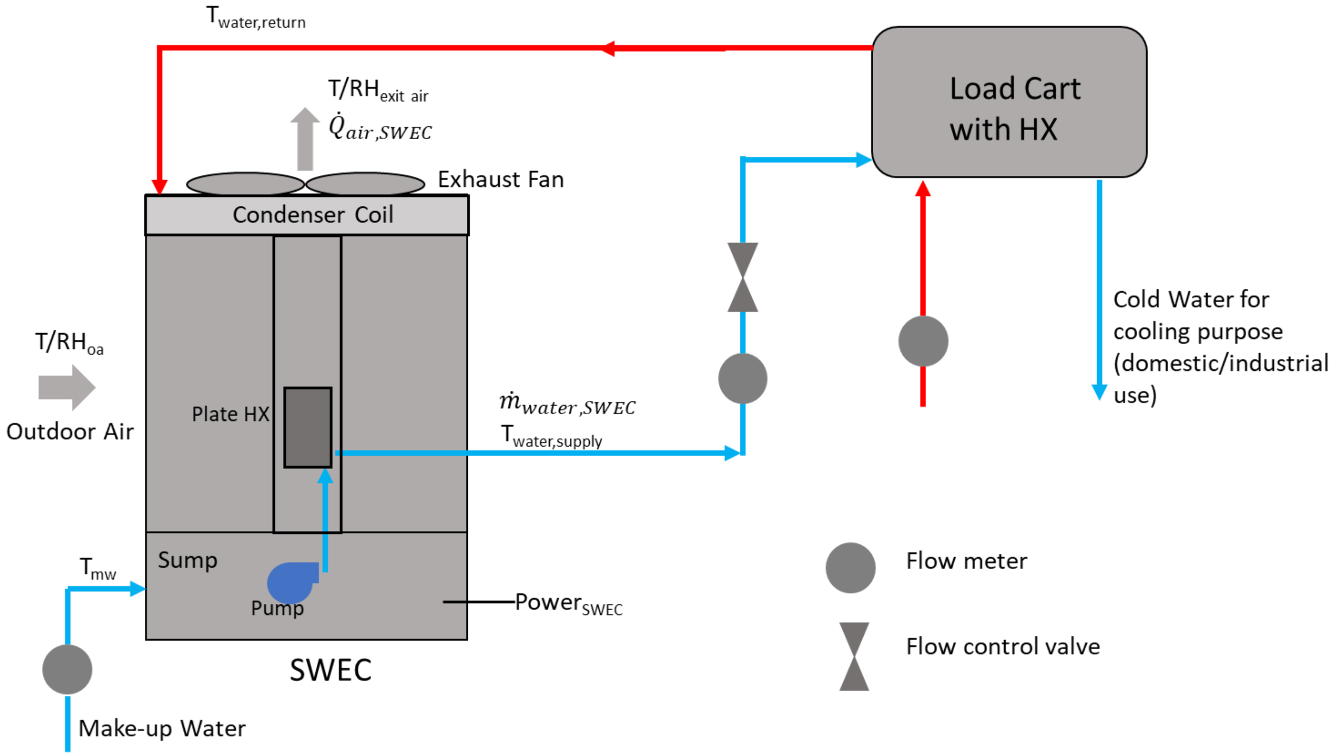
Sub Wet-Bulb Evaporative Chiller Laboratory Testing

Due to unexpected performance results for the SWEC cooling unit in field tests, the team pursued further testing in a controlled environment. After field monitoring over a full summer, one of the field cooling units was brought to the WCEC lab to assess its performance. The goal of the laboratory tests was to perform controlled testing of the SWEC to better understand optimal control strategies that could not be determined from the field data. The results were also used to validate a computer model capable of further evaluating the SWEC performance in different applications.

The SWEC unit was placed in WCEC's environmental chamber, connected to a water cart, which measured the cooling load provided by the SWEC and controlled the temperature of the water entering the SWEC (Figure 10).

While installed in the field, the SWEC was limited to operating at a fixed water-flow rate and a fixed exhaust fan-flow rate. For the lab tests, the exhaust-air and water-flow rates were varied to determine how the SWEC cooling performance changed in different operating and outdoor conditions (dry bulb temperature and relative humidity). The cold-supply water leaving the SWEC was pumped through a plate heat exchanger on the water cart, which simulated the indoor load, where it was heated and returned to the SWEC. This return-water temperature was held at a constant 70°F (21°C) to simulate a reasonable return-water temperature for residential applications. The tests were repeated for dry-bulb/wet-bulb outdoor temperatures, in degrees Fahrenheit, of 80/63 (27/17 °C), 90/61 (32/16 °C) and 105/68 (41/20 °C). The lab tests were repeated for the SWEC operating in both Stage 1 (evaporative cooling only) and Stage 2 (compressor cooling).

Figure 10: Details of Monitoring Sub Wet-Bulb Evaporative Chiller Performance Located in the Test Chamber



Source: University of California, Davis

Sub Wet-Bulb Evaporative Chiller Model

Due to the limitations of lab testing in simulating a range of variables including SWEC-system architecture, control strategies, and fan-coil pairing, a model was developed for the hybrid SWEC that collected suggestions for optimization of the system. An analytical model of the SWEC was developed for each of its components, essentially a series of daisy-chained heat exchangers and evaporative media (Yang et al. 2020). The model allowed various geometrical parameters for each individual heat exchanger and flow parameters that could be modified to improve performance. An R410a vapor compression model was integrated into the SWEC model to create a hybrid system that also allowed component modifications. A plate type-heat exchanger was modeled on the evaporator side, where refrigerant chilled the water from the SWEC. A microchannel condenser was coupled with the SWEC's exhaust air stream. The hybrid SWEC was additionally coupled with a central heat exchanger to model a central ducted system. Multiple heat exchangers additionally modeled a zoned system. After validation with a standard central coil used in the East House, a water-to-air microchannel polymer heat exchanger (MPHX) was used in the system.

CHAPTER 3: Project Results

Field Testing

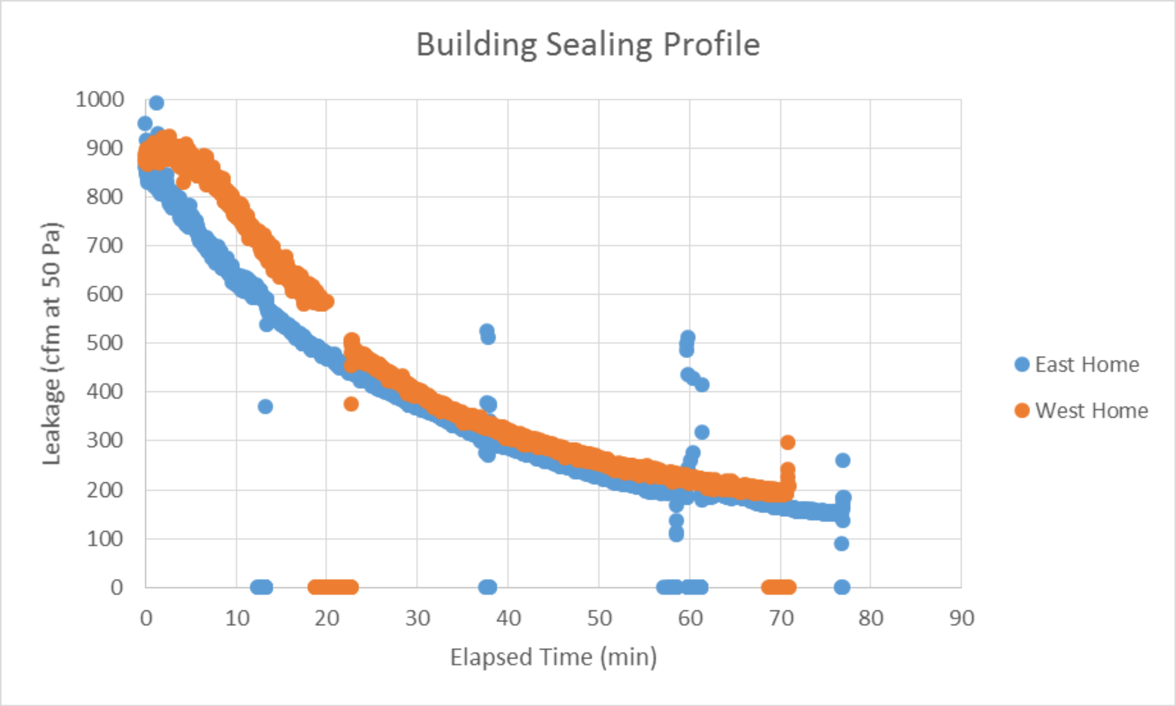
Baseline and Retrofit Comparison

Field measurements for the baseline equipment were compared with the retrofit equipment evaluated in this project. This included both the cooling and ventilation systems. Indoor-air quality was also compared for both pre- and post-retrofits, along with residents' evaluations of the new technologies.

Aerosol Sealing

Air leakage in both homes was measured and tracked throughout the sealing process to ensure that the sealant blocked leaks in a reasonable time. Six nozzles were placed in each home: two in the living room, one in the kitchen, and one in each of the three bedrooms. Leakage at the start of sealing after all prep was complete was between 800-900 CFM50 in both homes. The homes had similar sealing profiles. The aerosol sealing reduced the leakage by nearly 80 percent (Figure 11).

Figure 11: Sealing Profile for the West and East Houses



Disturbances resulted from changing to appropriate calibrated flow rings on the blower-door fan.

Source: University of California, Davis

After clean-up, the homes were leakage-tested one final time. Sealing reduced leakage by 37 percent in the West House and 64 percent in the East House; final leakages were 3.47 and 2.42 ACH50, respectively (Table 2). While the sealing profiles were very similar, there was a discrepancy in the amounts of sealing in the two homes. One potential reason for this was that the pre-seal baseline measured for the West House was conducted several months before the sealing and therefore could have changed before sealing commenced. In addition, the East House was measured in very similar states for pre-seal and post-seal with the windows, electrical outlets, and HVAC registers prepped for sealing. The West House pre-seal was performed with only the HVAC registers temporarily blocked, and the post-seal was performed in a similar condition as in the East House. These minor differences in the condition of the homes during leakage tests could have caused this discrepancy.

Table 2: Summary of Sealing Results From Both West and East Houses

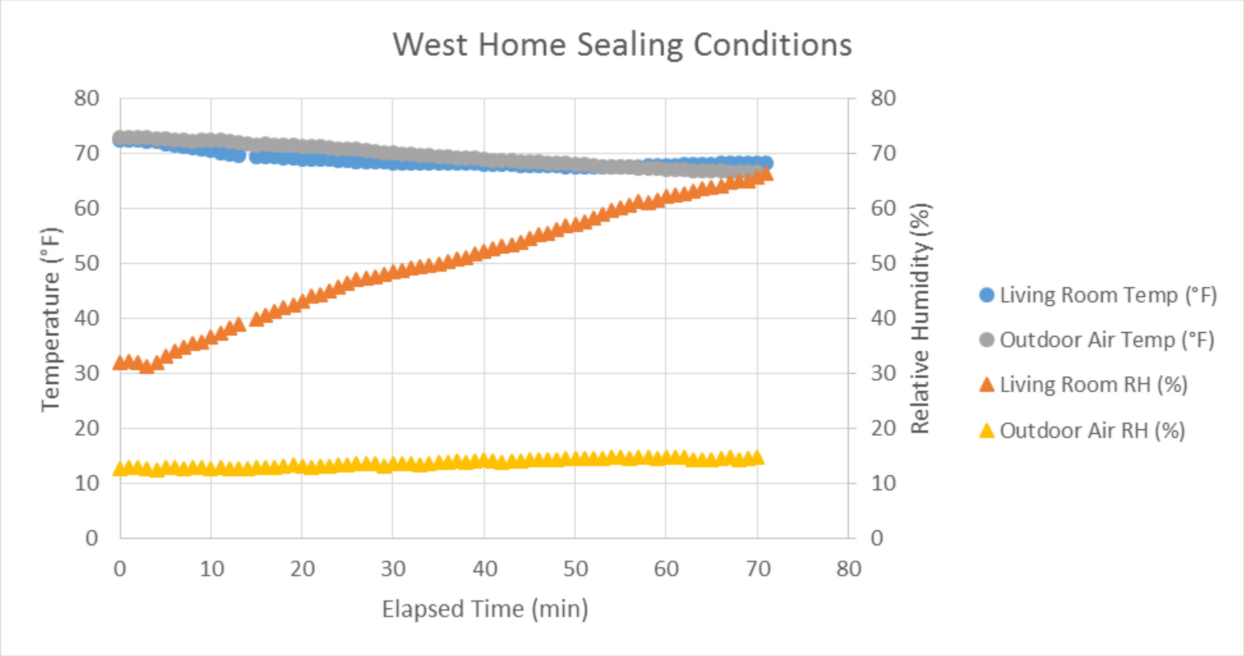
Home	Floor Area (ft^2)	Volume (ft^3)	Pre-Seal CFM50	Pre-Seal ACH50	Post-Seal CFM50	Post-Seal ACH50	Post-Seal % Reduction
East	900	8,500	940	6.64	343	2.42	64%
West	900	8,500	785	5.54	492	3.47	37%

Source: University of California, Davis

While successful, there were some minor issues during the sealing of both homes. In the West House, atomized sealant in two of the three bedrooms was too "wet." Figure 12 shows that the humidity monitor in the living room only reached about 70 percent during the process, well below the saturation point; however, temperature and relative humidity were only being monitored at the fan inlet (outdoor conditions) and in the living room. Elevated humidity in the smaller bedrooms was not discovered until after the sealing was complete. The result was that liquid sealant built up around leaks and on horizontal surfaces in these rooms, causing it to accumulate on light fixtures, ceiling electrical boxes, and door trims. During future applications it will be important to measure humidity in the smallest rooms to avoid high-humidity conditions. Since the sealant was still liquid, it was simply wiped off with a clean rag.

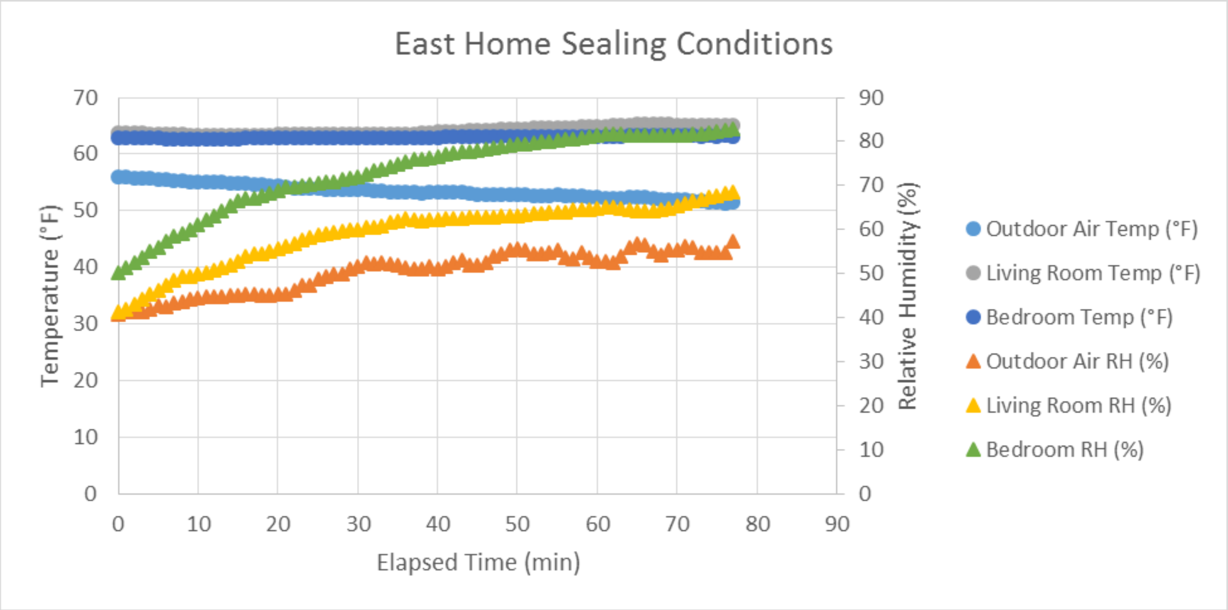
To prevent this in the East House, an additional temperature and relative humidity sensor was installed in the master bedroom (this room had the wettest conditions in the West House). Using data from this sensor, sealant injection rates were adjusted to prevent this room from experiencing elevated humidity levels. The injection rate was dropped from 186 cm^3/min to 120 cm^3/min 37 minutes into sealing, and an additional 4,500 W of heat were provided constantly during sealing. The bedroom humidity stayed below 70 percent for the entire sealing process (Figure 13). These changes improved conditions in the bedrooms, although some liquid sealant remained.

Figure 12: Temperature and Relative Humidity Conditions During West House Sealing



Source: University of California, Davis

Figure 13: Temperature and Relative Humidity Conditions During East House Sealing



Source: University of California, Davis

In general, the sealing went well, with leaks sealed in locations around the house including electrical boxes, lighting fixtures, plumbing penetrations, and baseboards (Figure 14). One cabinet in the West House had an outlet that went unnoticed during the preparation process and was discovered post-sealing during clean-up. This caused sealant deposits around the cabinet door.

Figure 14: Examples of Seals

Seals formed at baseboards (left) and at bottom of sliding door frame (right)

Source: University of California, Davis

Cooling

The performance of the baseline equipment in both homes was monitored for power, air flow and air temperature. The performance for the retrofit cooling systems in both homes was monitored for power, water flow, and water temperature. With these measurements, the capacity and efficiency of the baseline and retrofit cooling systems could be determined and compared. Outdoor air conditions were monitored to map the performance of the cooling systems to outdoor air temperature and humidity.

Since the baseline equipment in both homes was replaced with a water-based cooling system, the comparison of baseline to retrofit performance was slightly different for each home, depending upon how the retrofit system was installed.

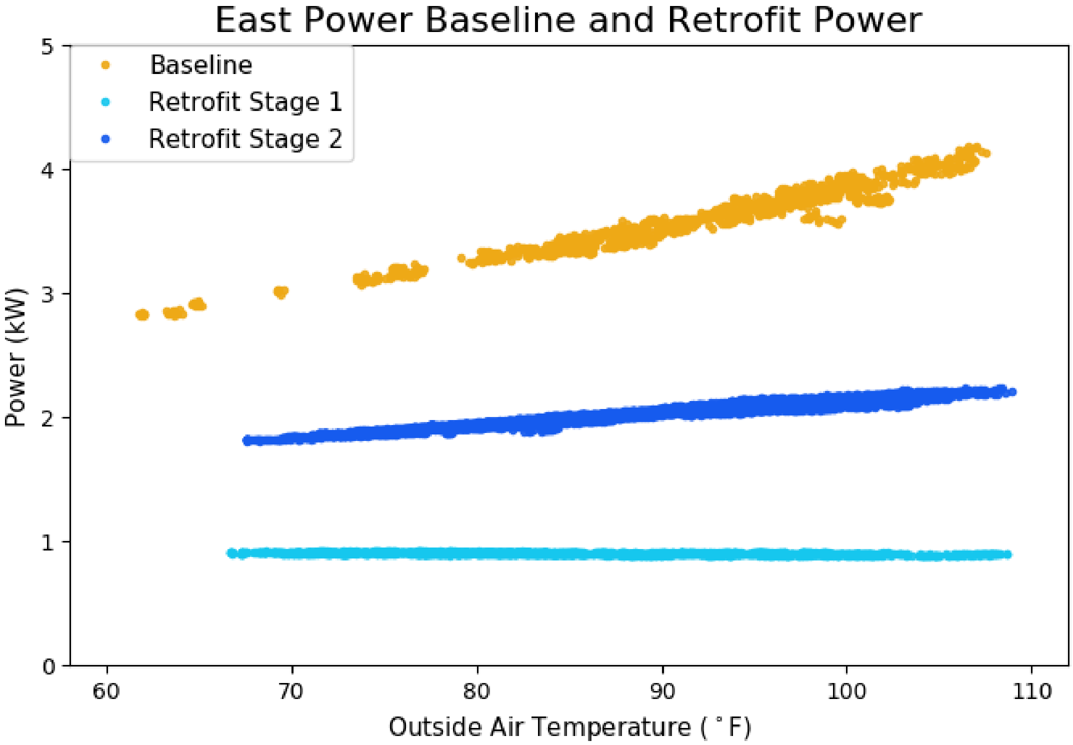
For the East House retrofit monitoring, air-flow and air-temperature measurements remained from the baseline monitoring since the retrofit cooling system was implemented as a ducted central system utilizing the existing furnace fan. This allowed for an air-side equipment capacity comparison between the baseline and retrofit systems. Both the baseline and retrofit equipment capacity calculations were based on air-side central-coil measurements.

For the West House, the retrofit cooling system was installed as a ductless mini-split system; the capacity was therefore calculated differently than for the baseline system. The capacity was calculated using air-side measurements for the baseline while the retrofit employed water-side measurements. Despite this difference, both methods provided the equipment capacity for each cooling system so therefore allowed for performance comparisons.

The energy consumption and coefficient of performance (COP) for baseline and retrofit equipment was compared similarly for each home. The details for the calculations for the capacity for both the baseline and retrofit cooling systems are described in Appendix C.

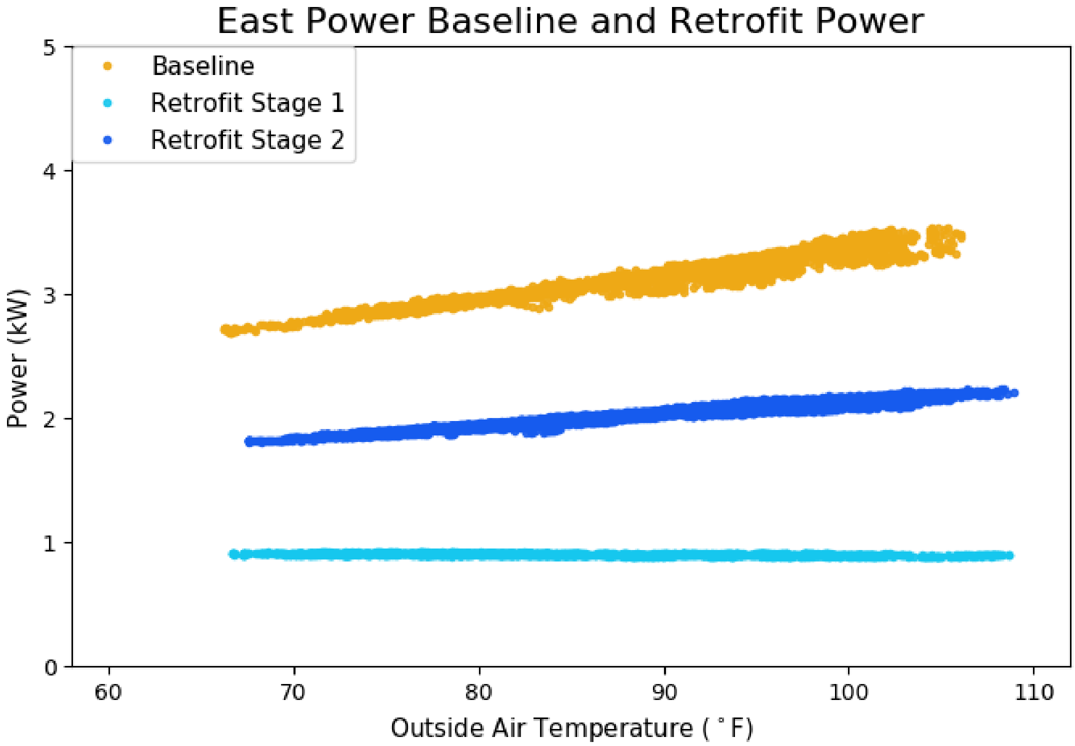
The first set of plots in Figure 15 compares baseline cooling-system performance with retrofit cooling-system performance for the East House. Figure 15 and Figure 16 compare the power for both systems before and after an anomaly with the baseline cooling system caused a shift in power draw and capacity output. The team was unable to determine the cause of this shift, but it caused power and capacity to decrease under similar operating conditions. Figure 15 plots the baseline power before this shift and Figure 16 plots the baseline power after the shift. Power for the retrofit cooling system is shown for Stage 1 (evaporative cooling only) and Stage 2 (evaporative and compressor cooling) in both plots.

Figure 15: East House Power Draw for Baseline and Retrofit Equipment Before Shift in Equipment Power for Baseline



Source: University of California, Davis

Figure 16: East House Power Draw for Baseline and Retrofit Equipment After Shift in Equipment Power Draw for Baseline

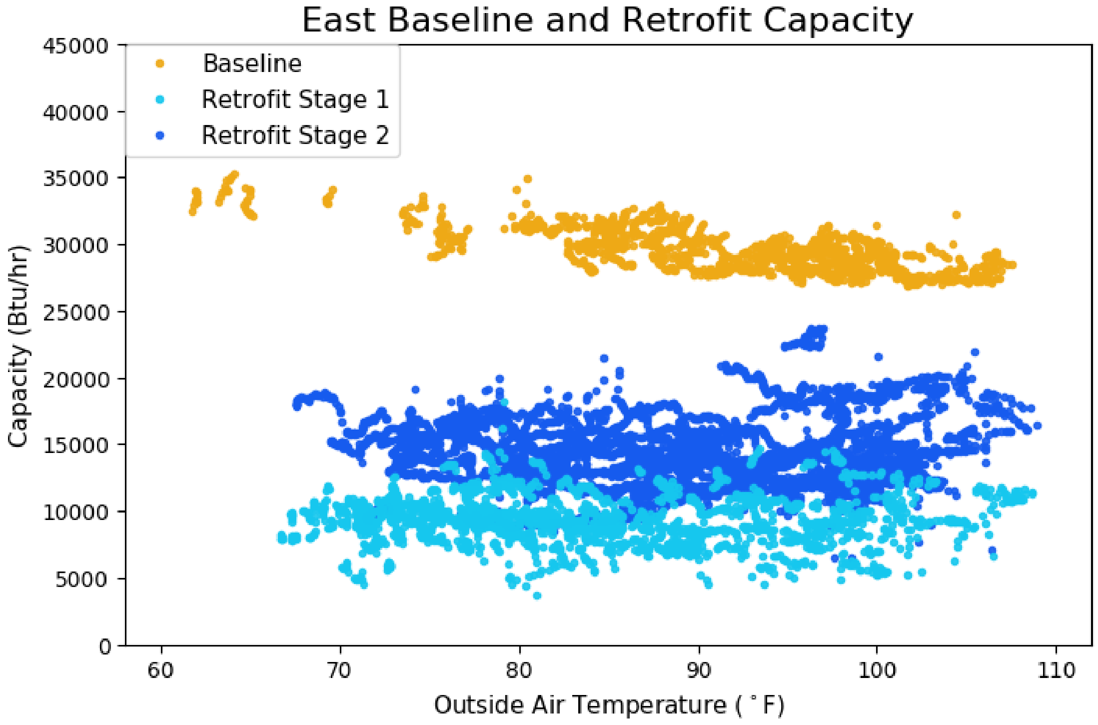


Source: University of California, Davis

The retrofit equipment drew less power in both Stage 1 and Stage 2 when compared with the baseline equipment, both before and after the power shift in the baseline equipment. For the retrofit equipment, Stage 1 only required running the SWEC pump, SWEC exhaust fan, and indoor air-handler systems. Stage 2 included the additional power of the compressor. The baseline equipment only had one operating stage that required the compressor and indoor air-handler system. Note that the power of retrofit Stage 1 cooling was constant and not dependent on outdoor air temperature, where the retrofit Stage 2 cooling and the baseline that included compressor power had an increase in energy use with increasing outdoor air temperature.

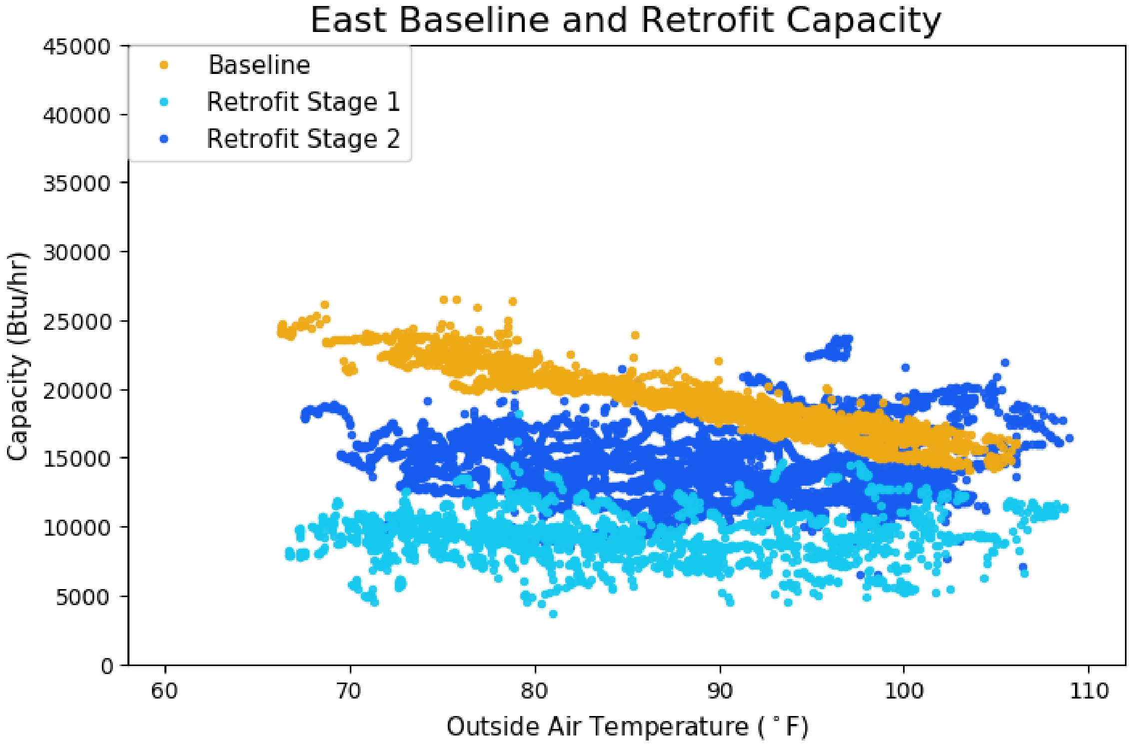
Figure 17 and Figure 18 compare the cooling capacity for the baseline cooling system (before and after the performance shift) to the retrofit system for the East House.

Figure 17: Equipment Cooling Capacity for Baseline Versus Retrofit Before Shift in Equipment Power for Baseline



Source: University of California, Davis

Figure 18: Equipment Cooling Capacity for Baseline Versus Retrofit After Shift in Equipment Power for Baseline

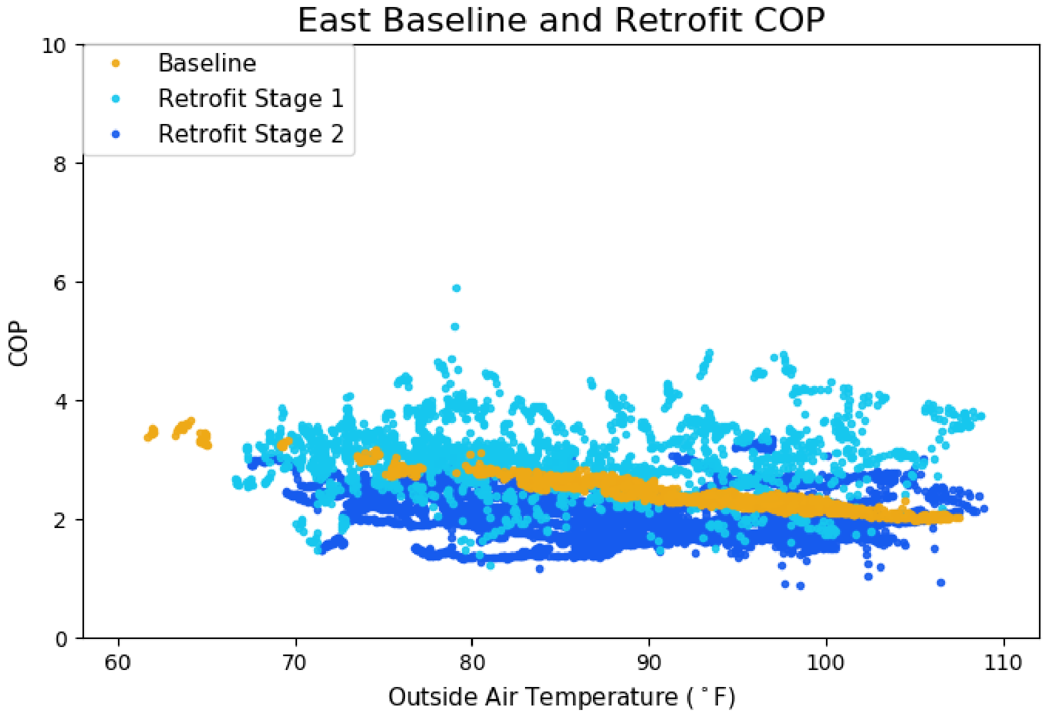


Source: University of California, Davis

Before the performance shift in the baseline equipment, the retrofit system in Stage 2 provided only about half of the cooling capacity as the baseline system, and about a third of the cooling capacity in Stage 1. After the shift in baseline performance, the retrofit equipment provided similar cooling capacity to the baseline equipment when operating in Stage 2 and about two-thirds cooling capacity in Stage 1 during hot outdoor-air conditions. Although the retrofit equipment provided less cooling capacity over all outdoor-air conditions, it was constant with increasing outdoor-air temperatures when compared with the baseline equipment, which experienced decreasing cooling capacity as outdoor temperatures increased.

Figure 19 and Figure 20 show the COP for the baseline and retrofit cooling equipment before and after the performance shift to the retrofit system for the East House, plotted against outdoor-air temperature.

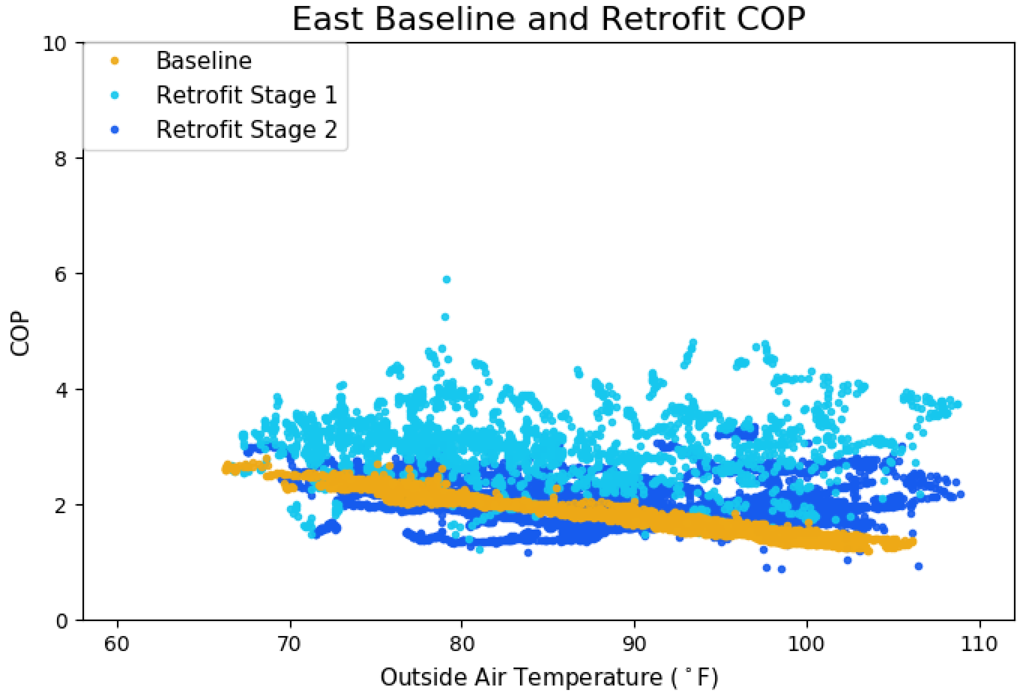
Figure 19: Coefficient of Performance for Baseline and Retrofit Equipment in East House



The baseline coefficient of performance shown is before the equipment power shift.

Source: University of California, Davis

Figure 20: Coefficient of Performance for Baseline and Retrofit Equipment in East House



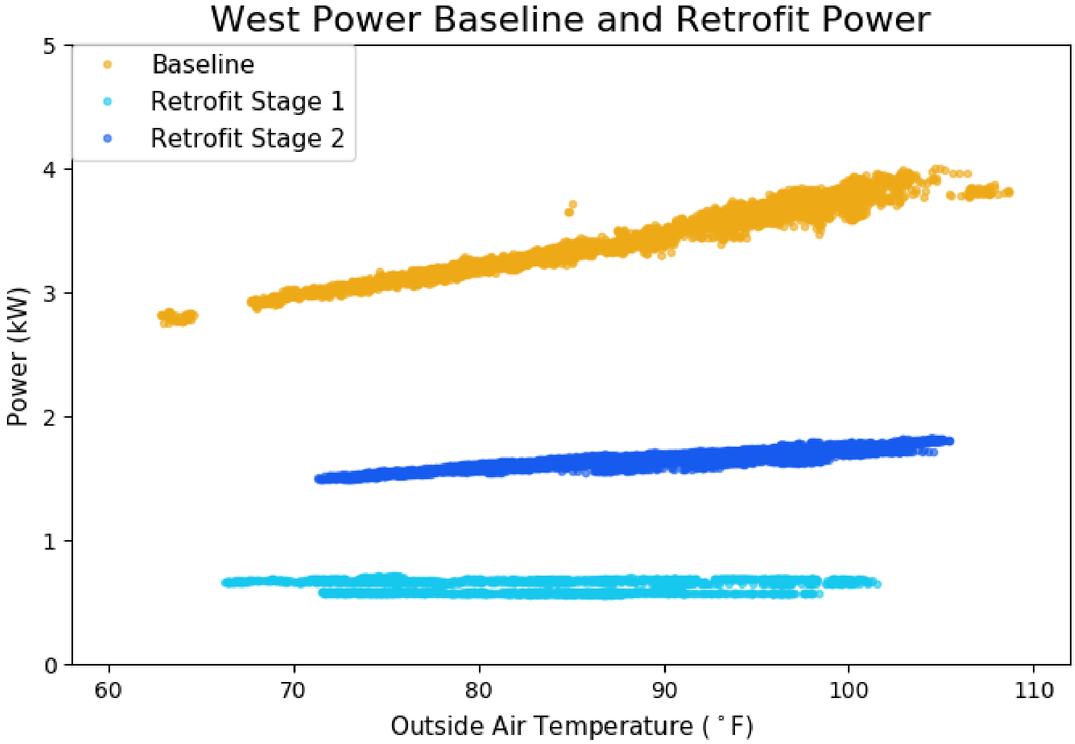
The baseline coefficient of performance shown is after the equipment power shift.

Source: University of California, Davis

The COP for the retrofit cooling system in Stage 1 was slightly higher than the baseline system before the performance shift, and even more so after the shift. The retrofit system Stage 2 COP was similar to the baseline system before the shift and slightly higher after the shift. Although the retrofit equipment drew less power than the baseline equipment, the lower capacity resulted in a lower COP. Earlier modeling of SWEC performance suggested that the system was not achieving optimal performance so it was decided to investigate the SWEC performance issues with additional lab testing. The lab results showed improvements could be made by optimizing the SWEC water- and fan-flow rates. More detailed discussion of the laboratory testing appears in a later section of this chapter.

The next series of plots compare the performance of the retrofit cooling equipment in the West House, integrated as a ductless hydronic mini-split system, to the baseline cooling equipment. Figure 21 shows the power draw of the retrofit and baseline cooling systems, plotted against the outdoor-air temperature.

Figure 21: Equipment Power for Baseline Versus Retrofit Cooling Equipment in West House



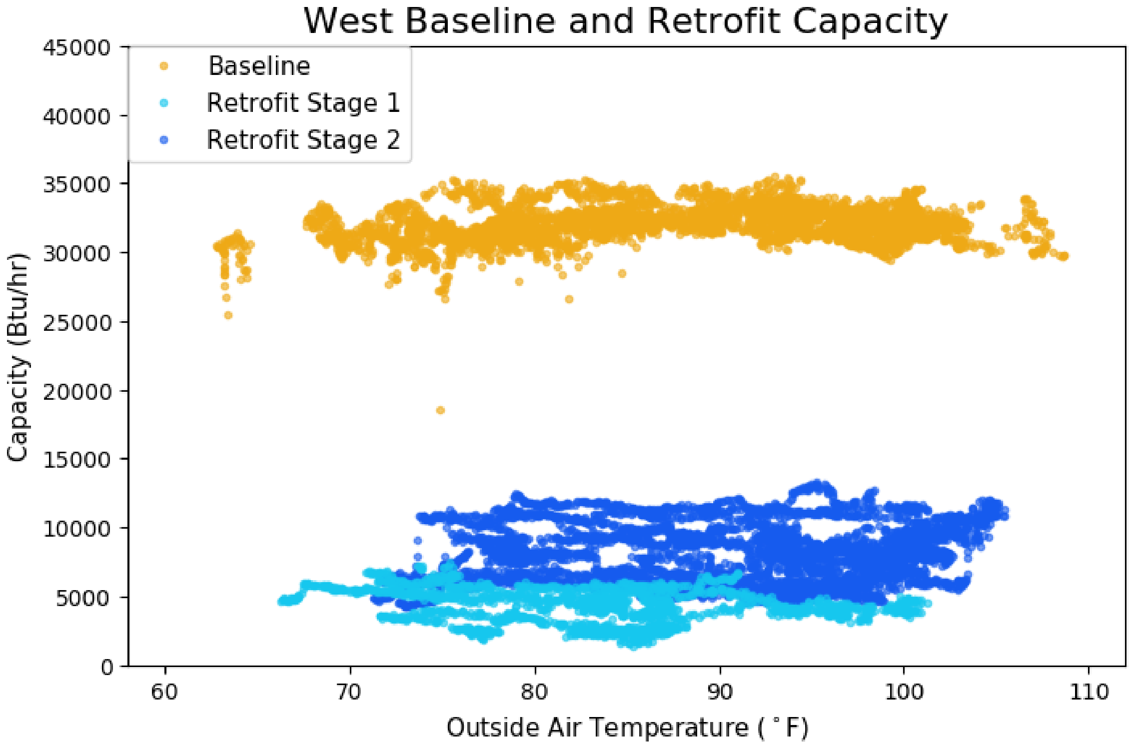
Source: University of California, Davis

Similar to the East House, the retrofit equipment in the West House used less energy than the baseline equipment. The retrofit equipment power was also relatively constant with increasing outdoor-air temperatures versus the baseline system, which showed power-draw increases with rising outdoor-air temperatures.

Figure 22 shows the equipment capacity comparison between the baseline and retrofit for the West house. The capacity for the retrofit cooling system in Stage 1 and Stage 2 was considerably lower than the baseline system. The capacity was also lower in the West house than the East house which suggests the indoor equipment utilized in the West House was achieving poorer performance.

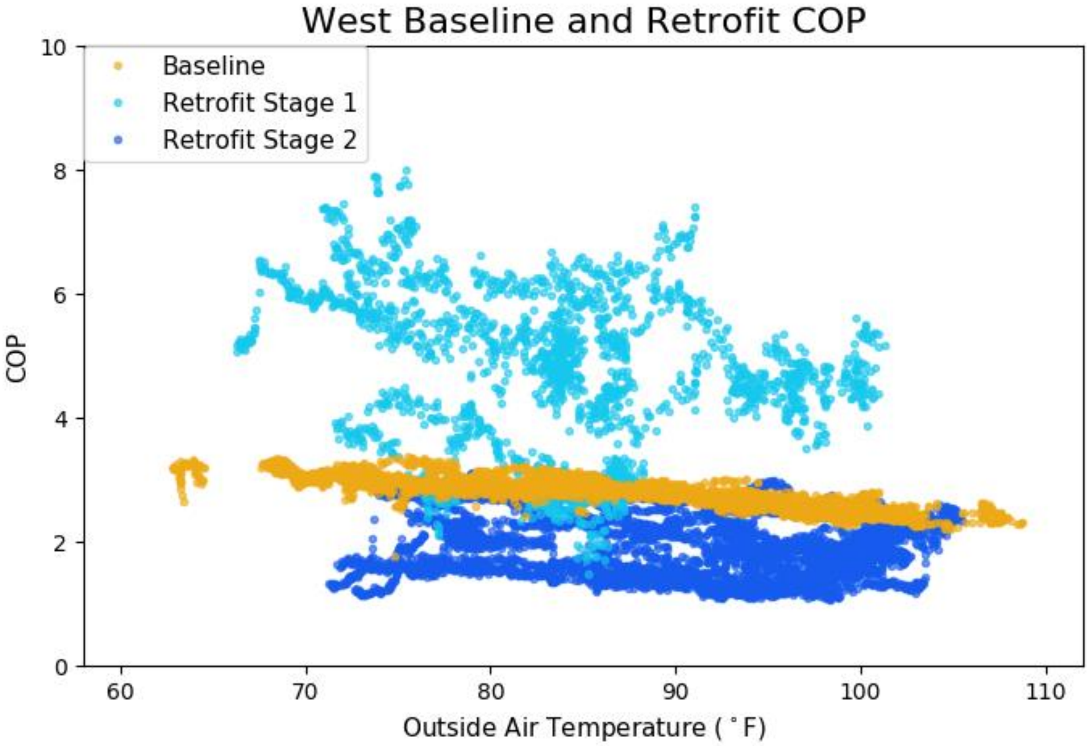
The retrofit COP for the West House (Figure 23) in Stage 1 was higher than the baseline but lower in Stage 2. Again, the team expected higher COP for the retrofit equipment, as the SWEC systems have had lab testing of previous designs that showed higher capacities.

Figure 22: Equipment Cooling Capacity for Baseline Versus Retrofit Equipment for West House



Source: University of California, Davis

Figure 23: Coefficient of Performance for Baseline and Retrofit for West House



Source: University of California, Davis

Although the design of the retrofit outdoor equipment in both homes was the same, the cooling capacity for Stage 2 in the West House was lower than in the East House. Part of this variance in performance can be attributed to how each retrofit cooling system was installed. Looking at the return-water temperatures (returning to the SWEC from the house) for both systems in Stage 2, the water coming back to the SWEC in the West House was cooler than in the East House (Figure 24). Lower water temperatures entering the SWEC have been shown to reduce the capacity and COP of the system.[4]

Figure 24: Return Water Temperatures for Stage 2 for West House Compared With East House

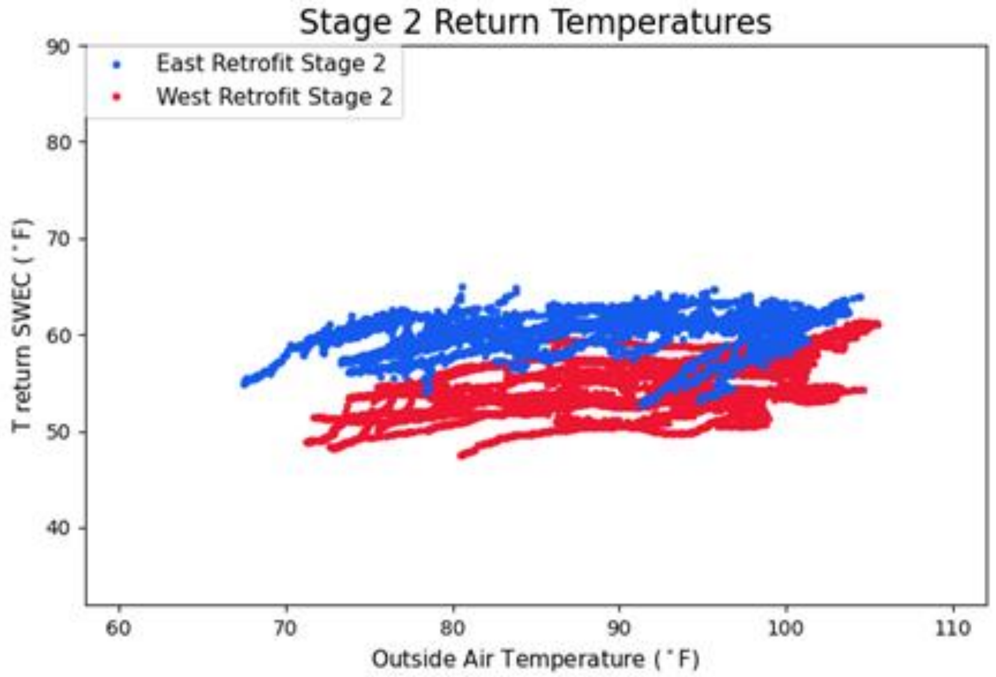


Figure shows the water temperature measured coming back to the sub wet-bulb evaporative chiller unit from the homes (after running through the central coil in the East House and after running through the fan coil units in the West home).

Source: University of California, Davis

The West House's lower return water temperature was an indication that less heat was being transferred in the West house than the East house. The West House used multiple "mini" fan coil units in the different zones in the home. The system was setup with all fan coils in parallel and without the ability to turn water flow off to individual coils that were not operating. Therefore, if only one coil was operating (fan turned on) most of the chilled water produced by the SWEC would be effectively bypassed back to the SWEC causing very cold return water temperatures. A more advanced control system could reduce SWEC speed and divert water flow only to active coils.

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[4] Narayanan V., Pistochini T., Ross D., Yang Y. "An Experimentally-validated Model of Cross-flow Sub-Wet Bulb Evaporative Chiller." Manuscript submitted for publication.

Ventilation

The following results provide a sample of the analysis and evaluation for each of the ventilation systems. Additional figures for weekly operations of both systems are provided in Appendix B. Those figures include weekly periods and specific daily figures for a zoomed-in snapshot of system performance trends and hourly variations in operations. The figures focus on cooling mode of operation for both systems.

The figures (25, 26, 27, 28, 29 and 30) show each ventilation system's power consumption, corresponding air flow delivered (CFM), corresponding indoor-air quality relative to outdoor-air quality (based on CO_2 concentrations), as well as total ventilation capacity (load) delivered for each 24-hour period on the selected dates, based on the temperature difference of outdoor air supplied to the building and the indoor air displaced by the ventilation air. A negative ventilation load refers to cooling provided into the space; a positive ventilation load indicates an additional load that must be satisfied by the cooling equipment. For the fan power and air flow delivered, the SRV figures are 10-minute-averaged data and the NightBreeze figures are 1-minute-averaged data. The air-quality figures are 10-minute-averaged data. Additionally, hourly-averaged data are presented for ventilation load and outdoor-air temperature. For the daily plots, the total energy consumed is calculated and summarized for each ventilation system and total CFM delivered for the 24-hour period.

Smart Residential Ventilation System

The data sets shown in Table 3 for the SRV system correspond to sample days from a week when the algorithm was operating in an optimized mode; for the consecutive week it was operating in a non-optimized mode (constant target CFM for each hour of the day). Since the algorithm calculates a target RPM for the fan to satisfy the target hourly CFM value, the fan may overshoot its target RPM at an initial stage, then modulate to satisfy the CFM target. **Error! Reference source not found.**Accordingly, the raw data for SRV summarized in the f ollowing graphs contain a pulse-like shape.

Figure 25 to Figure 30 show the data on the following dates and operating conditions:

Table 3: Smart Residential Ventilation Algorithm Optimization Schedule

Date	SRV Mode
July 22, 2020	Non-Optimized
July 25, 2020	Optimized

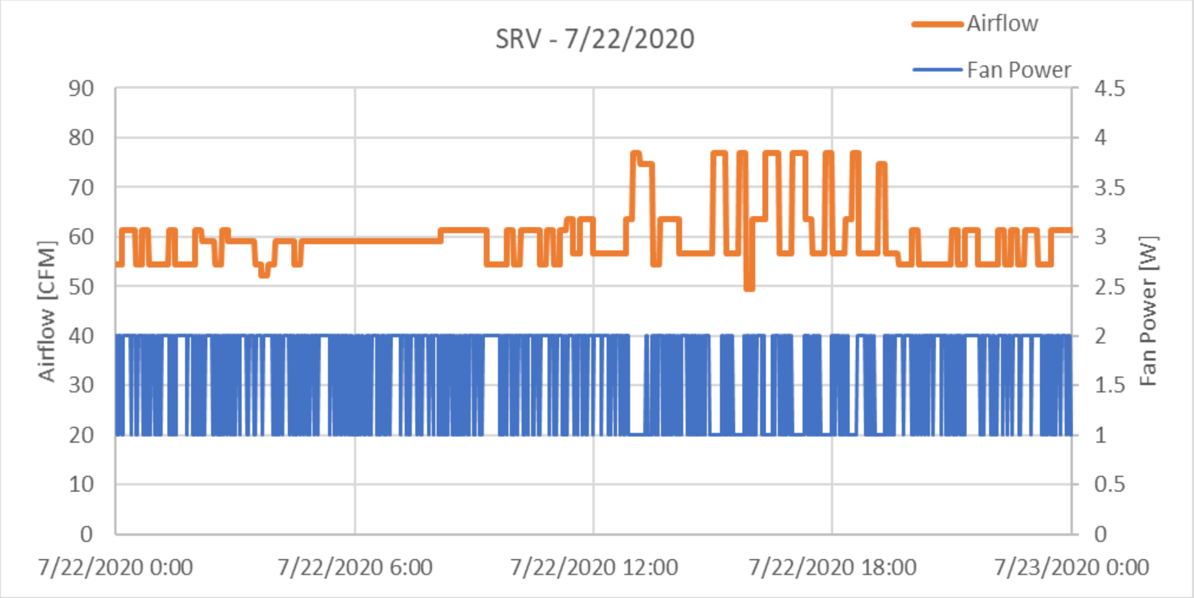
Source: Electric Power Research Institute

Figure 25 and Figure 26 illustrate the comparison in the ventilation air flow delivered (CFM) and the corresponding power consumption by the SRV system when it was operating in the non-optimized (July 22, 2020 data set) mode versus the optimized (July 25, 2020 data set) mode, as seen in Table 3. About 23 percent less volumetric air flow was delivered in the optimized mode, corresponding to about 22 percent less energy consumed.

In the non-optimized mode, the fan was on continuously and pulsed incrementally to increase the air flow each hour. In the optimized mode, based on the weather forecast, the fan operated at a higher speed from midnight through the early morning hours around 8 am - 9 am, providing "precooling" before transitioning to a steady lower speed operation for the rest of the day.

The indoor CO_2 levels on both days were nominally below 1,500 ppm (Figure 27 and Figure 28), except for short spurts above 1,500 ppm on the optimized day around noon, when the fan speed was ramping down to minimize ventilation with hotter ambient air that would counter the cooling load. The outdoor temperature profile is comparable on both (Figure 29 and Figure 30), with about 20 percent less total ventilation load delivered on the optimized day.

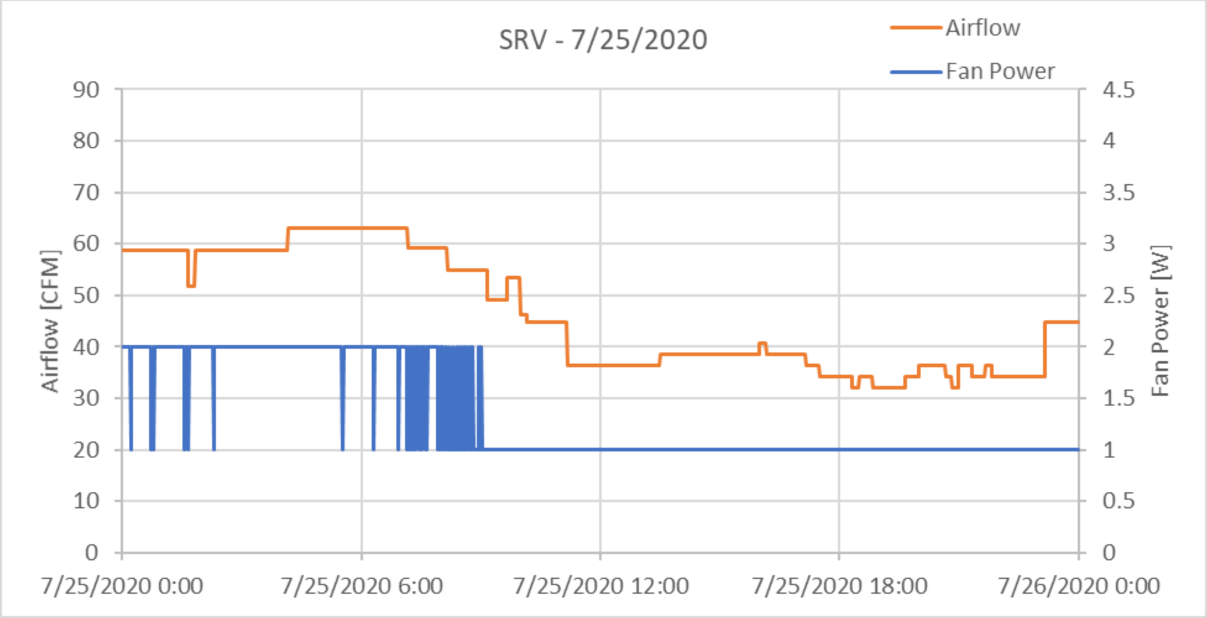
Figure 25: Total Ventilation Delivered and Power Consumption on July 22, 2020 for Smart Residential Ventilation in Non-Optimized Mode



Total mechanical ventilation: 86,221 cubic feet, total energy: 41 watt-hours.

Source: Electric Power Research Institute

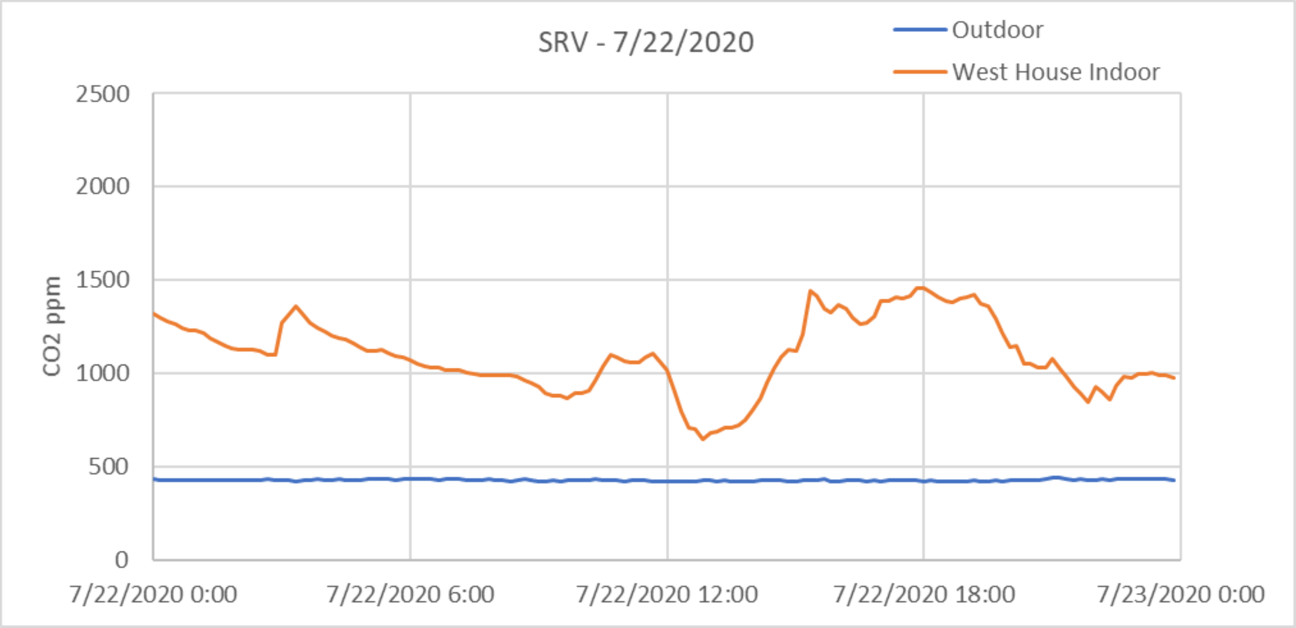
Figure 26: Total Ventilation Delivered and Power Consumption on July 25, 2020 for Smart Residential Ventilation in Optimized Mode



Total mechanical ventilation: 66,760 cubic feet, total energy: 32 watt-hours.

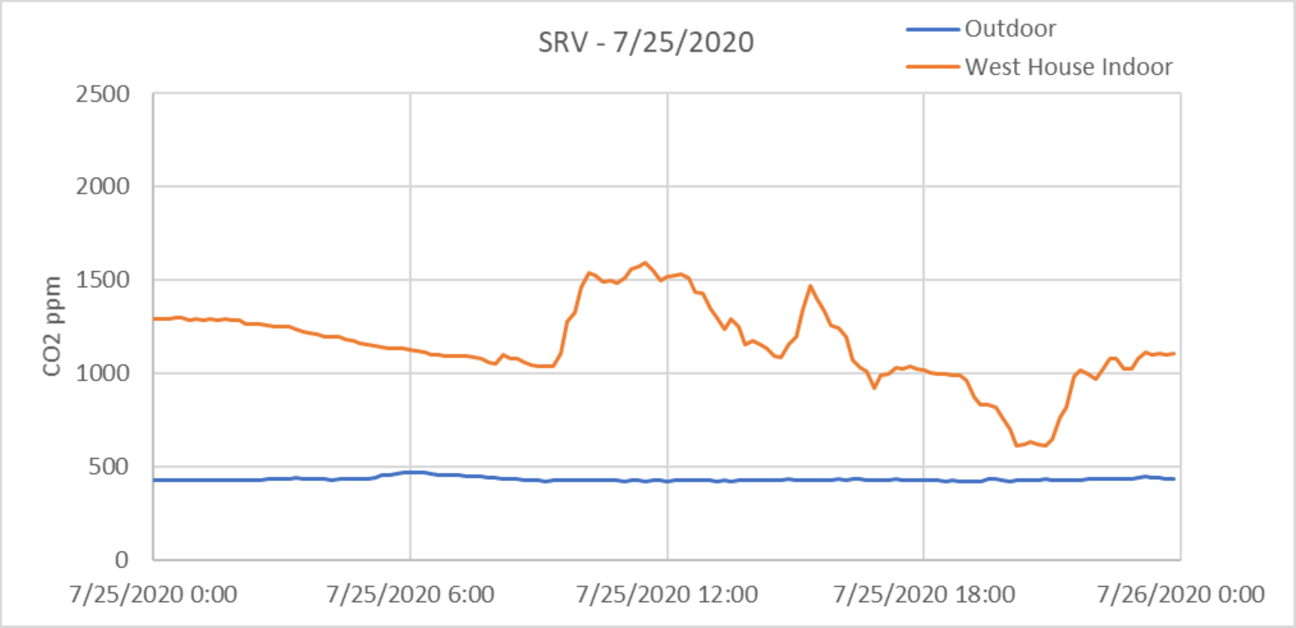
Source: Electric Power Research Institute

Figure 27: Indoor- and Outdoor-Air Quality in Carbon Dioxide Parts per Million Levels on July 22, 2020 for Smart Residential Ventilation in Non-Optimized Mode



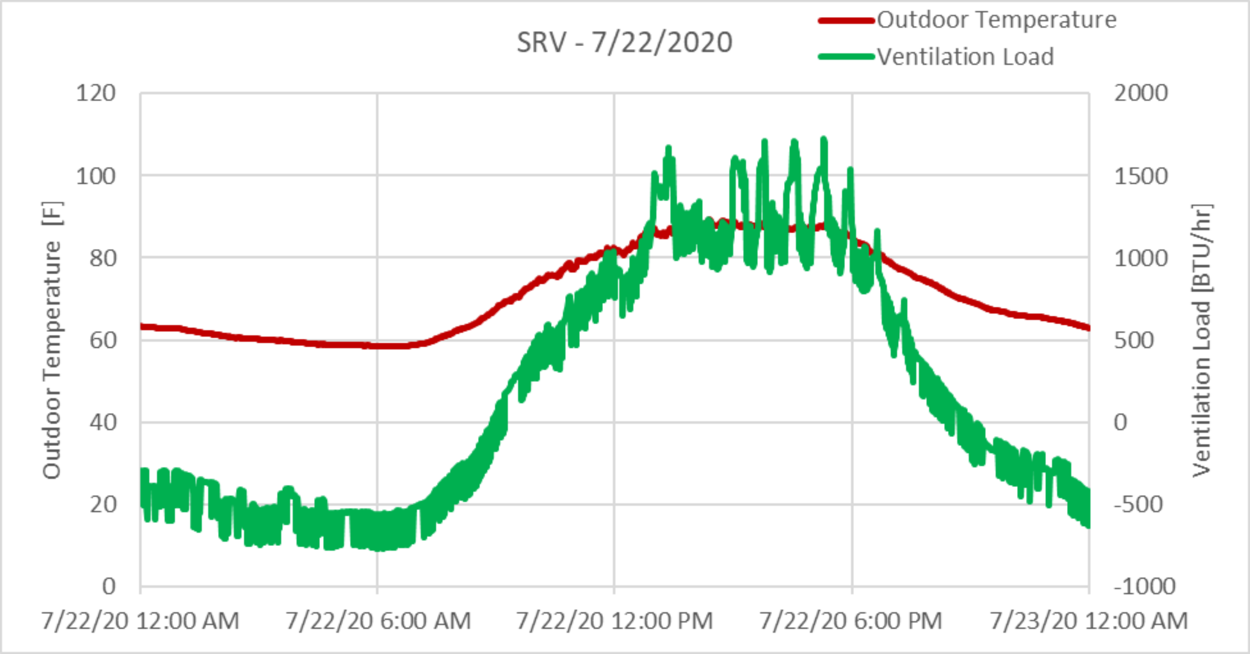
Source: Electric Power Research Institute

Figure 28: Indoor- and Outdoor-Air Quality in Carbon Dioxide Parts per Million Levels on July 25, 2020 for Smart Residential Ventilation in Optimized Mode



Source: Electric Power Research Institute

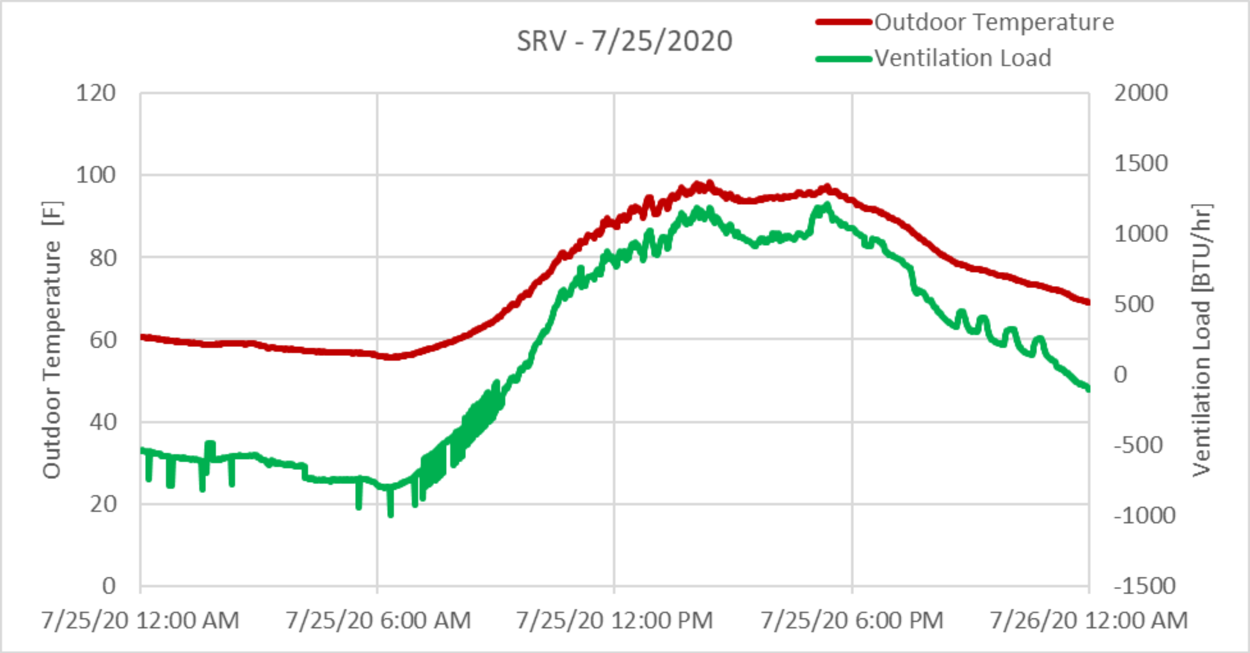
Figure 29: Outdoor-Air Temperature and Ventilation Cooling Delivered on July 22, 2020 for Smart Residential Ventilation in Non-Optimized Mode



Total ventilation load: 5,300 British thermal units (Btu).

Source: Electric Power Research Institute

Figure 30: Outdoor-Air Temperature and Ventilation Cooling Delivered on July 25, 2020 for Smart Residential Ventilation in Optimized Mode



Total ventilation load: 4,214 Btu.

Source: Electric Power Research Institute

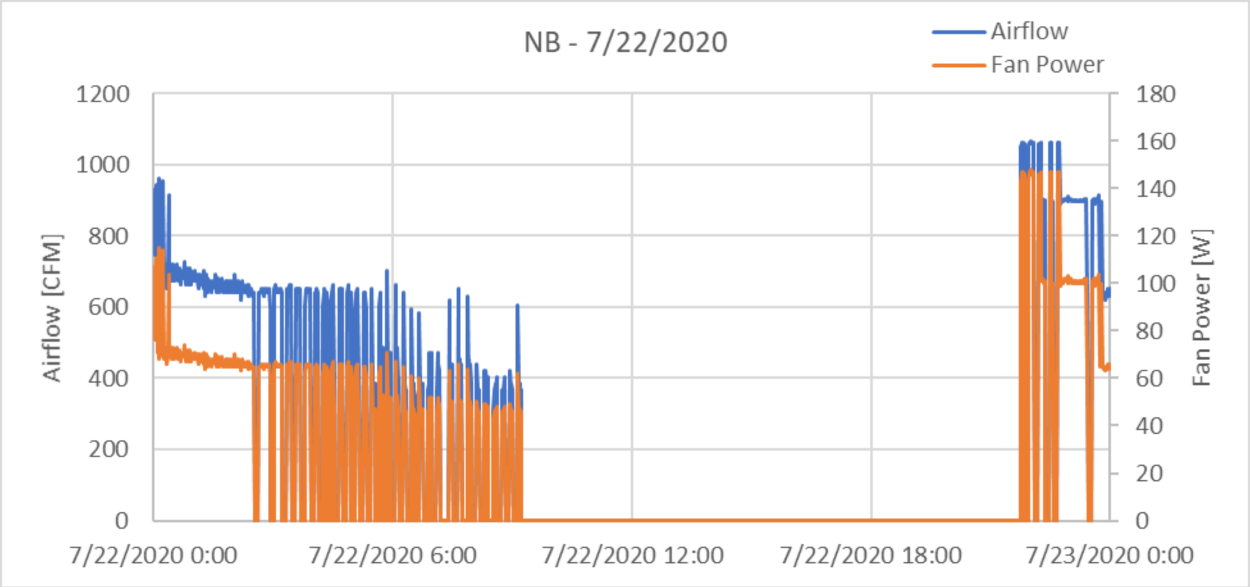
NightBreeze System

Figure 31 to Figure 36**Error! Reference source not found.** show the NightBreeze performance data on the same dates (July 22 and 25, 2020); the SRV data was shown with comparable outdoor-temperature profiles.

In both Figure 31 (July 22) and Figure 34 (July 25), the ventilation air flow by the NightBreeze system was an order of magnitude larger than the SRV system because the NightBreeze system provided both cooling and ventilation. On July 22, the total ventilation load delivered was approximately double than that on July 25. Recall that the control settings for the NightBreeze system in cooling mode depend on the temperature differential between the indoor temperature settings and outdoor ambient temperature.

In cooling mode, NightBreeze ventilated when the outdoor temperature fell below the indoor temperature by a set number of degrees, typically 5°F. The fan speed varied with current weather conditions, with higher cfm during hotter weather. It stopped ventilating when the indoor-outdoor differential was lower than 5°F, or when the indoor "low limit" temperature was reached. The low-limit temperature was a user setting but was automatically adjusted upward during mild weather to prevent over-cooling. Also, if the outdoor temperature is below the indoor temperature (by 0-1°F) while the air conditioner is operating, the damper will switch, causing the fan to draw in outdoor return air (economizer function).

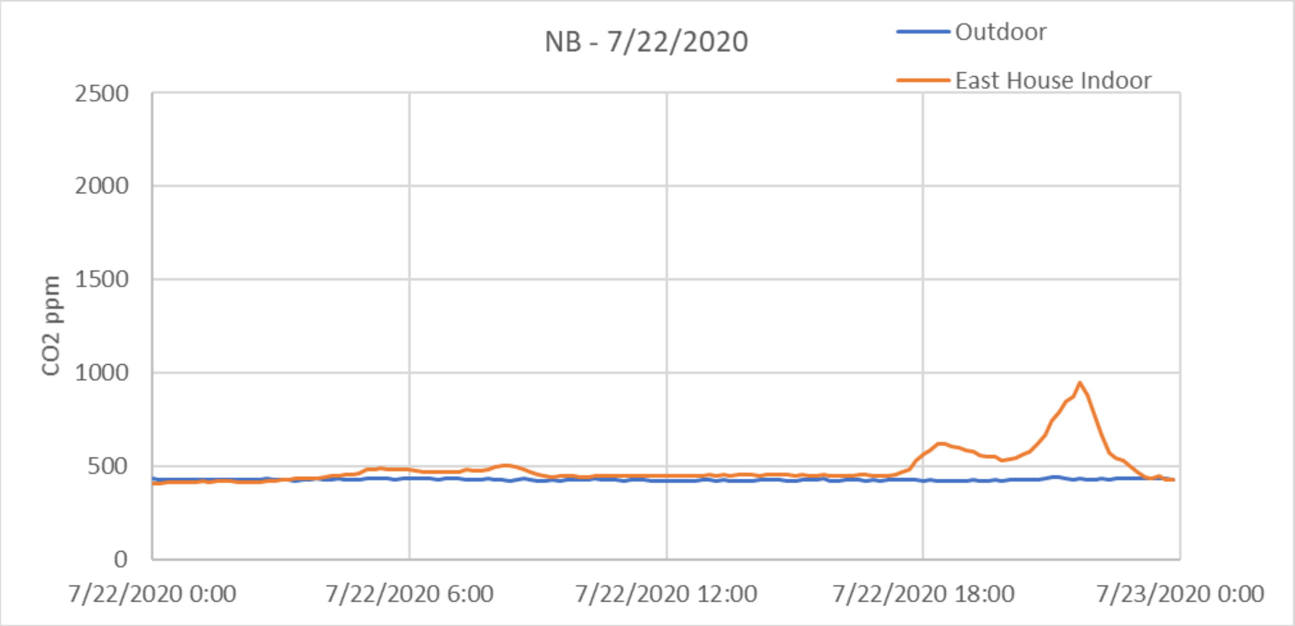
Figure 31: Total Ventilation Delivered and Power Consumption on July 22, 2020 for NightBreeze System



Total mechanical ventilation: 327,883 cubic feet, total energy: 339 watt-hours.

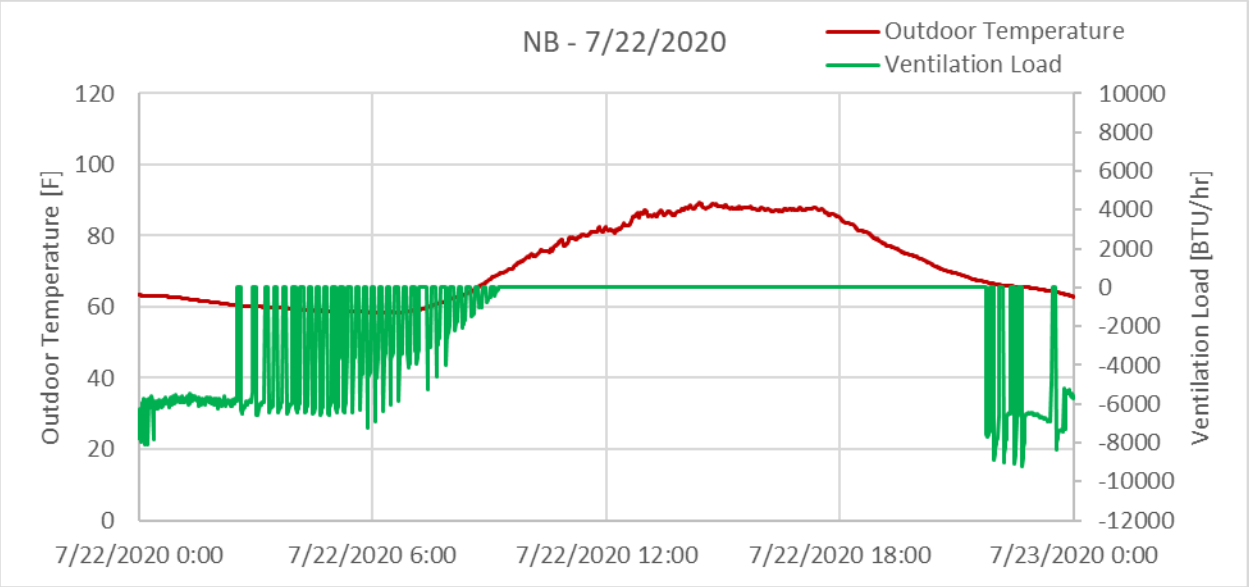
Source: Electric Power Research Institute

Figure 32: Indoor and Outdoor-Air Quality in Carbon Dioxide Parts per Million Levels on July 22, 2020 for NightBreeze System



Source: Electric Power Research Institute

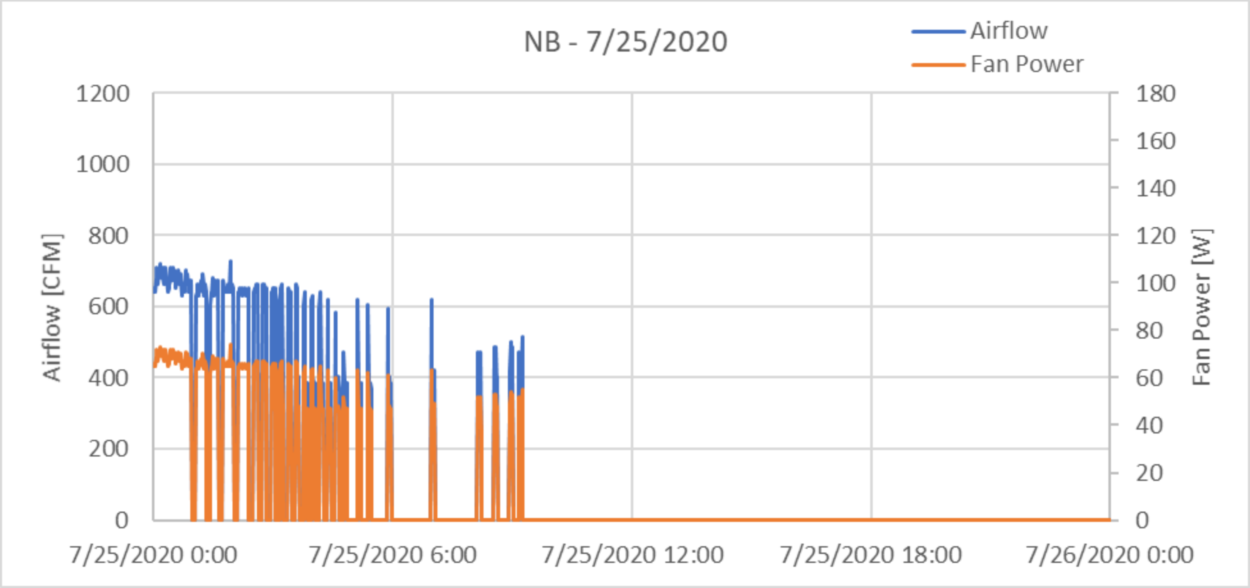
Figure 33: Outdoor-Air Temperature and Ventilation Cooling Delivered on July 22, 2020 for NightBreeze System



Total ventilation load, -42,390 Btu.

Source: Electric Power Research Institute

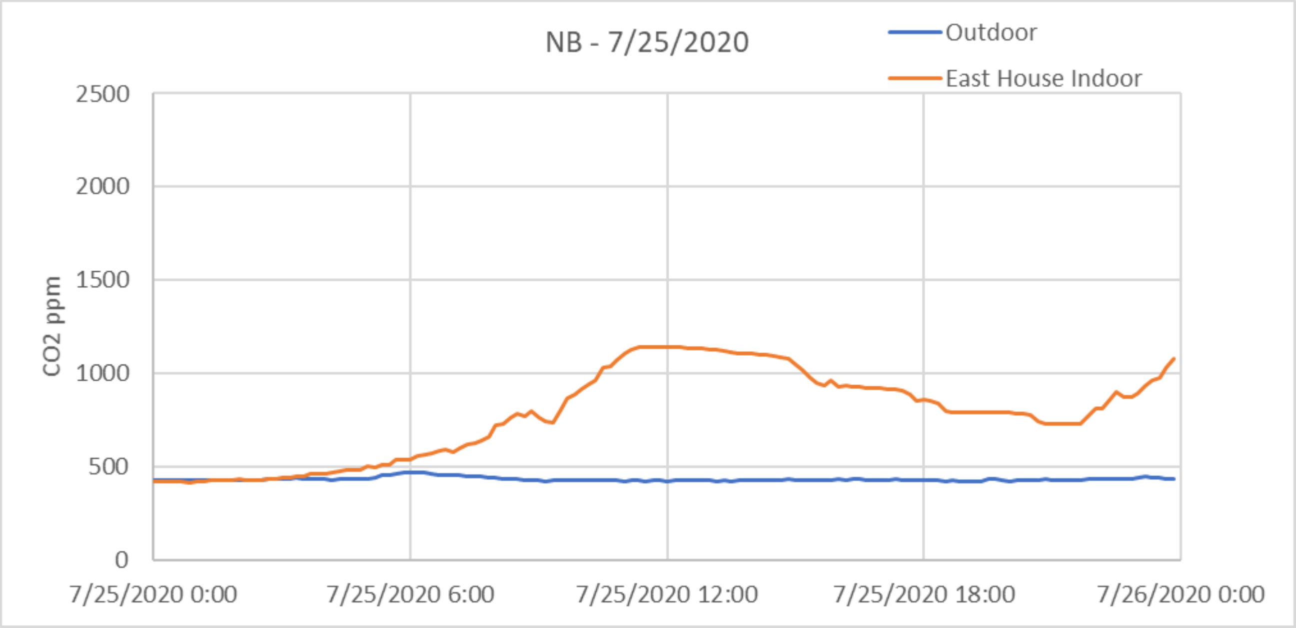
Figure 34: Total Ventilation Delivered and Power Consumption on July 25, 2020 for NightBreeze System



Total mechanical ventilation, 150,244 cubic feet total energy: 143 watt-hours.

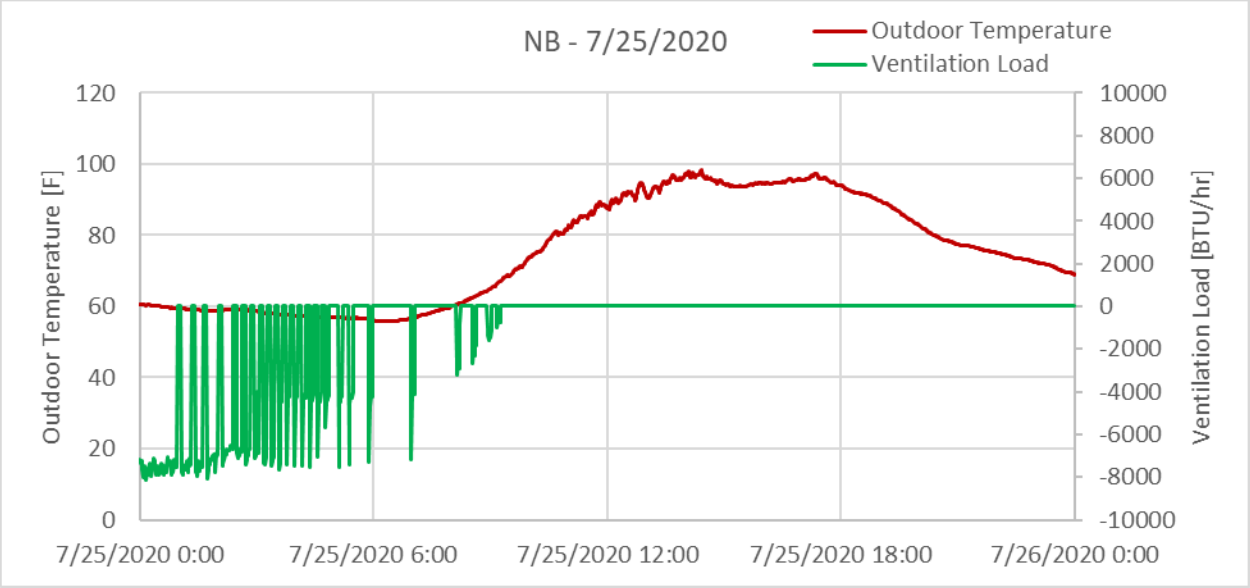
Source: Electric Power Research Institute

Figure 35: Indoor and Outdoor-Air Quality in Carbon Dioxide Parts per Million Levels on July 25, 2020 for NightBreeze System



Source: Electric Power Research Institute

Figure 36: Outdoor-Air Temperature and Ventilation Cooling Delivered on July 22, 2020 for NightBreeze System



Total ventilation load, -24,790 Btu.

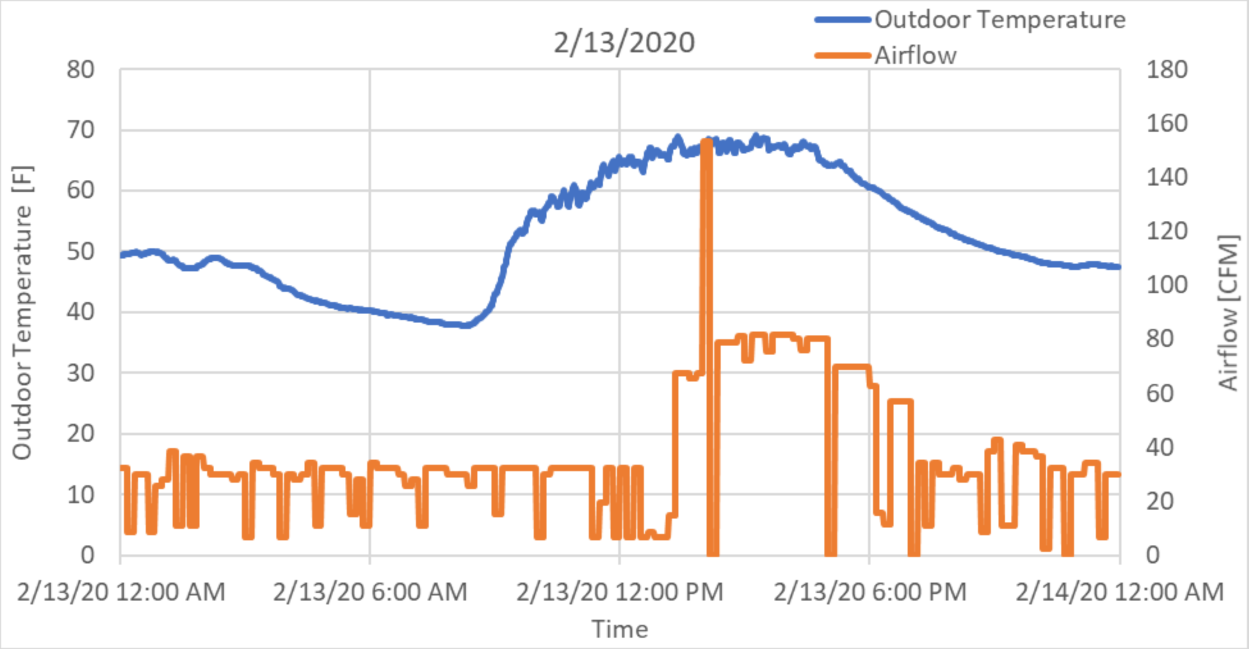
Source: Electric Power Research Institute

Heating Mode: For heating mode, the NightBreeze fan was set to an average ventilation rate of 50 CFM. Using that setting and assuming that at minimum speed the fan delivers 200 CFM, the control operates the fan for 15 minutes of each hour. The NightBreeze system consumes 6 W in standby mode and about 23 W while operating, so the power averages about 10.5 W. Due to low resolution of the power meter, no useful data could be plotted for the NightBreeze in heating mode.

For the SRV system, only CFM and capacity calculation data can be plotted due to the low resolution of the power meter during that testing time. The SRV controller logs CFM, while for the NightBreeze system, CFM is calculated from power measurements.

In the optimized mode for heating (Figure 37), the SRV fan operated at higher speeds during the warmer duration of the day, but maintained the lower fan-speed operation otherwise. The optimized mode of operation during heating provided approximately 36 percent more total mechanical ventilation (total volumetric air flow) than the non-optimized mode in heating (Figure 38).

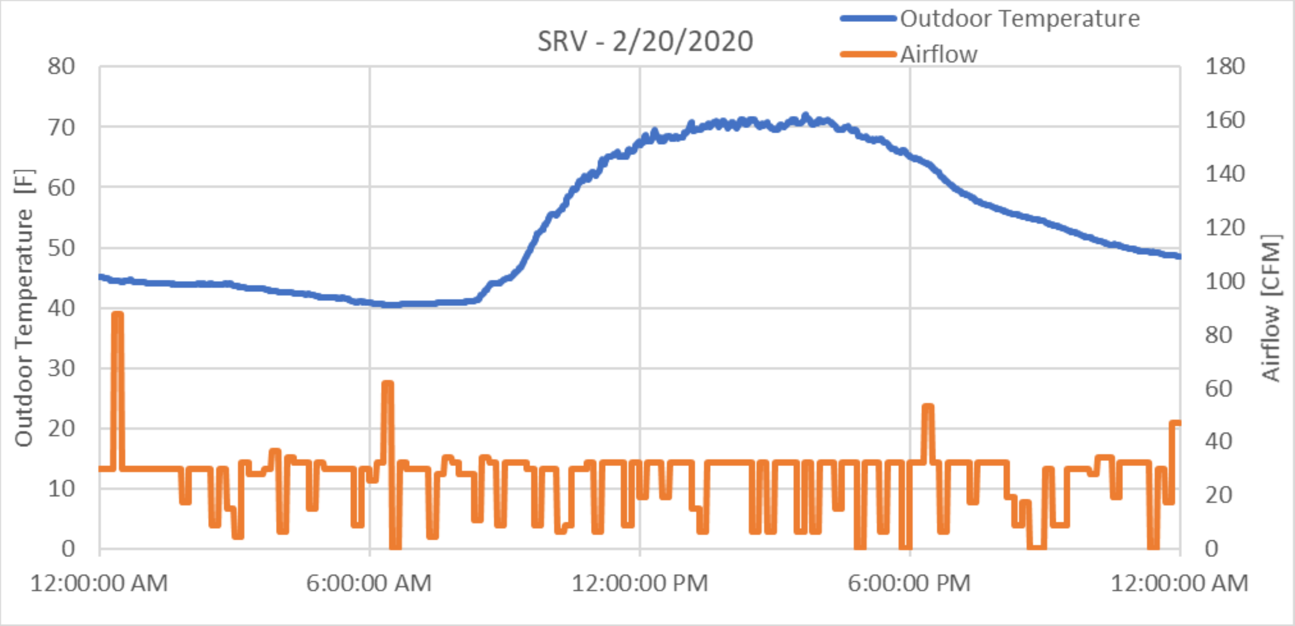
Figure 37: Total Ventilation Delivered and Power Consumption on February 13, 2020 for Smart Residential Ventilation in Optimized Mode



Total mechanical ventilation, 50,560 cubic feet.

Source: Electric Power Research Institute

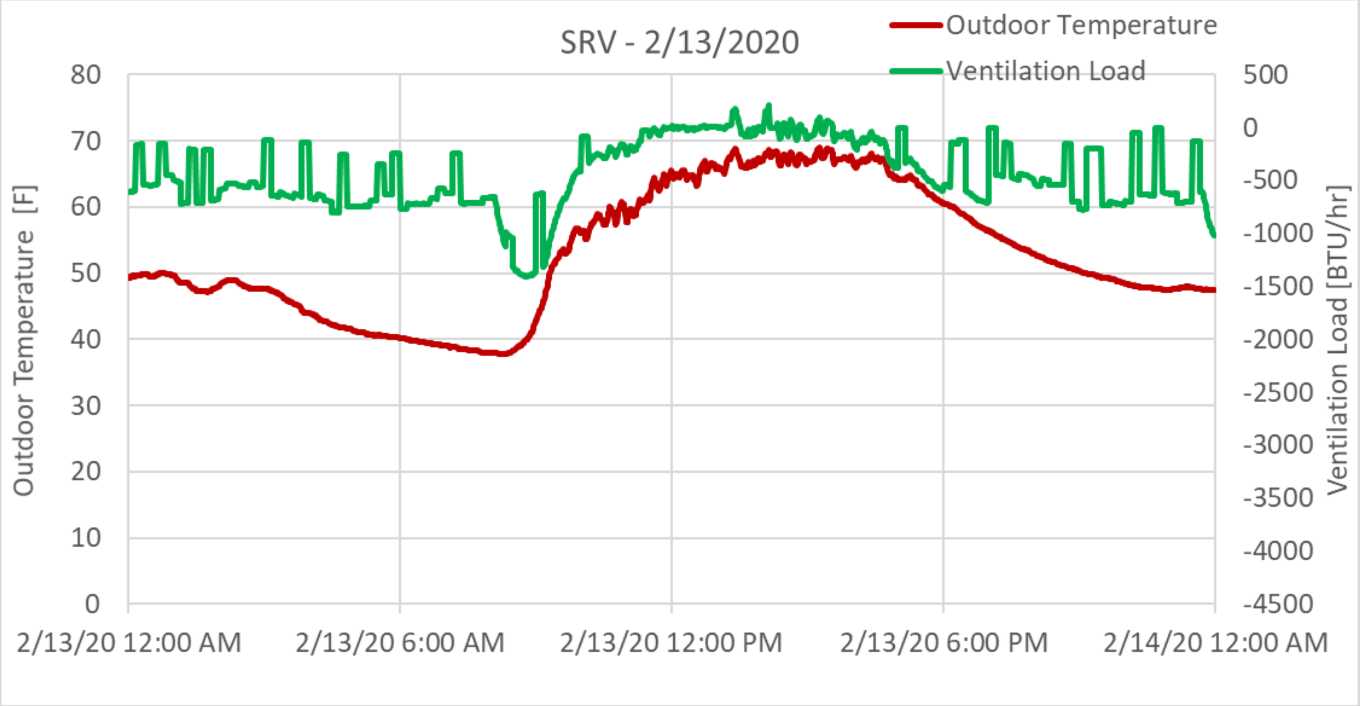
Figure 38: Total Ventilation Delivered and Power Consumption on February 20, 2020 for Smart Residential Ventilation in Non-Optimized Mode



Total mechanical ventilation, 37,145 cubic feet.

Source: Electric Power Research Institute

Figure 39: Outdoor-Air Temperature and Ventilation Cooling Delivered on February 13, 2020 for Smart Residential Ventilation System

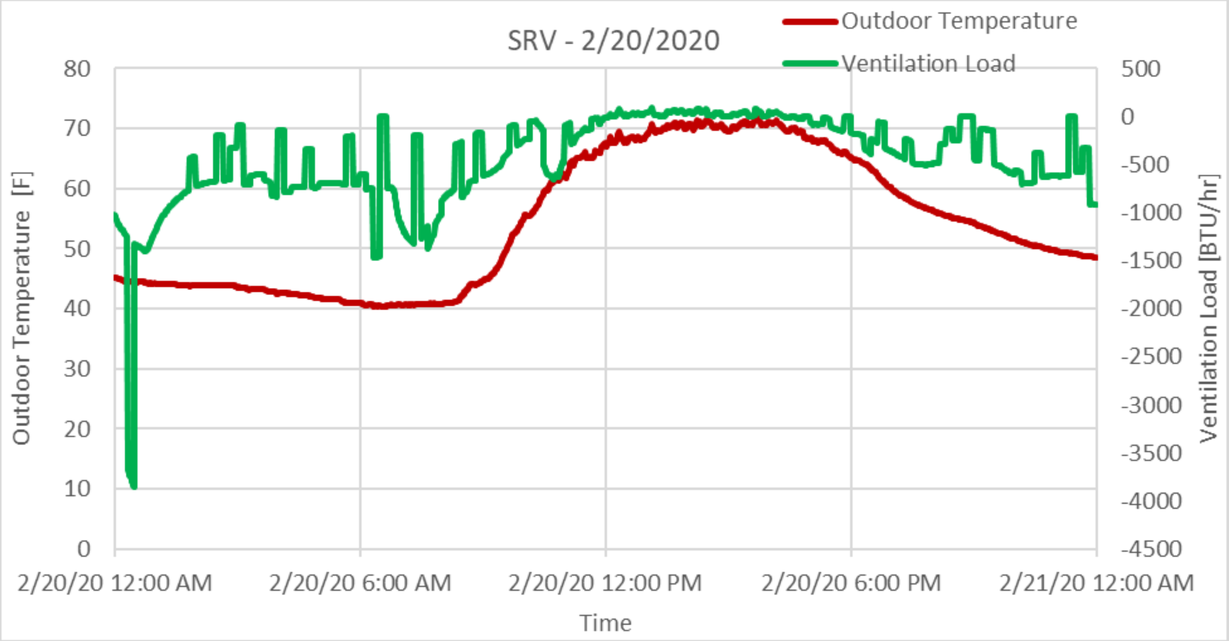


Total ventilation load,-10,078 Btu.

Source: Electric Power Research Institute

Smart Residential Ventilation in Non-Optimized Mode (Heating Season)

Figure 40: Outdoor-Air Temperature and Ventilation Cooling Delivered on February 20, 2020 for Smart Residential Ventilation in Non-Optimized Mode



Total ventilation load, -10,418 Btu.

Source: Electric Power Research Institute

Both the SRV and NightBreeze ventilation systems could serve as effective options for ventilation retrofits of existing residential homes without active ventilation systems. The SRV installed and tested in this project was the first prototype built. The proof of concept was demonstrated with the SRV controller that uses weather forecasts for each day to determine when to "over ventilate" to reduce building cooling loads. It minimized heat gain from the ventilation in cooling mode by venting more during cooler hours and at a minimum speed during hotter periods to satisfy the target-ventilation requirement.

Table 4, Table 5, and the subsequent figures summarize the performance metrics of the two residential ventilation systems, SRV, and NightBreeze, for the duration of the one-year testing period (Aug 2019 through Aug 2020). Due to intermittency in the data collection, a selection of dates appears when both ventilation systems are operating and reliable data are collected. Additional plots for the week-long operation of both ventilation systems are shown in Appendix B.

Table 4: Summary of Ventilation System Daily Performance in Cooling Mode

Net Daily Values	Net Daily Values	SRV	NightBreeze	% Difference (NightBreeze-SRV) /NightBreeze
July 18 (see appendix)	Energy (Wh)	31	385	95
July 18 (see appendix)	Mechanical Ventilation (CF)	65,300	349,397	81
July 18 (see appendix)	Net Ventilation Load (BTU)	9,178	-31,416	129
July 22 (non-optimized SRV)	Energy (Wh)	40	339	88
July 22 (non-optimized SRV)	Mechanical Ventilation (CF)	86,221	327,883	74
July 22 (non-optimized SRV)	Net Ventilation Load (BTU)	5,300	-42,390	113
July 25	Energy (Wh)	31	143	78
July 25	Mechanical Ventilation (CF)	66,760	150,244	56
July 25	Net Ventilation Load (BTU)	4,214	-24,790	117

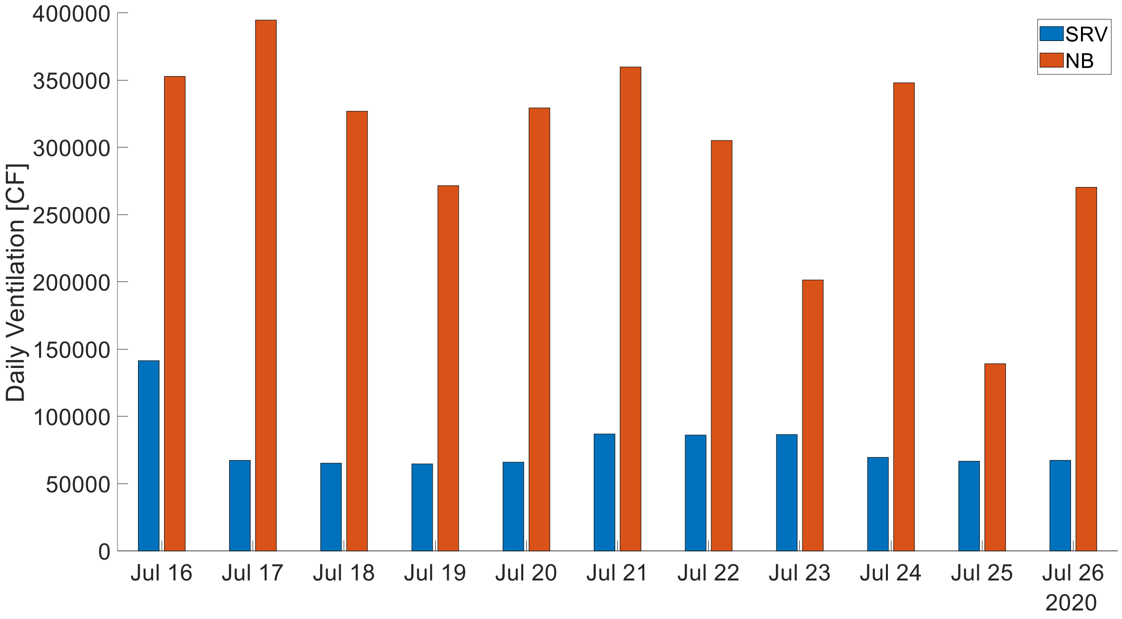
Source: Electric Power Research Institute

In Table 4, the net daily-performance metrics (energy consumption, air flow delivered and net ventilation load) are compared between SRV and NightBreeze. On July 18, 2020, and July 25, 2020, SRV operated in the optimized mode, and on July 22, in the non-optimized mode (constant CFM target each hour). For the optimized mode, SRV operation showed a 20-22.5 percent energy reduction in energy consumption for ventilation delivered over the non-optimized baseline.

The main differences between NightBreeze and SRV operations correspond to the lower power consumption and operating air-flow (CFM) range of SRV system. SRV operates at about one order of magnitude less for both power consumption and CFM compared to NightBreeze. Comparing the percent difference for each of the three metrics between NightBreeze and SRV, SRV system ranges 78-95 percent less energy consumption than NightBreeze in July; providing 56-81 percent less total ventilation air flow for 24-hr period and effectively 113-129 percent more ventilation load than NightBreeze.

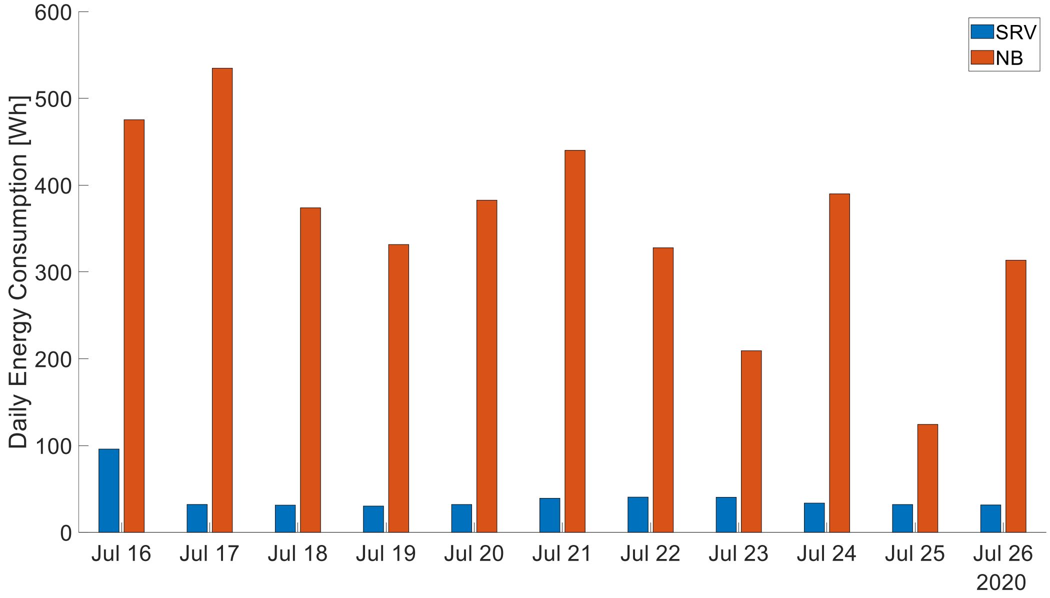
The difference in magnitude between the two systems is further illustrated in Figure 41 through Figure 46, showing the daily values during the testing period of July 16 through July 26, 2020. The SRV system operated in optimized mode on July 17-20 and July 24-26, 2020, and in non-optimized mode on July 21-23, 2020. The target daily-ventilation requirement for the houses' configuration was 86,400 cubic feet (CF) per day (based on the 60 CFM each hour target; 60 CFM* 60 min/hr* 24 hr/day = 86,400 CF per day). While the NightBreeze system more than comfortably fulfilled that requirement when it was operating, the SRV system met this requirement when accounting for the ventilation from infiltration (200,219 CF per day), as outlined in Section A for the SRV algorithm equations for total ventilation (delivered as a combination of infiltration and mechanical ventilation). It should be noted that the minimum ventilation rate, based on ASHRAE standards, was met with the estimated infiltration ventilation rates, and mechanical ventilation provided additional ventilation.

Figure 41: Comparison of Daily Total Ventilation Delivered (Cubic Feet) for NightBreeze Versus Smart Residential Ventilation During July 16-26, 2020



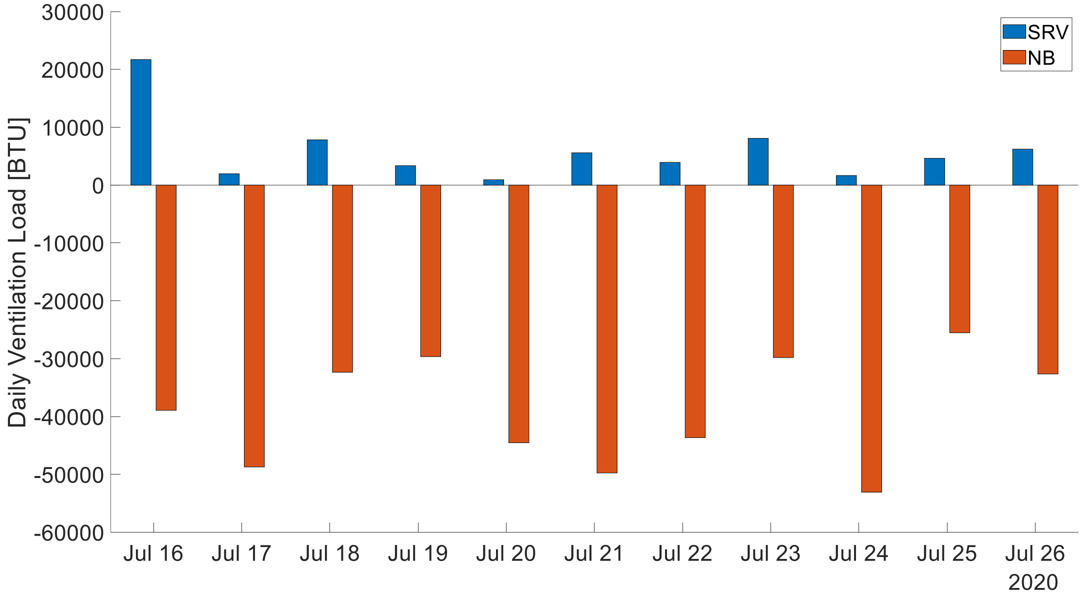
Source: Electric Power Research Institute

Figure 42: Comparison of Daily Energy Consumption (Watt-Hours) for NightBreeze Versus Smart Residential Ventilation During July 16-26, 2020



Source: Electric Power Research Institute

Figure 43: Comparison of Daily Ventilation Load (Btu) for NightBreeze Versus Smart Residential Ventilation During July 16-26, 2020



Source: Electric Power Research Institute

Table 5 provides a range of values throughout the testing period for each of the performance metrics and also notes the order of magnitude difference between SRV and NightBreeze.

Table 5: Summary Range of Values From Ventilation Analysis

Metric	SRV	NightBreeze
Operating Fan Power	1 – 4 W	0 – 160 W
CFM Range	0 – 95 CFM	0 – 12,00 CFM
Daily Mechanical Ventilation	65,300 – 146,221 CF	170,244 – 386,920 CF
Daily Energy Consumption	31 – 98 Wh	143 – 540 Wh
Indoor Air Quality	600 – 2000 ppm CO_2	400 – 2000 ppm CO_2

Source: Electric Power Research Institute

Pre-retrofit CO_2 concentrations were high, with peaks as high as 2,200 ppm and mean values in both houses around 1,400 ppm (after correcting the data with the 95 percent correction factor). Previous studies have measured CO_2 concentrations in homes in California with means reported in the 600 ppm range.

During operation in cooling mode, indoor air-quality measurements ranged between 600-2,000 ppm CO_2 for SRV sample dates shown, while indoor air quality ranged between 400-2,000 ppm CO_2 for NightBreeze. However, a more effective evaluation of the ventilation impact on indoor air quality is illustrated in Figure 44 through Figure 46. Both ventilation systems resulted in higher CO_2 ppm during the daytime when temperatures were hotter and the ventilation systems were in cooling mode, while the East House with the NightBreeze system had lower CO_2 ppm due to the much higher ventilation rate (compared with SRV).

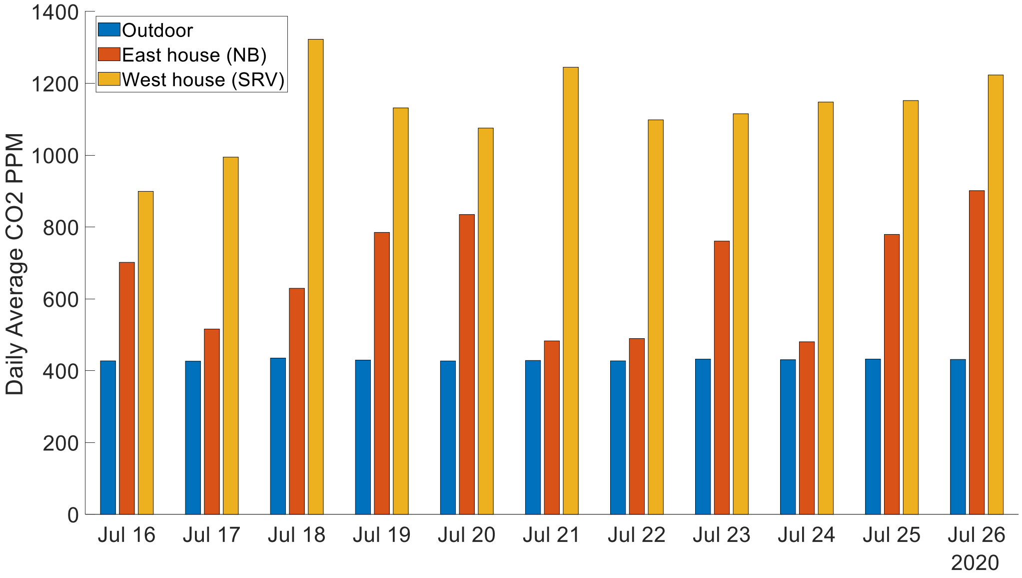
It is important to note how the SRV system met minimum ventilation requirements. Previous versions of ASHRAE Standard 62.2 included an intermittency table that made it relatively easy to determine the efficacy of non-continuous ventilation. With the adoption of ASHRAE 62.2-2016 Addendum V and Normative Appendix C, this was replaced with a tedious calculation of relative exposure that effectively requires modeling to prove equivalency to required ventilation volumes. Another change that reduces the value of ventilation in non-balanced systems (supply or exhaust) nearly eliminates the contribution of infiltration, especially for tight houses, and places more weight on mechanical ventilation.

ASHRAE 62.2 states: *It* (referring to Addendum V) *establishes a short-term exposure limit of 5 times the long-term exposure limit which must be considered when using non-continuous ventilation*. Since the long-term exposure limit is undefined it is not possible to determine ventilation requirements. Section 4.5.1, which covers short-term average ventilation and is essentially the prescriptive approach, allows the mechanical ventilation rate to vary, provided that the average rate over any three-hour period is greater than that calculated by the equations shown here, where A_{floor} is the conditioned floor area, N_{br} is the number of bedrooms, and Q_{inf} is the infiltration rate. Equation 4.2 applies only single-family homes with exhaust or supply ventilation.

Equation 4.1: $Q_{tot} = 0.03 \times A_{floor} + 7.5(N_{br} + 1)$

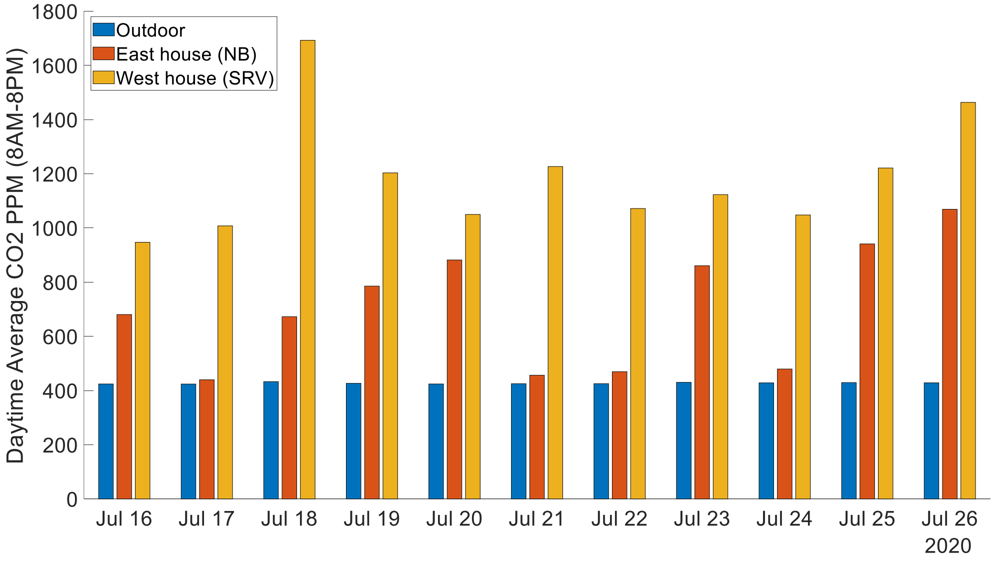
Equation 4.2: $Q_{fan} = Q_{tot} - (Q_{inf}^2 / Q_{tot})$

Figure 44: Comparison of Daily Average Carbon Dioxide Parts per Million Level for Each House Relative to Outdoor Carbon Dioxide Levels During July 16-26, 2020



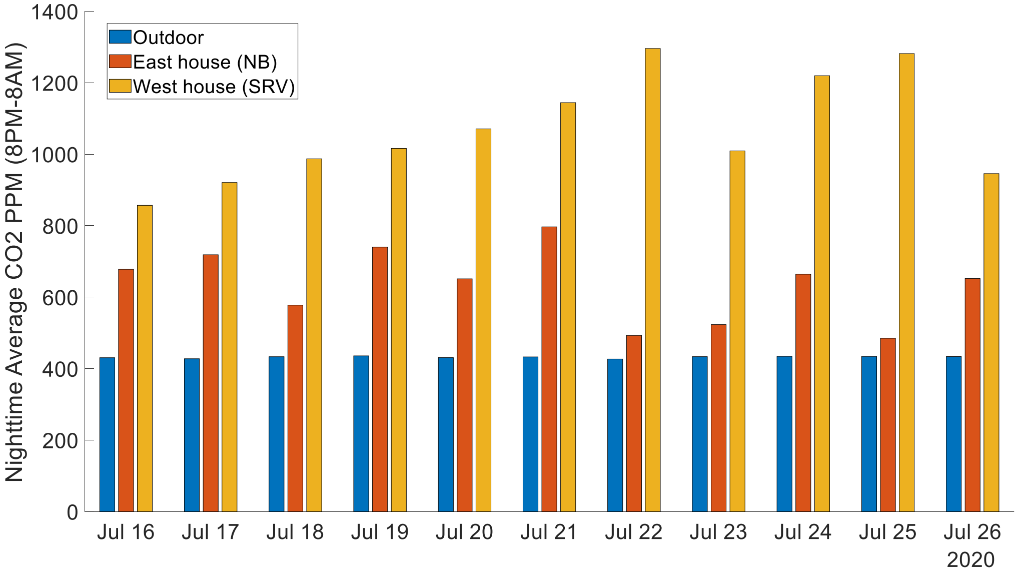
Source: Electric Power Research Institute

Figure 45: Comparison of Daytime Average Carbon Dioxide Parts per Million Levels for Each House Relative to Outdoor Carbon Dioxide Levels During July 16-26, 2020



Source: Electric Power Research Institute

Figure 46: Comparison of Nighttime Average Carbon Dioxide Parts per Million Levels Relative to Outdoor Carbon Dioxide Levels for Each House During July 16-26, 2020



Source: Electric Power Research Institute

Indoor Air Quality

The indoor-air quality (IAQ) of the houses was assessed by comparing PM2.5, CO_2 and formaldehyde levels before and after the retrofit. CO_2 is generated by occupants; higher levels indicate insufficient ventilation, while lower values indicate sufficient ventilation. Outdoor concentrations are relatively constant over time, so only indoor levels were considered. The 24-hour average indoor concentrations were calculated, as were nighttime values where occupancy was assumed to be fairly consistent. Levels before and after the retrofit were compared to evaluate the effectiveness of the retrofit for improving both ventilation and IAQ.

For $PM_{2.5}$, several measures were considered. First, there were indoor concentrations, which included both particles infiltrating from the outdoors and indoor-generated particles. These must therefore be evaluated within the context of outdoor concentrations. To more directly consider how well the building envelope protected the house from outdoor particles, the ratio of the indoor concentration to the outdoor concentration could be calculated during time periods when there were no anticipated indoor sources. Finally, to evaluate how effectively the house removed particles generated within, various measures are compared between the indoor and outdoor concentrations. Formaldehyde is typically much higher indoors than outdoors, typically from items such as furniture and wood that contain and release formaldehyde. Indoor levels measured before and after the retrofit were compared.

All data analyses for IAQ data were performed using SAS software (Version 9.4).

Carbon Dioxide

CO_2 concentrations were collected every minute using Vaisala sensors inside and outside the house. All data were converted to 10-minute averages. The Vaisala sensors were collocated with TSI Q-trak monitors, and reported concentrations about 5 percent high on both indoor sensors. Because the primary objective of this project was to compare pre- and post- retrofit periods to evaluate the impact of the retrofit, a constant but high measurement was not problematic. Nevertheless, reported concentrations were adjusted to 95 percent of the reported value to align with values reported by the TSI Q-trak. More details can be found in the following quality assurance/quality control (QA/QC) section.

The amount of ventilation in the home can be evaluated by comparing CO_2 levels between periods with different settings. Both the 24-hour average CO_2 concentrations and the nighttime averages (midnight to 5 am) were calculated. During the night, it was assumed that occupancy was consistent. Seasonal-average values are presented in the following tables, with the seasons adjusted to reflect changes in ventilation status. Outdoor CO_2 concentrations typically remain fairly constant, so indoor concentrations are generally reported. During this study, the average outdoor CO_2 concentration was 462 ppm.

Table 6 through Table 13 show the CO_2 data from both houses. The first column indicates the season and ventilation, the second column shows the number of days in that month, and the third column shows the average concentration for that time. The remaining columns illustrate variability in the average concentration and present the 25th percentile, median, 75th percentile, and 90th percentile of daily average concentrations, for both time and ventilation. The SRV in the West House during the heating season was run in both the baseline and optimized modes; the summary statistics are listed separately for both modes. Note that the time periods reported are shorter than for the other modes.

Table 6: Pre-Retrofit Indoor Carbon Dioxide Concentrations (PPM) in the West House Calculated as Daily Means for 24 Hours

	N	Mean	25th Pctl	Median	75th Pctl	90th Pctl
Winter/Spring	121	1460.85	1282.13	1471.18	1653.70	1843.96
Summer / Early Fall	152	1452.48	1317.90	1448.87	1591.31	1724.95

Values averaged by retrofit status and season. Post-retrofit also includes baseline and optimized mode periods for the smart residential ventilation system.

Source: University of California, Davis

Table 7: Post-Retrofit Indoor Carbon Dioxide Concentrations (PPM) in West House Calculated as Daily Means for 24 hours

	N	Mean	25th Pctl	Median	75th Pctl	90th Pctl
Winter/ Spring-No Ventilation	124	1551.92	1361.66	1553.75	1730.56	1920.07
Summer/ Early Fall-SRV Installed	107	609.62	563.77	599.14	637.78	685.27
January 2020- Baseline mode	12	829.94	642.18	901.22	995.48	1159.79
January 2020- Optimized Mode	19	1172.37	1113.40	1152.33	1221.27	1317.25

Source: University of California, Davis

Table 8: Pre-Retrofit Indoor Carbon Dioxide Concentrations (PPM) in East House Calculated as Daily Means for 24 Hours, With Values Averaged by Retrofit Status and Season

	N	Mean	25th Pctl	Median	75th Pctl	90th Pctl
Winter/Spring	94	1566.56	1359.36	1558.14	1813.91	1948.42
Summer/Early Fall	135	1487.70	1329.47	1493.00	1638.19	1805.58

Source: University of California, Davis

Table 9: Post-Retrofit Indoor Carbon Dioxide Concentrations (PPM) in East House Calculated as Daily Means for 24 Hours, with Values Averaged by Retrofit Status and Season

	N	Mean	25th Pctl	Median	75th Pctl	90th Pctl
Winter/Spring-NightBreeze Heating	73	1447.61	1215.92	1401.46	1652.86	1874.18
Summer/Early Fall-NightBreeze Cooling	111	650.09	573.16	626.12	700.91	820.03

Source: University of California, Davis

Table 10: Pre-Retrofit Indoor Carbon Dioxide Concentrations (PPM) in West House Calculated as Daily Means for Nonsource Period, with Values Averaged by Retrofit Status and Season

	N	Mean	25th Pctl	Median	75th Pctl	90th Pctl
Winter/Spring	121	1409.15	1171.66	1358.03	1613.44	1924.84
Summer/Early Fall	152	1441.07	1271.84	1420.61	1607.31	1727.62

Source: University of California, Davis

Table 11: Post-Retrofit Indoor Carbon Dioxide Concentrations (PPM) in West House Calculated as Daily Means for Non-Source Period, With Values Averaged by Retrofit Status and Season

	N	Mean	25th Pctl	Median	75th Pctl	90th Pctl
Winter/Spring-No Ventilation	124	1555.74	1328.06	1519.00	1797.69	2038.04
Summer/Early Fall-SRV Installed	97	523.84	498.73	512.76	537.68	564.34
January 2020- Baseline mode	12	774.34	477.36	857.40	907.99	1063.55
January 2020- Optimized Mode	19	1095.31	1025.78	1066.66	1174.59	1199.81

Source: University of California, Davis

Table 12: Pre-Retrofit Indoor Carbon Dioxide Concentrations (PPM) in East House Calculated as Daily Means for Non-Source Period, with Values Averaged by Retrofit Status and Season

	N	Mean	25th Pctl	Median	75th Pctl	90th Pctl
Winter/Spring	94	1622.99	1341.19	1672.31	1974.10	2052.07
Summer/Early Fall	135	1539.69	1327.28	1534.75	1711.28	1925.45

Source: University of California, Davis

Table 13: Post-Retrofit Indoor Carbon Dioxide Concentrations (PPM) in East House Calculated as Daily Means for Non-Source Period, With Values Averaged by Retrofit Status and Season

	N	Mean	25th Pctl	Median	75th Pctl	90th Pctl
Winter/Spring-NightBreeze Heating	73	1575.36	1331.62	1508.17	1886.74	2052.31
Summer/Early Fall-NightBreeze Cooling	105	552.39	435.31	473.08	608.69	794.01

Source: University of California, Davis

Prior to the interventions, neither the east nor the west houses appeared to have sufficient ventilation, as indicated by the relatively high CO_2 levels. Pre-retrofit, measured CO_2 concentrations were higher than expected, with peaks as high as 2,200 ppm, and with mean values in both homes around 1,400 ppm, after correcting the data with the 95 percent correction factor. Previous studies have measured CO_2 concentrations in homes in California with means reported in the 600-ppm range. The ASHRAE 62.1 guideline level for CO_2 is 1100 ppm (700 ppm above outdoor background and applies during occupied periods only).

When the West House was sealed, it did not have any ventilation initially, and again, CO_2 levels were very high with a 24-hour average of 1,552 ppm, much higher than the ASHRAE 62.1 guidance level. This value is also higher than the pre-retrofit period, as expected since ventilation was reduced by the sealing of the house. Once the SRV system was installed in the West home, the CO_2 levels were reduced, substantially dropping to near outdoor levels (typically in the 400-500 ppm range), with a mean value of 610 ppm, indicating improved ventilation. The SRV system was designed to bring in a constant flow rate of 75 CFM of outdoor air, filtered. This value was based on ASHRAE 62.2 requirements, using the air leakage measurement taken post-sealing. In the heating season, the non-optimized mode for the SRV system was also set to bring in 75 CFM of outdoor air, filtered, resulting in an average CO_2 concentration of 830 ppm. The optimized mode brings in less outdoor air, and as a result the average CO_2 concentration increased to 1,172 ppm, just over the ASHRAE 62.1 recommended value of 1100 ppm.

In the East House, the NightBreeze showed more variable results. When it was set in heating mode, NightBreeze was set to run for 15 minutes every hour in order to achieve an average ventilation rate of 50 CFM. Given that the average 24-hour CO_2 concentration over the period was 1,448 ppm, and during the night the average was 1,575 ppm, it is clear that the system was not providing sufficient ventilation. Once the NightBreeze was shifted to cooling mode, there was a notable increase in ventilation to the home. In cooling mode, CO_2 concentrations dropped to near outdoor levels (typically in the 400-500 ppm range), with a mean 24-hour concentration of 650 ppm and a mean night average value of 552 ppm. In cooling mode, the NightBreeze is designed to bring more air into the home at night, reflected in the lower night-time CO_2 concentrations.

Particulate Matter

Particulate Matter ($PM_{2.5}$) data was collected every minute using Plantower PMS3003 sensors both inside and outside the home. As there is considerable minute-to-minute fluctuations in the concentrations, all data was first converted to 10-minute average data. Data was examined for three time periods: all day (24 hours), non-source period, estimated as the hours between 12 am and 5 am, when people are likely sleeping and not generating PM, and the source period, between the hours of 12 pm and 6 pm, when people are likely home, awake, and performing activities, such as cooking, that would generate PM indoors.

The first measure is the daily average concentrations both inside and outside the home.

The monthly 24-hour average indoor $PM_{2.5}$ concentrations are presented in Appendix D. Focusing on the West house mean values, the indoor concentrations were increased after sealing the home, but before installation of the SRV, relative to the winter/spring values measured prior to the sealing of the home (19 µg/m^3 after sealing versus 11 µg/m^3 before sealing). The occupants in this home do a considerable amount of cooking and if the ventilation rate is reduced, one would anticipate the indoor concentrations to rise, as ventilation is an important removal process for indoor generated $PM_{2.5}$. Once the SRV was installed, indoor concentrations dropped substantially, with a mean indoor 24-hour average concentration of 6 μg/m^3, as compared to an average concentration of 13 μg/m^3 in the same time period before the retrofit occurred. It is noted that the indoor concentration in the summer/ early fall of the pre-retrofit period is higher than the average concentration in the winter/spring of the pre-retrofit period. Indoor concentrations result from PM infiltration from outdoor air, as well as PM generated indoors. In August 2018, during the summer/early fall pre-retrofit period, outdoor concentrations were elevated due to fires in Northern California. The indoor concentration in the West house was also high in this month, driving up that season's average indoor concentration. Apart from this isolated month, outdoor concentrations remained fairly steady in the pre-retrofit period. The average indoor value for the heating season in the non-optimized mode for the SRV in January was 11 μg/m^3, slightly lower than measured in the optimized mode, 14 μg/m^3. The concentration measured while the system was in the non-optimized mode was similar to that measured pre-intervention.

Concentrations in the East House were lower after installation of the NightBreeze, compared with the pre-retrofit period. In the heating period, the 24-hour average concentration dropped from 22 μg/m^3 to 9 μg/m^3. In the cooling period, the 24-hour average was 4 μg/m^3, compared with 10 μg/m^3 before the intervention.

The indoor/outdoor (I/O) ratio is calculated during the non-source time period to determine the effectiveness of both the building shell and ventilation system at removing particles of outdoor origin, referred to as *penetration efficiency*. The I/O ratio is calculated by dividing the indoor concentration for a given 10-minute period by the outdoor concentration for the same 10-minute period. If the outdoor concentration is zero, the I/O ratio cannot be calculated. Additionally, when the recorded outdoor values are extremely low, the impact of the measurement error relative to the absolute value becomes large. This is not a problem when reporting actual concentrations, but when dividing a small number by another small number with uncertainty, the numbers become unrealistic for the I/O ratio. Therefore, for the nights when the 25th percentile of the outdoor concentration was less than 0.5 μg/m^3, the I/O ratio was not calculated. Practically speaking, only a few nights were excluded from this I/O calculation. The distribution for the I/O ratio is often skewed, so the median values were considered primarily when comparing pre- and post-retrofit periods.

The median values of the I/O ratio for the West House, before the retrofit, were 0.55 and 0.63 for winter/spring and summer/early fall, respectively. These values are typical for California's housing stock. Once the house was sealed but before ventilation was provided, the median I/O ratio from midnight to 5 am was 1.24. This is likely because the particulate matter (PM) generated before midnight had not yet been removed from the home; the primary ways PM is removed is through deposition and ventilation, and ventilation was substantially reduced. Therefore, midnight to 5 am is not a non-source period. No period appeared to be unaffected by indoor sources. This value, therefore, does not represent the penetration efficiency of the house.

Once the SRV was installed in the West House, the median I/O ratio during the nighttime period was 0.50, lower than the pre-retrofit period. The values in the distribution were also much more consistent; with the 90th percentile at 0.71 the building shell was almost always protecting residents from $PM_{2.5}$. It was clear that the SRV improved IAQ during the night.

During the heating season, the I/O ratios with the SRV were very low, with a median value of 0.21 in the baseline mode and a value of 0.25 in the optimized mode.

The East House had much higher and more variable pre-retrofit values, with the median winter/spring value measured as 2.35 and the summer/early fall measured as 0.69. During the winter/spring period, it is likely that there were indoor sources that increased concentrations very late in the evening. These concentrations were similar to the winter/spring, post-sealing, but were not similar to the ventilation period in the West House. Looking at the post-retrofit periods, when NightBreeze was in heating mode and bringing in less ventilation, the median value was 0.72 and the 90th percentile was 6.70, indicating that the ventilation was not always clearing away PM generated indoors during the evening. When the NightBreeze was set to cooling mode, the median value was 0.44, while the 90th percentile was 0.59, indicating that the added ventilation was successfully removing particles generated indoors on the vast majority of nights, as well as removing a fraction of the particles being brought in from the outdoors as the system was providing filtered air.

Next, the impact of indoor sources was considered. Indoor sources were variable, with both day-to-day variability and house-to-house variability depending on activities in the home that day. Combustion-related activities, primarily cooking, comprise a large part of this variation. For example, frying generates far more particles than simmering a meal in a covered pot. Another relevant source of particles in these homes is re-suspension, either from activities such as vacuuming or from kids being active indoors. Interpreting indoor sources is further complicated by the infiltration of outdoor particles that contribute to indoor levels. Note that the contribution of outdoor particles to indoor particle concentration varies as the outdoor concentration changes, and as windows are opened or closed. The filter and HVAC system can remove particles of indoor origin, and it is valuable to compare values before and after the retrofit. To separate out the influence of outdoor particles, the outdoor concentration is subtracted, adjusted to reflect the portion likely to enter the indoors, from the indoor concentration. This was done in the afternoon when there were more sources, 12 pm-6 pm, for each 10-minute period, using the following equation:

$$C_{ind\text{-}ind}=C_{ind}-C_{out}*I/O_{avg}$$

Where:

$C_{ind\text{-}ind}$ is the indoor concentration from indoor sources (μg/m^3).

C_{ind} is the measured indoor concentration (μg/m^3).

C_{out} is the measured outdoor concentration (μg/m^3).

I/O_{ave} is the average I/O value from the nighttime measurements (unitless).

For pre-retrofit periods, the average I/O ratio values for the whole nighttime (non-source) period were used: 0.61 for the West House and 0.87 for the East House. An I/O ratio of 1 was used, the theoretical maximum, when calculating $C_{ind\text{-}ind}$ from indoor sources, during the period when the house was sealed without ventilation, which will underestimate calculated levels. The average value for each afternoon was calculated and the summary statistics for each home, by season, were presented with monthly average values in the appendix B. In the West House, during the pre-retrofit period, the values were slightly lower in the winter/spring period than in the summer/early fall period, potentially because windows were open more in the summer. When the home was sealed and there was no ventilation, the values increased as the only removal pathway for the particles was deposition. Note that the presented values for this season underestimated the actual value as it was assumed that all particles of outdoor origin reach the inside since a penetration efficiency could not be calculated. Once the SRV was installed, the indoor source concentration decreased substantially. Due to the relatively short monitoring period for the SRV in the heating period, these values were not calculated.

Data for the East House was more difficult to interpret, as there were negative values. Compared with the average nighttime I/O ratio between the homes, the one for the East House is higher than for the West House. The true penetration efficiency for the East house may have been overestimated. This, in combination with no indoor sources, would result in a calculated negative value. Comparing the pre- and post-retrofit periods, the winter/spring period when NightBreeze was in heating mode had lower values than the pre-retrofit period. The summer/early fall, with NightBreeze in cooling mode, values were larger than the pre-retrofit values; but as previously stated, the pre-retrofit values were likely inaccurate. The post-retrofit values were very low and it can be interpreted that NightBreeze efficiently removed particles that were generated indoors.

There are no indoor regulatory standards for $PM_{2.5}$. Outdoor regulatory levels are part of the National Ambient Air Quality Standards (NAAQS). The three-year annual average outdoor standard for $PM_{2.5}$ is 12 $\mu g/m^3$[2]. The average concentration in the West House over the 10 months of pre-retrofit data recorded was slightly over this standard, with an average of 12.54 $\mu g/m^3$. The East House exceeded this value as well, with an average of 15.40 $\mu g/m^3$. In general, indoor concentrations in these homes were higher than for outdoor concentrations, indicating significant sources within the homes. The sensors used were light-scattering measures, as opposed to gravimetric measures. The QA/QC work compared the low-cost sensor with a research-grade sensor but did not compare gravimetric measures. In general, concentrations calculated with light-scattering devices are higher than with the integrated gravimetric values used for regulatory values.[3] The values measured in this report should therefore not be strictly compared with regulatory values. The other regulatory value to consider is the NAAQS 24-hour standard, which states that the 98th percentile over a one-year period should not exceed 35 $\mu g/m^3$. There were days in the homes that exceeded this value. Again, note that the sensors used overestimated high concentrations. These high values do point to days with notable indoor sources. Increased ventilation and filtration could mitigate indoor sources in these periods.

Behavioral

West House

The experiences and behaviors of West House occupants in the post-retrofit period are described here. Tables with these survey responses are located in Appendix E.

- **Household Composition and Occupancy Patterns:** The West House household was a family of four: mother, father, and two young children. The home was nearly always occupied during the day, the evening, and night during the post-retrofit period.

  Respondents were asked how temperature preferences differed among the family members. The mother reported that she usually feels colder than her husband, particularly in winter when she preferred warmer set points (75°F) compared with her husband (74°F). In summer, husband and wife generally preferred the same temperature.

- **Cooling Season:** The occupants reported maintaining set points between 65°F and 75°F for all fan-coil units during the cooling season and leaving the air conditioner (A/C) running all night during the spring and summer. Generally, temperatures maintained in the home were considered "warm" by the adults. There are no health considerations among members of the household that affect how the family cools its home. They reported using fans to supplement cooling during the post-retrofit period on especially hot days.

  In the absence of an exhaust fan, the household typically leaves the bathroom window open during the day to alleviate the humidity, but keeps windows and doors closed at night for safety. During the summer and fall post-retrofit, temperatures were too hot to continue this practice.

  The family in the West House was generally very dissatisfied with their home's air conditioner. It was reported not to work well on the hottest days, make too much noise, and fail to maintain comfortable temperatures throughout the house. For example, despite having the setpoint set to 65°F at each fan coil unit, during the summer indoor temperatures of 80°F and 78°F were achieved during the daytime and nighttime, respectively, in the summer, and 75°F -77°F degrees during the day in the fall. The noise level was reported to have increased from both the indoor and outdoor units, but the latter did not bother the occupants.

  Occupants of the West House were very dissatisfied with the retrofit package installed. The respondent said it "doesn't distribute cool air well to the living room," and "rarely reached the programmed temperature - usually 79 or 80 - never less than 79 degrees". In addition to discomfort, the family "used more A/C because [the unit] didn't cool well enough." They "needed to have it on all day." Overall, complaints included: noise indoors, slow and inadequate cooling, and inconvenience, given the need to operate five thermostats.

- **Heating Season:** The occupants reported maintaining setpoints between 72°F and 76°F during the heating season, with slightly higher temperatures at night. When the heat is on, the respondent and her husband found the temperature to be comfortable. The respondent did not report using space heaters to supplement heating during the post-retrofit period.
- **Thermostat:** Before the retrofit, the household used the thermostat manually; they did not use the programming. The respondent (wife) reported the thermostat was "very easy" to use (from among the options: very easy, easy, hard, and very hard). Both adult occupants used the thermostat to adjust settings manually. The respondent reported that the new thermostat was, although "not difficult" to operate, "a little more inconvenient" than the previous thermostat since it was necessary to operate "five thermostats in the house" and "before just one button" controlled the space conditioning in the whole house.
- **Retrofit Process:** The sealing procedure was reportedly very inconvenient for the West House household. Surfaces were sticky from the aerosol treatment, and it took a lot of time to return the family's belongings to their rightful place.

East House

Here, the experiences and behaviors of the occupants in the East House in the post-retrofit period are described.

- **Household Composition and Occupancy Patterns:** The East House is occupied by a family of four: mother, father and two young children. From Summer 2018 through Fall 2019, the home was unoccupied during the daytime work week, and occupied on evenings, nights, and weekends.

  In all seasons, the respondent reported that family members in the household had the same temperature preferences. After the retrofit, however, the respondent noted that she liked it better than her family members. She did not know why she liked it better than her family members but just that she did like it better.

- **Cooling Season:** The occupants reported that they maintained set points between 73°F and 75°F during the cooling season and shut the A/C off at night during spring and fall. The temperatures maintained in the home were considered "comfortable" by the adult occupants. There were no health considerations among members of the household that impacted how the family cooled the home. They did not report using fans to supplement cooling during the retrofit period.

  Daytime use of the bathroom window and slider door for fresh air varied by season, and most often in the fall. Safety concerns precluded opening windows and doors at night during the post-retrofit period.

  The family in the East House was generally satisfied with their home's air conditioner. It was reported to work "okay" on the hottest days, was relatively quiet, and easy to control. The respondent liked that the ventilation system operated when it was cool outside and allowed cooler outdoor air to enter the home. However, the new A/C "did not get as cold as the old unit" or "as cold as (the respondent) would like." Specifically, it never cooled below 73 degrees. It did, however, achieve satisfactory levels of comfort and noise.

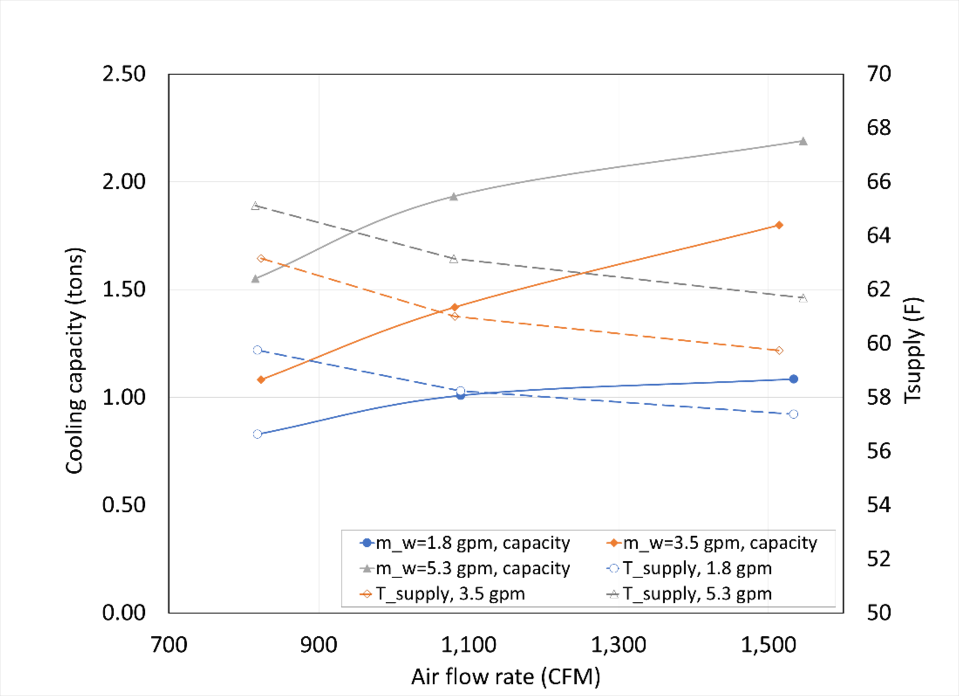
- **Heating Season:** The respondent reported maintaining a set point of 72°F during the day in the winter and shutting the heat off before going to bed. When the heat was on, the respondent and her husband found the home to be comfortable. At night, with the heat off, it also felt comfortable to both the respondent and her husband. The respondent did not report using space heaters to supplement heating during the post-retrofit period.
- **Thermostat:** The thermostat installed with the retrofit was reportedly "harder at first, then easier" to operate. The household used the new thermostat manually; they did not use the programming.
- **Retrofit Process:** The East House reportedly had no issues (mess, dust) with the sealing procedure.

Lab Testing

The performance of the SWEC cooler was determined by the cooling capacity (in tons), electric power consumed, coefficient of performance (COP), and the temperature of the supply water. The return-water temperature was fixed for all experiments at 70°F, based on a conservative estimate of the water temperature exiting the water coil. The plots of the lab test results can be found in the appendix B.

Results of the SWEC performance for outdoor dry bulb (DB) and wet bulb (WB) conditions of 90°F and 61°F are presented in Figure 47**Error! Reference source not found.** and Figure 48**Error! Reference source not found.**. The WB depression for this condition is 29°F. Figure 47 shows the cooling capacity (in tons) and the supply-water temperature, (T_{supply}) (in °F), as a function of the air-flow rate in the SWEC generated by the central fan located atop the unit. For this moderate outdoor condition with low humidity, it was seen that for any given water-flow rate through the evaporative medium, the cooling capacity increased with air-flow rate, from 800 CFM to 1,500 CFM. At a given air-flow rate, an increase in the water-flow rate resulted in an increase in cooling capacity. However, this also resulted in an increase in T_{supply}, which could result in lower cooling capacity when coupled with a hydronic coil. For example, at an air-flow rate of 1,100 CFM, increasing the water-flow rate from 1.8 gpm to 5.3 gpm resulted in an increase in T_{supply} by 5°F, from 58°F to 63°F. It should be noted that at the highest water-flow rate of 5.3 gpm, the T_{supply} is above the outdoor WB temperature at all air-flow rates. Thus, based on the cooling capacity and T_{supply} performance metrics, it appears that the medium water-flow rate of 3.5 gpm and high air-flow rate of 1,500 CFM provide the most promising results.

Figure 47: Sub Wet-Bulb Evaporative Chiller Cooling Capacity and Supply Water Temperature

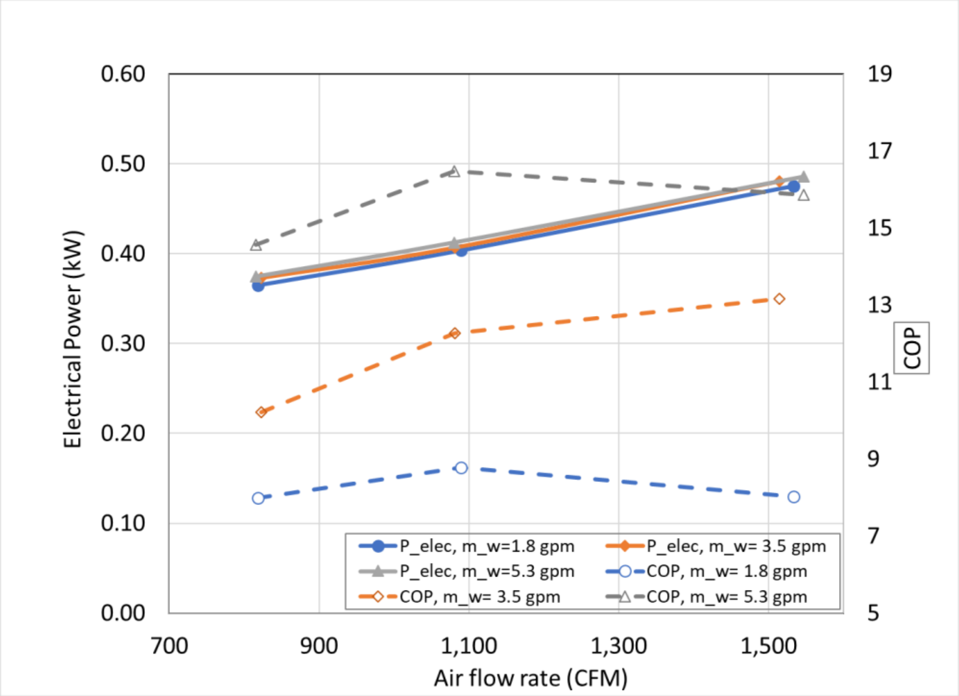


Cooling capacity and supply-water temperature as a function of the fan-flow rate for various water-flow rates at outdoor dry bulb and wet bulb temperatures of 90°F and 61°F, respectively

Source: University of California, Davis

Figure 48 shows the electric power and COP as a function of the air-flow rate in the SWEC for the same outdoor conditions as in **Error! Reference source not found.**. The COP results indicate that the highest water flow of 5.3 gpm is the most beneficial to the cooling performance at any air-flow rate. This trend was determined from the electric power trends for the three water-flow rates. Since a fixed-speed pump consumed a constant 220 W in these experiments, there was virtually no difference in the electric power consumed with variations in the water-flow rate. However, if a variable-speed pump were used, the COP at the lower flow rates would increase, leading potentially to a different conclusion based on COP. If reducing the flow rate from 5.3 gpm to 3.5 gpm reduced the pumping power by 100 W, the COP would increase for the lower flow rate.

Figure 48: Sub Wet-Bulb Evaporative Chiller Electric Power and Coefficient of Performance Results



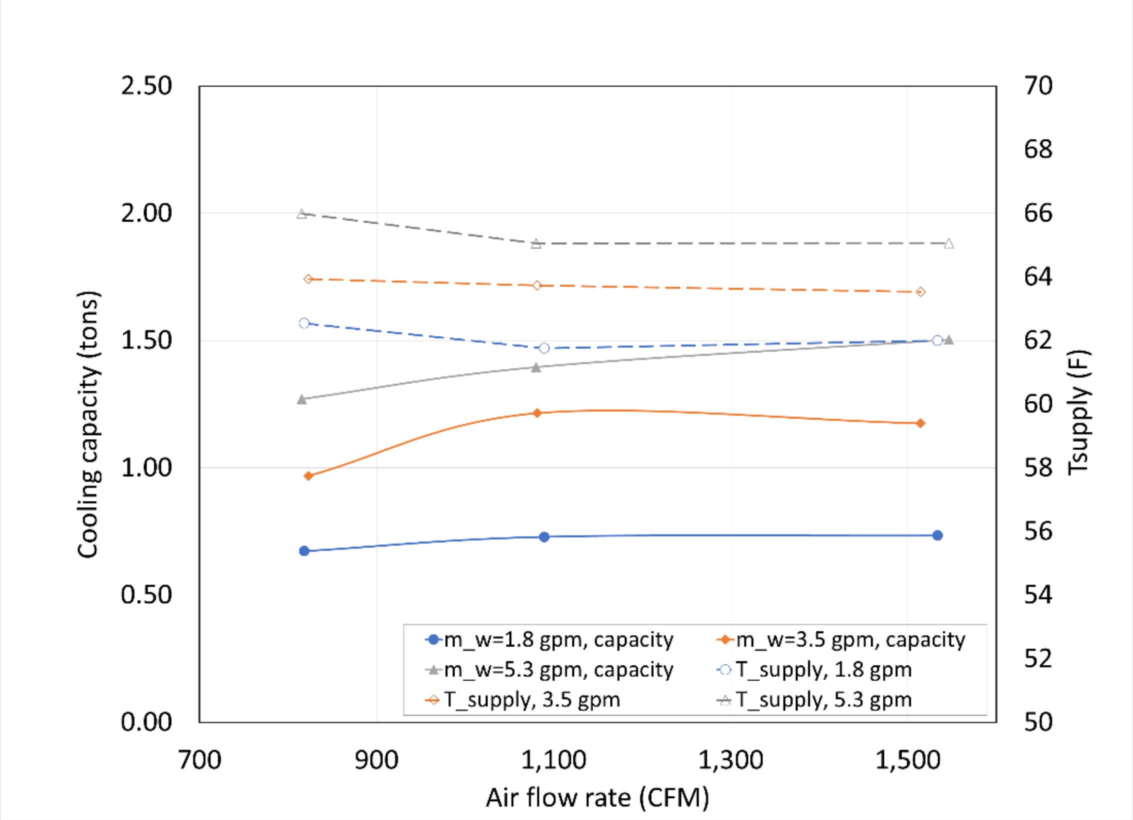
Results for outdoor dry bulb and wet bulb temperatures were 90°F and 61°F respectively

Source: University of California, Davis

Given the trends in Figure 47 and Figure 48, it can be concluded that for the outdoor conditions of 90°F DB and 61°F WB, the highest air-flow rate of 1,500 CFM and medium water-flow rate of 3.5 gpm resulted in the best compromise cooling capacity of 1.5 tons, COP of 13, and T_{supply} of 59°F. If there is a need for a higher capacity, the water-flow rate can be increased to 5.3 gpm; however, the system performance may not be improved due to the lower performance of the water coil at higher T_{supply}. The impact of this performance will be studied further by ongoing modeling efforts.

Results of the SWEC performance for outdoor dry bulb and wet bulb conditions of 105°F and 68°F are shown in Figure 49 and Figure 50. This outdoor condition represents the highest wet bulb depression of 37°F. Figure 49 shows the cooling capacity (in tons) and the supply water temperature, T_{supply} (in °F) as a function of the air-flow rate in the SWEC generated by the central fan located atop the unit. For this low humidity and high dry bulb temperature for the low-water flow rate of 1.8 gpm, there is little change in cooling capacity. At the medium-water-flow rate of 3.5 gpm, the cooling capacity increased with air-flow rate from 0.97 tons at 800 CFM, to 1.2 tons at 1,100 CFM, and there was very little change in cooling capacity from 1,100 CFM to 1,500 CFM. For the highest water-flow rate, the capacity increased slightly with an increase in air-flow rate from 1.3 tons at 800 CFM, to 1.5 tons at 1,500 CFM. At this outdoor condition, it was observed that the T_{supply} was lower than the wet bulb temperature at all water-flow rates and all air-flow rates. Moreover, there was little difference in T_{supply} between the 1,100 CFM and 1,500 CFM air-flow rates.

Figure 49: Sub Wet-Bulb Evaporative Chiller Cooling Capacity and Supply Water Temperature as a Function of Fan-Flow Rate for Various Water-Flow Rates at Outdoor Dry-Bulb and Wet-Bulb Temperatures of 105°F and 68°F, Respectively

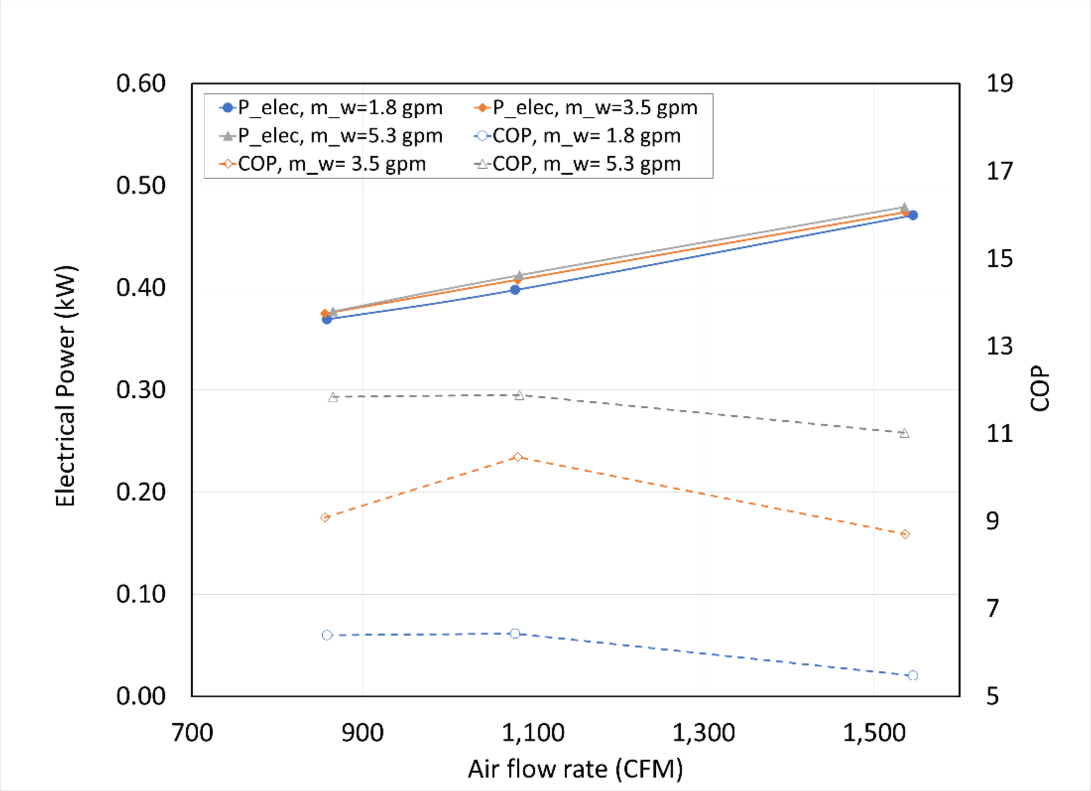


Chiller cooling capacity and supply water temperature shown as a function of fan flow rate for various water-flow rates at outdoor dry bulb and wet bulb temperatures of 105°F and 68°F, respectively

Source: University of California, Davis

Results of electric power and COP are shown in Figure 50. For all water-flow rates, it is clear that the COP at the highest air-flow rate of 1,500 CFM drops when compared with the medium air-flow rate of 1,100 CFM. This is an indication that there is diminished increase in cooling capacity relative to increase in fan power when going from 1,100 CFM to 1,500 CFM.

Figure 50: Electric Power and Coefficient of Performance



Electric power and coefficient of performance at outdoor dry bulb and wet bulb temperatures of 105°F and 68°F, respectively

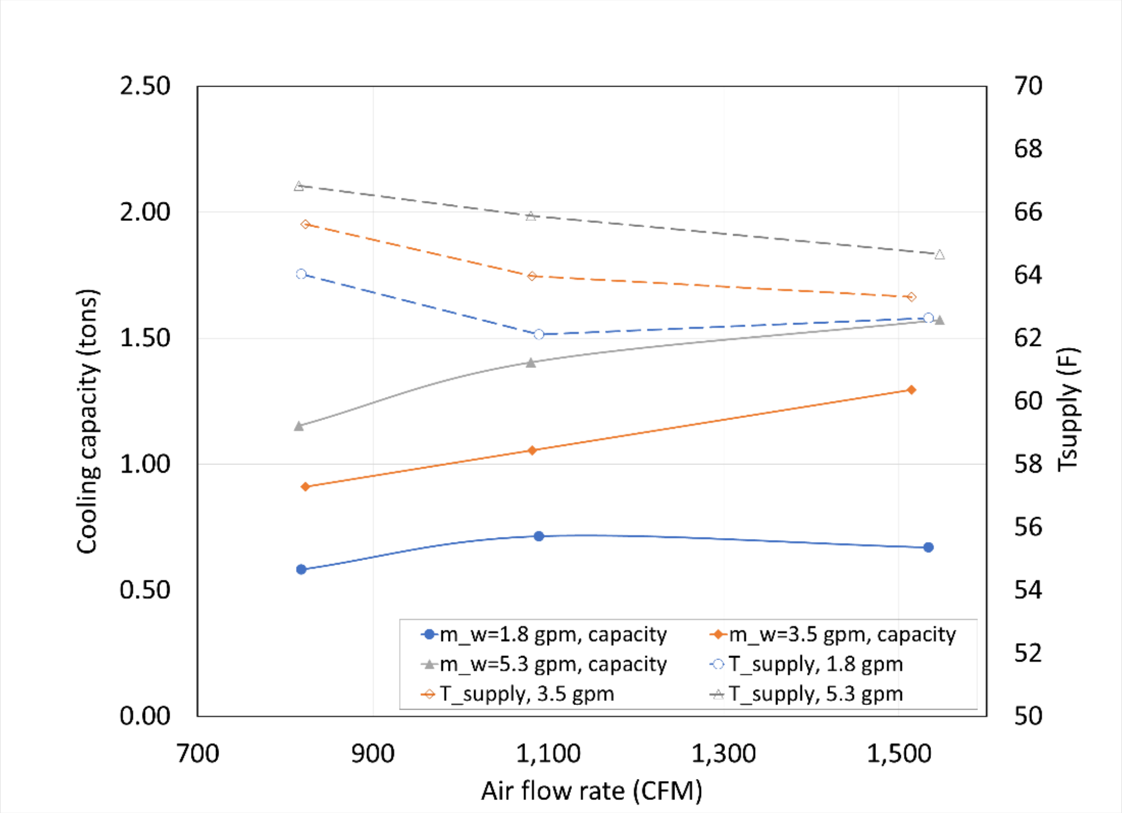
Source: University of California, Davis

Based on cooling capacity, T_{supply}, and COP, the medium air-flow rate and medium water flow rate condition yields the optimal balance. For the hot and dry outdoor condition of 105°F DB and 68°F WB, the medium air-flow rate of 1,100 CFM and medium water-flow rate of 3.5 gpm results in the best compromise of cooling capacity of 1.2 tons, COP of 10.5, and T_{supply} of 63.7°F. If there is a need for a higher capacity, the water-flow rate can be increased to 5.3 gpm at the same air-flow rate.

Results of the SWEC performance for outdoor dry bulb and wet bulb conditions, respectively, of conditions of 80°F and 64°F are presented in Figure 51 and **Error! Reference source not found.**Figure 52. This outdoor condition is mild but also represents the lowest wet bulb depression of 16°F. Figure 51**Error! Reference source not found.** shows the cooling capacity (in tons) and the supply water temperature, T_{supply} (in °F), as a function of the air-flow rate in the SWEC generated by the central fan located atop the unit. For this outdoor-air condition, similar to trends for 105/68°F condition, it is seen that for the low water-flow rate of 1.8 gpm, there is little change in cooling capacity with air-flow rate. For the 3.5 gpm and 5.3 gpm flow rates, the cooling capacity increases with air-flow rate. For the 3.5 gpm water flow rate, the capacity increases from 0.9 tons at 800 CFM to 1.3 tons at 1,500 CFM. For the 5.3 gpm water flow rate, the capacity increases from 1.15 tons at 800 CFM to 1.57 tons at 1,500 CFM. However, at this high water-flow rate, T_{supply} is higher than the wet bulb temperature at all air-flow rates. Hence, similar to the 90/61 DB/WB condition, this is not a desirable water-flow rate.

Figure 52 presents the electric power and COP for the 80/64 DB/WB outdoor condition. It is seen that the highest air-flow rate and medium water-flow rate condition results in a high COP.

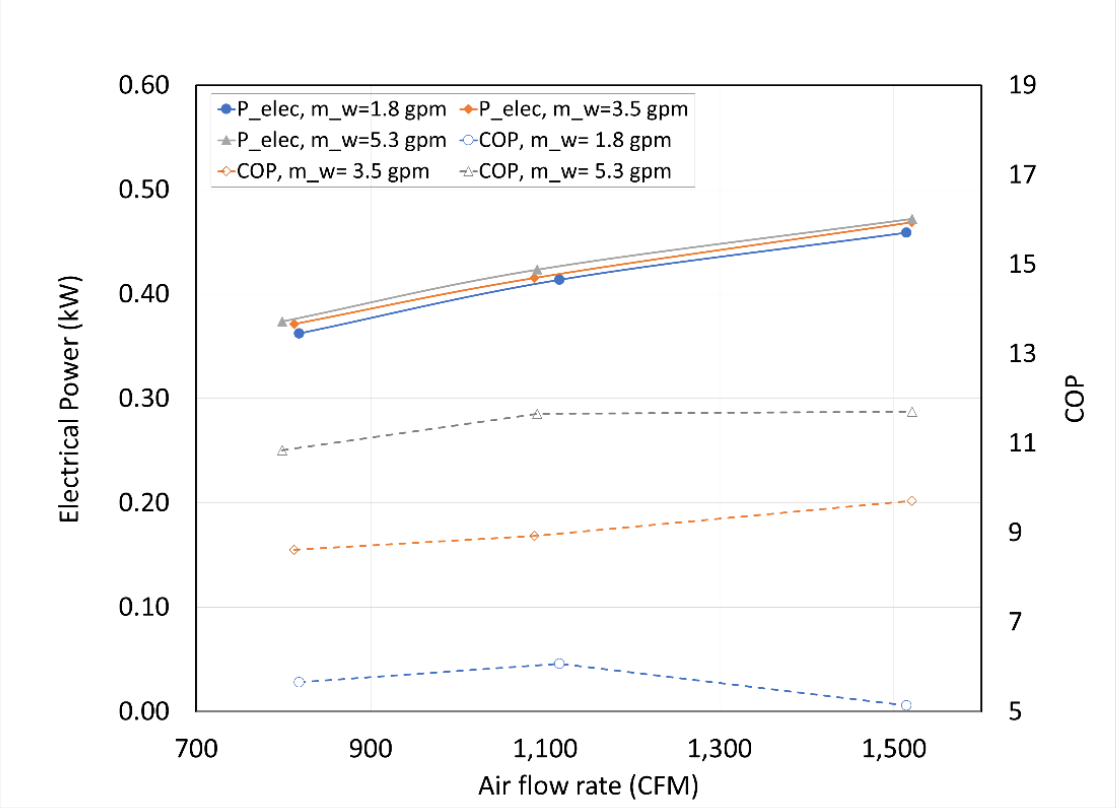
Figure 51: Sub Wet-Bulb Evaporative Chiller Cooling Capacity and Supply Water Temperature



Cooling capacity and supply water temperature as a function of fan-flow rate for various water flow rates results for an outdoor dry bulb and wet bulb temperatures are 80°F and 63°F, respectively

Source: University of California, Davis

Figure 52: Sub Wet-Bulb Evaporative Chiller Electric Power and Coefficient of Performance



Electric power and coefficient of performance as a function of fan flow rate for various water flow rates results for an outdoor dry bulb and wet bulb temperatures are 80°F and 63°F, respectively

Source: University of California, Davis

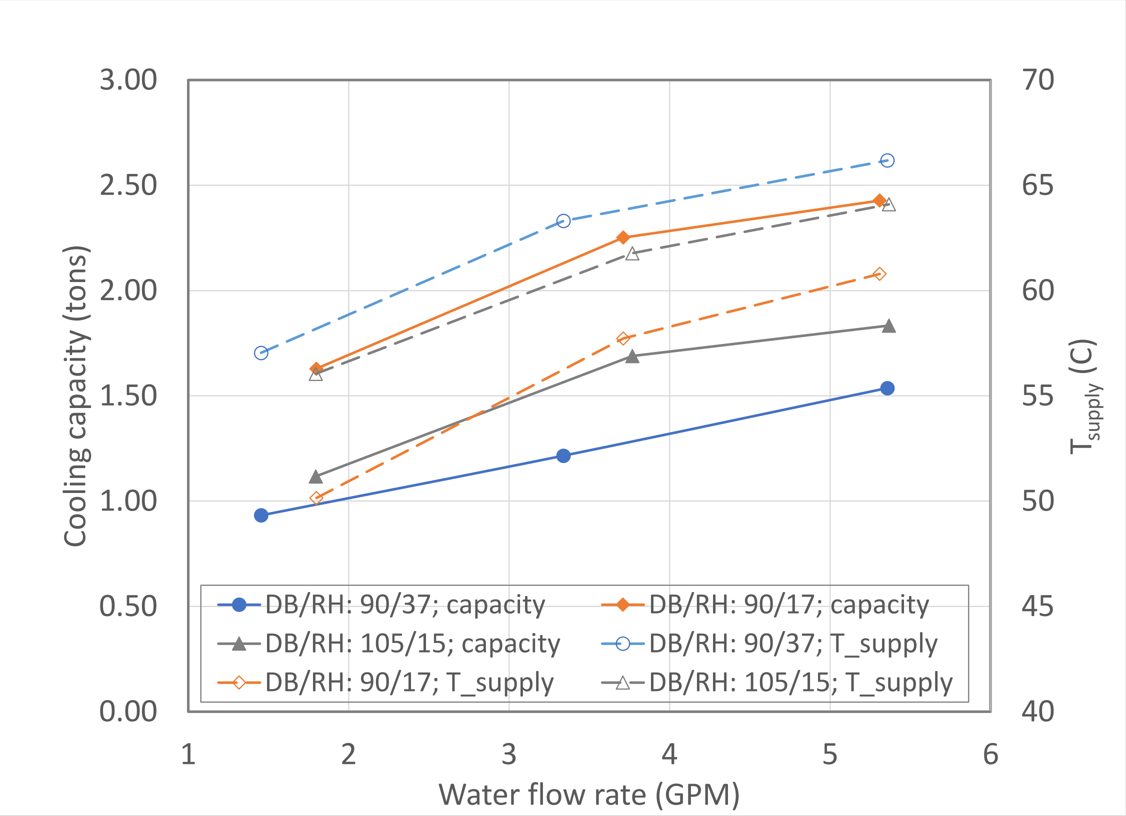
Based on cooling capacity, $T_{supply,}$ and COP, the high air-flow rate and medium water flow rate condition yields the optimal balance. For the mild and higher humidity outdoor condition of 80°F DB and 64°F WB, the high air-flow rate of 1,500 CFM and medium water flow rate of 3.5 gpm results in the best compromise of cooling capacity of 1.3 tons, COP of 9.7, and T_{supply} of 63.3°F.

One key takeaway from the SWEC evaporative cooling testing is that a variable speed pump and fan are required to optimize the performance of the SWEC. Additionally, SWEC performance is optimal at the moderate outdoor-air temperature and low humidity (DB/WB of 90/61 condition). The performance at the lower temperature and higher humidity (DB/WB of 80/64) and higher temperature and low humidity (DB/WB of 105/68) is similar. The results also show that higher water flow rates result in higher capacity at any given air-flow rate; however, it also results in increased T_{supply}, which could reduce system performance due to lower heat transfer in the water coil. For the 80/64 and 90/61 conditions, high air-flow rate of 1,500 CFM and medium water flow rate of 3.5 gpm are the best conditions, while for the 105/68 F condition, medium air and water flow rate condition is better. COPs of 10 and higher were obtained under these conditions; with use of a variable speed pump to modulate water flow rate, a higher COP is expected. Cooling capacity between 1.2-1.5 tons can be obtained for the range of outdoor conditions with these water and air-flow rate settings.

The next set of plots present the results for the SWEC performance in Stage 2 cooling (evaporative and compressor cooling). Three different outdoor-air conditions were tested with the SWEC in Stage 2: DB/WB of 90/70 (moderate and humid), 90/62 (moderate and dry), and 105/69 (hot and dry). Most of the tests were performed with airflow at 1,100 CFM and varying water flow rates; however, air-flow rates were varied for a few cases as well.

Results of cooling capacity and T_{supply} for the three outdoor conditions as a function of water flow rate for a fixed air-flow rate of 1,100 CFM are shown in Figure 53. The general trend of increasing capacity and T_{supply} with increase in water flow rate is observed at all three outdoor conditions. The SWEC in Stage 2 performs best in moderate and dry condition (DB/WB of 90/62) with capacity ranging from 1.6 tons (at 1.8 gpm) to 2.4 tons (at 5.3 gpm). The unit performance is worst at the moderate and humid condition (DB/WB of 90/70) with capacity ranging from 0.93 ton (at 1.8 gpm) to 1.54 tons (at 5.3 gpm). Under all outdoor-air temperatures and water flow rates, it is seen that T_{supply} is always lower than the outdoor wet bulb temperature.

Figure 53: Sub Wet-Bulb Evaporative Chiller Stage 2 Cooling Capacity and Supply Water Temperature

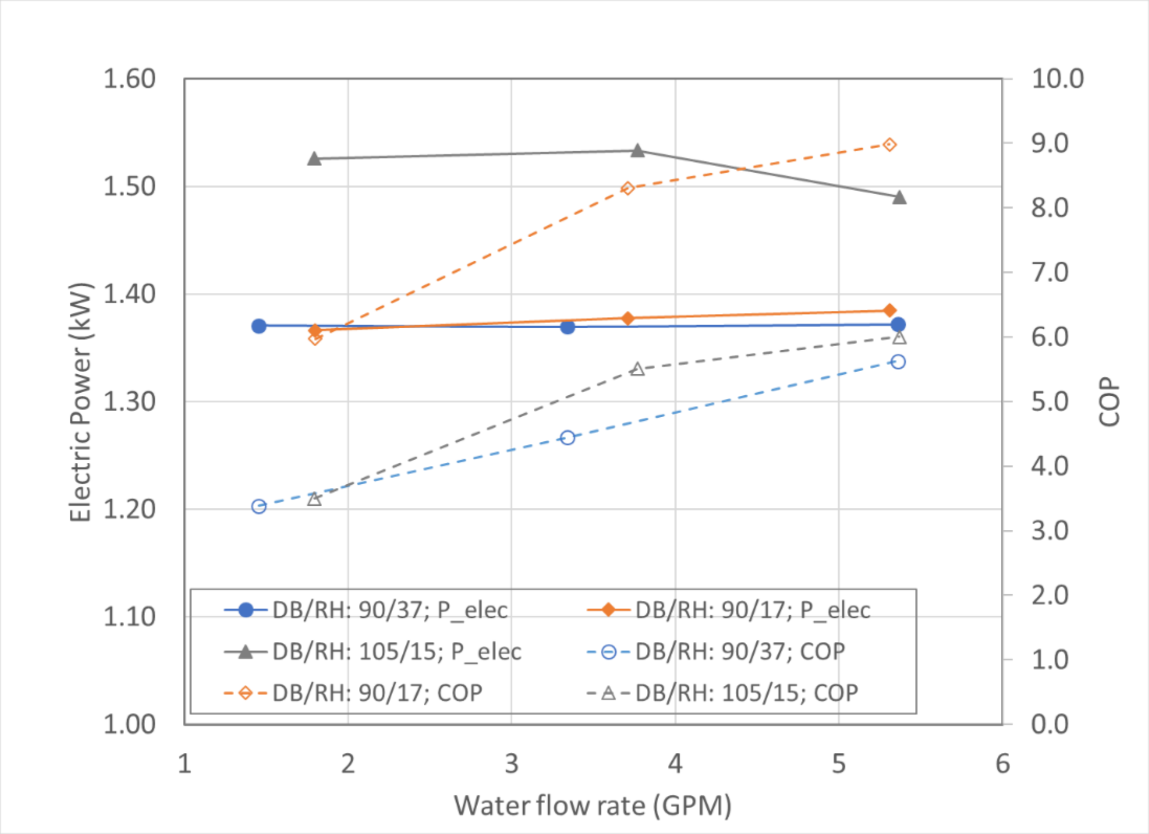


Stage 2 cooling capacity and supply water temperature as a function of water flow rate through the sub wet-bulb evaporative chiller under three different outdoor-air conditions at a fixed nominal fan flow rate of 1100 cubic feet per minute.

Source: University of California, Davis

The electric power and COP corresponding to the capacity in Figure 53 are shown in Figure 54. The COP was highest at the highest water-flow rate of 5.3 gpm for all outdoor conditions. The COP values at this flow rate ranged from 5.6 at 90/70 to 9 at 90/62.

Figure 54: Sub Wet-Bulb Evaporative Chiller Stage 2 Electric Power and Coefficient of Performance



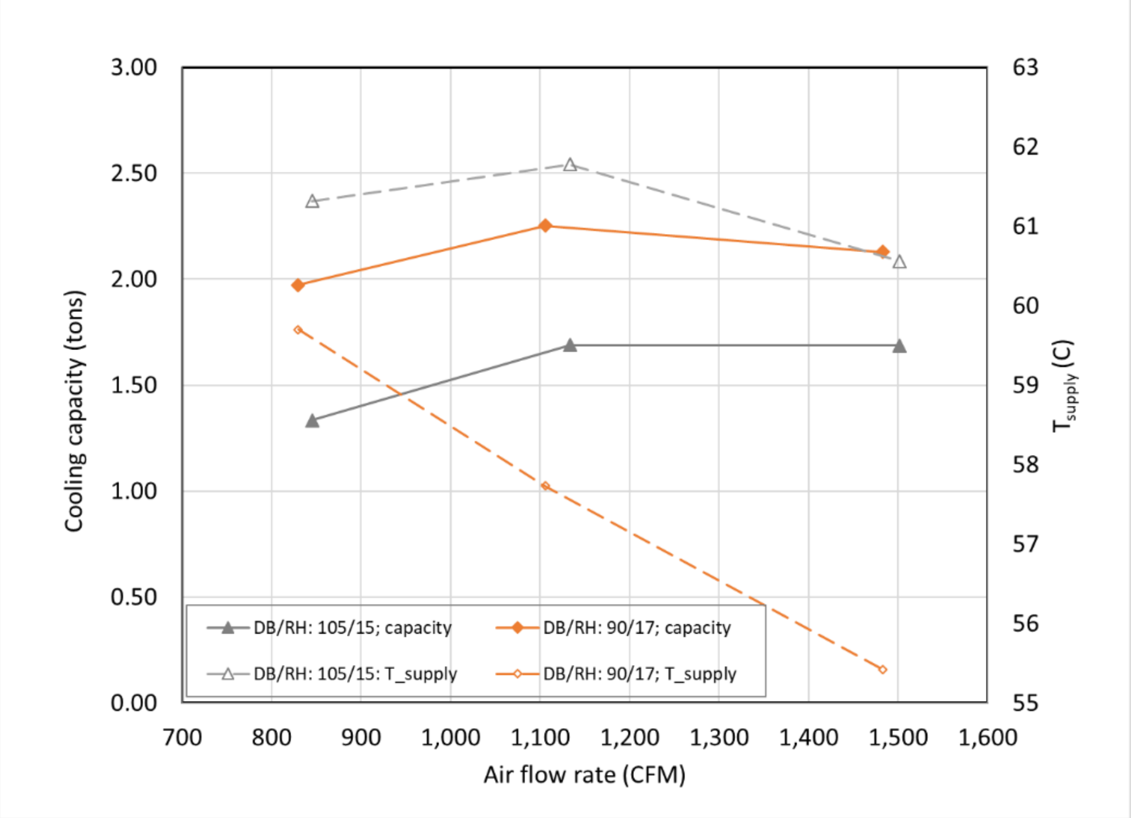
Stage 2 electric power and coefficient of performance as a function of water flow rate through the sub wet-bulb evaporative chiller under three different outdoor-air conditions at a fixed nominal fan flow rate of 1100 cubic feet per minute.

Source: University of California, Davis

Figure 55 shows the impact of variation of air-flow rate on the performance of the SWEC in Stage 2 cooling for two outdoor conditions, DB/WB 90/61 and 105/68. At both outdoor conditions, it is seen in Figure 55 that the cooling capacity increases from 800 CFM to 1,100 CFM and plateaus at this level between 1100 CFM and 1500 CFM. However, the T_{supply} value decreases from 1,100 CFM to 1,500 CFM, which could be beneficial for system performance when coupled with a central water coil, as was installed in the field demonstration for this project.

Figure 56 shows that the COP varies from 5.8 for the 105/68 condition to 8.3 for the 90/61 outdoor condition.

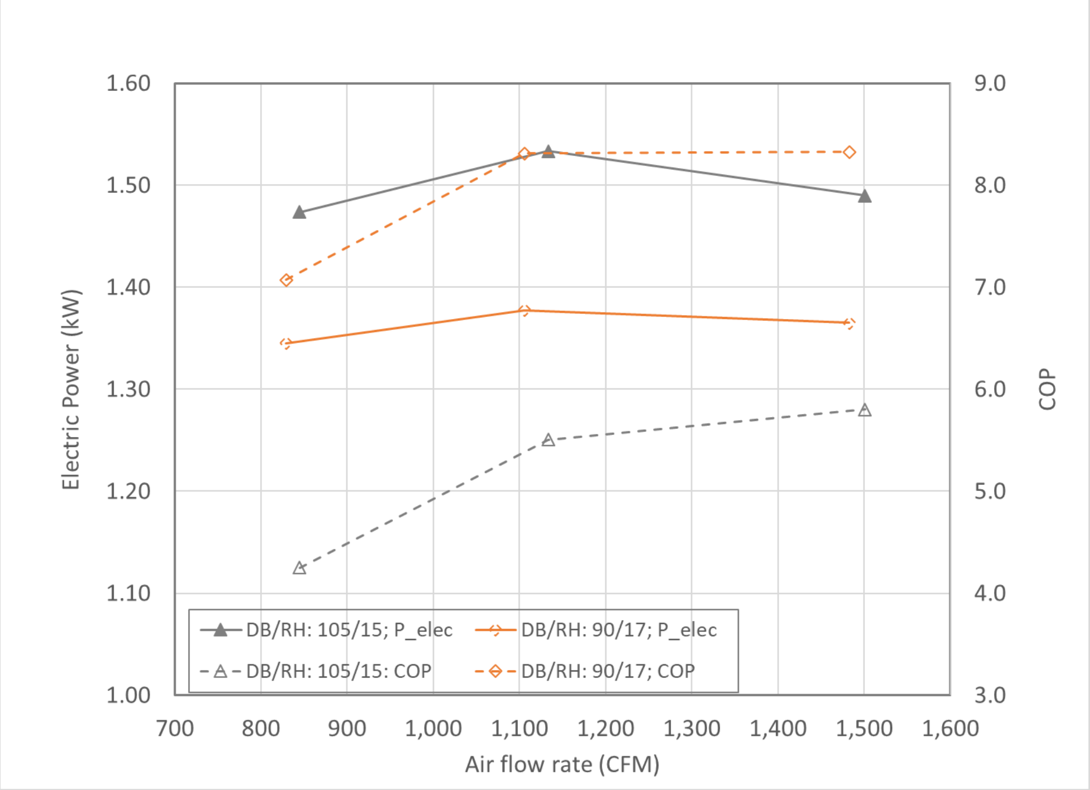
Figure 55: Sub Wet-Bulb Evaporative Chiller Stage 2 Cooling Capacity and Supply Water Temperature



Stage 2 cooling capacity and supply water temperature as a function of air-flow rate through the sub wet-bulb evaporative chiller under two different outdoor-air conditions at a fixed nominal water flow rate of 3.5 gallons per minute.

Source: University of California, Davis

Figure 56: Sub Wet-Bulb Evaporative Chiller Stage 2 Electric Power and Coefficient of Performance



Stage 2 electric power and coefficient of performance as a function of air-flow rate through the sub wet-bulb evaporative chiller under two different outdoor-air conditions at a fixed nominal water flow rate of 3.5 gallons per minute.

Source: University of California, Davis

In summary, high water flow rate and high air-flow rate condition seems to be the most beneficial for the SWEC in Stage 2 cooling for all tested outdoor-air conditions.

A comparison of the performance of the SWEC Stage 1 versus Stage 2 cooling at DB/WB of 105/68 can be drawn at this stage. At the medium air-flow rate of 1100 CFM and high water flow rate of 5.3 gpm, Figure 49 indicates that the cooling power of the SWEC in Stage 1 is 1.4 tons at a T_{supply} of 65°F and with a COP of 11.9. In contrast, for the similar outdoor-air condition and air and water flow rates, Figure 53 indicates that the SWEC in Stage 2 cooling is able to provide a cooling power of 1.83 tons at a T_{supply} of 60.8°F and with a COP of 6. Thus, it may be beneficial to use the SWEC in Stage 2 cooling in the hottest parts of the day when additional cooling power at a lower supply temperature is needed while using the SWEC in Stage 1 to optimize COP, cooling power and T_{supply} (system performance).

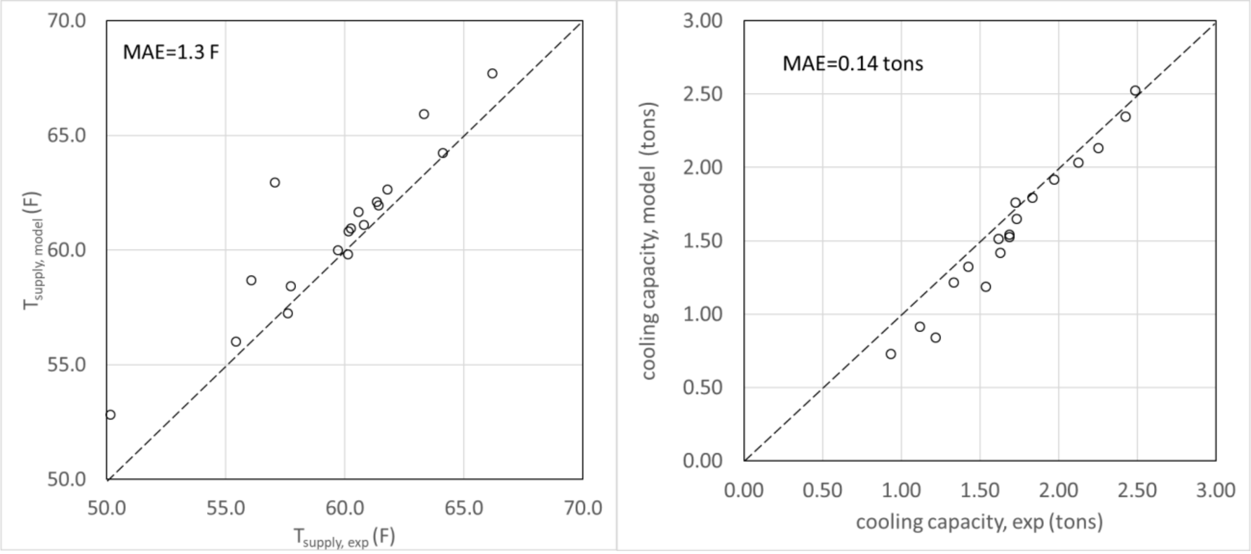
A second comparison between the SWEC in Stage 1 and Stage 2 performance can be drawn at DB/WB of 90/61, corresponding to moderate and dry condition. At the medium air-flow rate of 1100 CFM and high-water flow rate of 5.3 gpm, Figure 47 indicates that the cooling power of the SWEC is 1.93 tons at a T_{supply} of 63°F and with a COP of 16.5. The optimum condition for the SWEC Stage 1 operation for this outdoor-air condition was selected at a high air-flow rate and medium water flow rate, giving a cooling capacity of 1.8 tons, a T_{supply} of 59.8°F and a COP of 13.2. In contrast, for the same outdoor-air condition and air and water flow rates, Figure 53 indicates that the SWEC in Stage 2 is able to provide a cooling power of 2.43 tons at a T_{supply} of 60.8°F and with a COP of 9. If a medium water flow rate of 3.5 gpm is selected, the cooling capacity would be lowered to 2.25 tons but T_{supply} would be at a lower value of 57.7°F.

Sub Wet-Bulb Evaporative Chiller Model

Model Calibration

Some parameters in the model including the temperature difference between the condenser air and the refrigerant, the degree of superheat of refrigerant vapor entering the compressor, and the evaporator pressure needed to be calibrated with lab experimental data. Upon calibration, the water temperature exiting the SWEC and the cooling capacity for Stage 2 cooling (using compressor) were compared between the model and lab data (Figure 57). These two comparisons show a reasonable correlation between the model and lab data with a mean absolute error (MAE) of 1.3°F and 0.14 tons for supply temperature and cooling capacity, respectively. The larger deviations were found for the low water flow rate condition of 1.8 gpm. In general, the model predictions are conservative relative to the experiments.

Figure 57: Comparison of Lab Data With Model

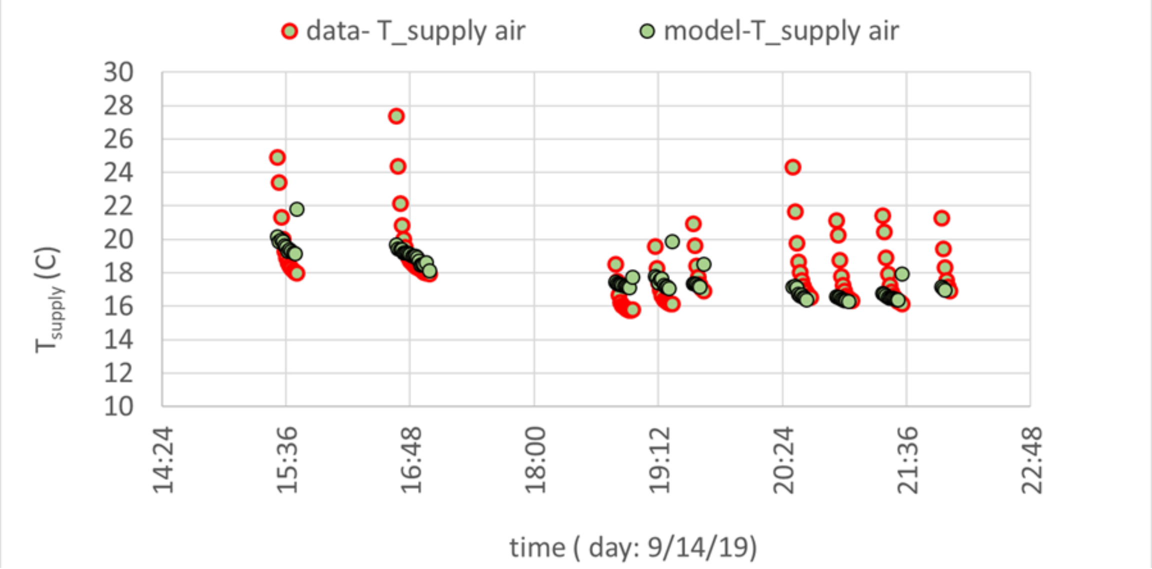


Left: for water temperature exiting the sub wet-bulb evaporative chiller; right: cooling capacity of the sub wet-bulb evaporative chiller

Source: University of California, Davis

Upon completion of the calibration, the hybrid SWEC model was coupled with a central water coil heat-exchanger model to simulate the performance of the hybrid SWEC and water-coil system. Water-coil dimensions from the field data (21 in x 24 in, 6 rows) were used and a validation was performed with the field data for the condition when just the SWEC was operational (Stage 1), and when the hybrid SWEC was in operation (Stage 2). The system capacity and supply air temperatures were compared between the model and a sample set of field measurements for the East House (Figure 58).

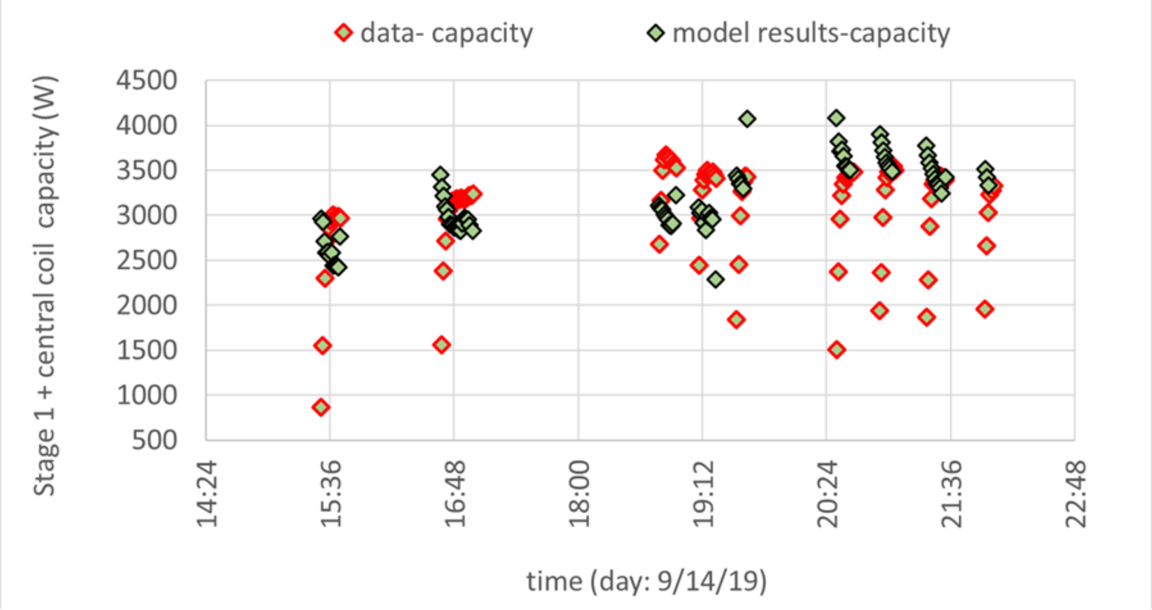
Figure 58: Comparison of Supply Air Temperature for Modeled Sub Wet-Bulb Evaporative Chiller Operating in Stage 1 (Evaporative Cooling Only) to Field Data for East House (Central System)



Source: University of California, Davis

The field data had minimal periods of steady-state operation, as indicated by the wide range of capacities and supply temperatures at the beginning of each cycle; however, during the brief periods when the system reached a steady state (indicated by the cluster of data points after the transient response) for Stage 1 cooling, the model and field data matched well (Figure 59).

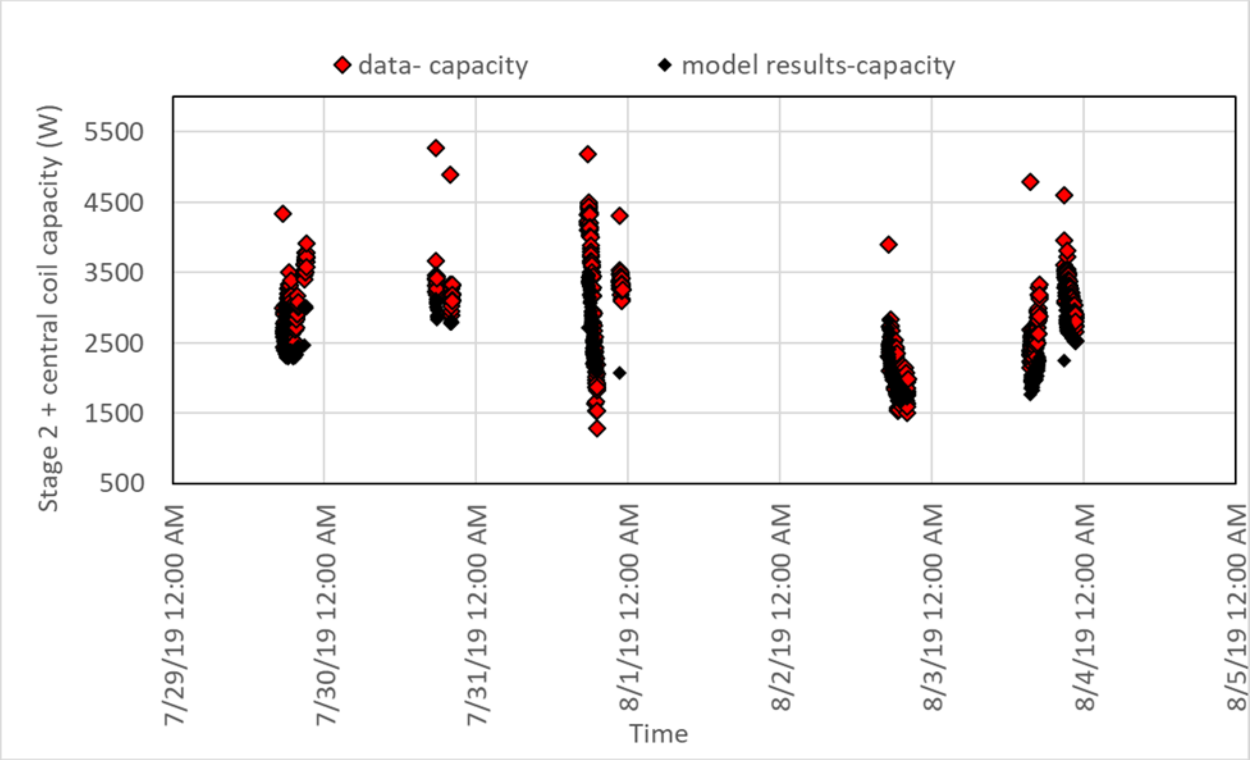
Figure 59: Comparison of System Capacity for Modeled Sub Wet-Bulb Evaporative Chiller Operating in Stage 1 (Evaporative Cooling Only) to Field Data for East House (Central System)



Source: University of California, Davis

The capacity for the system was also compared between the model and field data for the SWEC in Stage 2 cooling (Figure 60). Again, during the steady-state periods, the model and field data matched well.

Figure 60: Comparison of Field Data for East House (Central System) Sub Wet-Bulb Evaporative Chiller Capacity to Model for Sub Wet-Bulb Evaporative Chiller in Hybrid Cooling Mode (Compressor on)



Source: University of California, Davis

Sub Wet-Bulb Evaporative Chiller Optimization

Once the hybrid SWEC system (paired with the water coil) model was validated by the field data, system parameters were adjusted to optimize the SWEC system performance. The model considered five scenarios for the SWEC system and compared the results with the field data. The following five scenarios were modeled for the SWEC:

- Baseline SWEC Stage 2 Using a Finned-Tube Heat Exchanger (FTHX)
    - Represents the SWEC in Stage 2, as tested in the field. The Stage 2 SWEC fan-flow rate was 1,800 CFM, the water-flow rate was 5.2 gpm, and the air-handler flow rate was 800 CFM.
- SWEC Stage 2 Using a Micro-Channel Polymer Heat Exchanger (MPHX)
    - Represents the SWEC in Stage 2 as tested in the field, but paired with a more effective central-fan coil that reduced the water-flow rate of 3 gpm
- Optimized SWEC Stage 2 Using a MPHX
    - Represents an optimized SWEC in Stage 2 paired with a more effective central-fan coil operating at a 3 gpm water-flow rate. The optimized SWEC had a thicker evaporative medium pad and larger condenser area.

- Optimized SWEC Stage 2 Using a MPHX and 5.2 Gpm Water-Flow Rate
    - Represents an optimized SWEC in Stage 2 paired with a more effective central-fan coil operating at 5.2 gpm
- Optimized SWEC Stage 1 Using a MPHX
    - Represents an optimized SWEC in Stage 1 paired with a more effective central-fan coil at a SWEC fan-flow rate of 1,100 CFM

It was determined during the optimization effort that the evaporative media pad and the condenser in the SWEC used in the field evaluation were undersized. The optimized SWEC scenarios increased the size of the condenser and evaporative media, adjusted the SWEC fan and pump flows, and coupled the system with more efficient fan coils. The implications of these changes on overall system geometry are expected to increase the system footprint by about six inches on each side and increase the height by about six inches. The improved fan-coil effectiveness from changing from a traditional finned-tube heat exchanger to the micro-channel polymer heat exchanger also reduced pressure drops across the heat exchanger and its fan energy. The MPHX, while not yet commercially available, has been demonstrated in the laboratory[5] and is on the road to commercialization; however, this scenario could also represent a situation where an oversized conventional hydronic coil (FTHX) is used, albeit with additional fan power.

Each of these scenarios were modeled and compared with field data from the East House (central system) for the SWEC running in Stage 2, shown in Figure 61. The optimized air- and water-flow rates used for each scenario were chosen based on results from the lab tests. Figure 61 shows the cooling capacity for each scenario. The two highest cooling capacities were both achieved with the optimized SWEC using the MPHX fan coil; the lower water-flow rate (3 gpm) yielded the highest capacity. In some cases, the capacity was more than double what was observed in the field trials. Furthermore, the optimized SWEC in Stage 1 achieved a similar capacity to the original SWEC design operating in Stage 2.

Figure 63 shows the COP of each scenario which includes the power of the hybrid SWEC unit and the blower fan power for the same week as in Figure 61. Figure 64 shows the COP variation for a single day in July corresponding to the cooling capacity shown in Figure 62. Unsurprisingly, the highest COP was achieved with the optimized SWEC in Stage 1 and MPHX which achieved a COP of over 6. The COP achieved for the two optimized cases with MPHX were also higher than the baseline performance. The optimized SWEC designs modeled showed a major improvement in performance over the system demonstrated in the field trials, with COPs in Stage 2 ranging between 2.5 to 5. This COP range is similar to standard vapor-compression cooling equipment used in residential buildings, showing that the primary advantage of the SWEC system is when it is able to operate in Stage 1 and achieve very high efficiencies.

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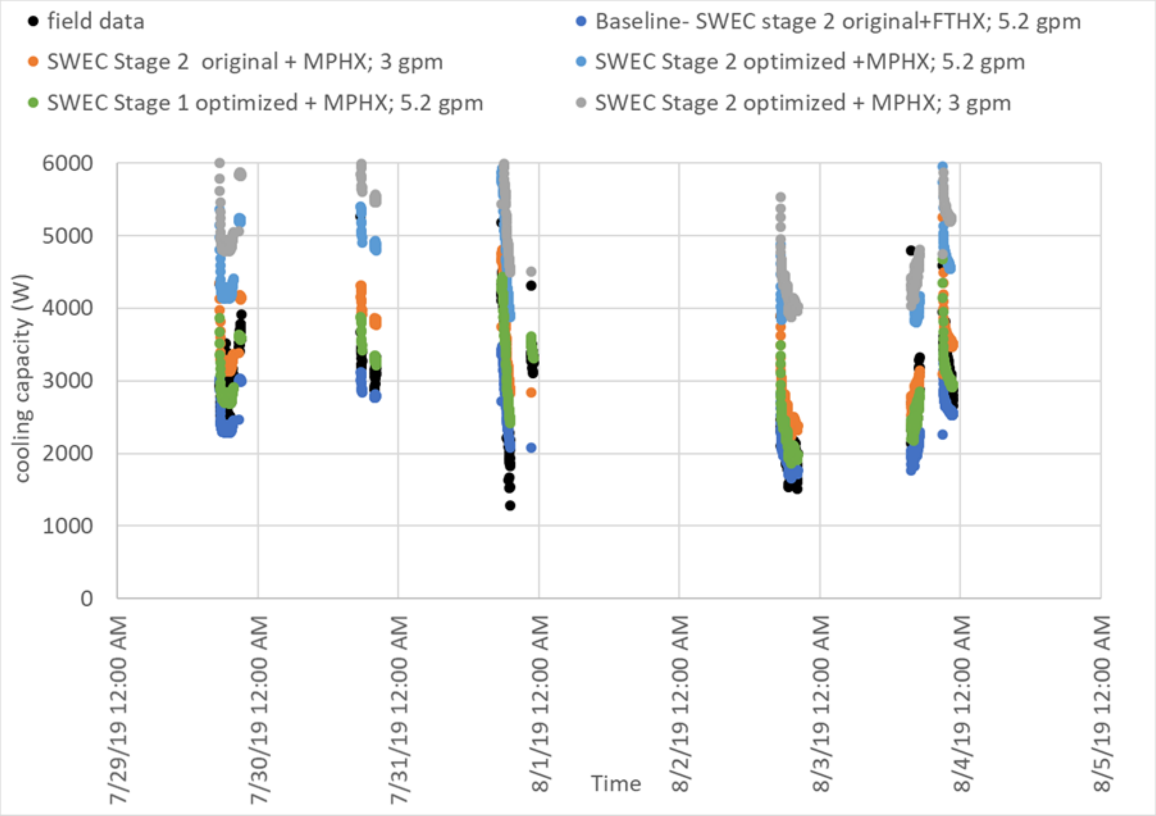
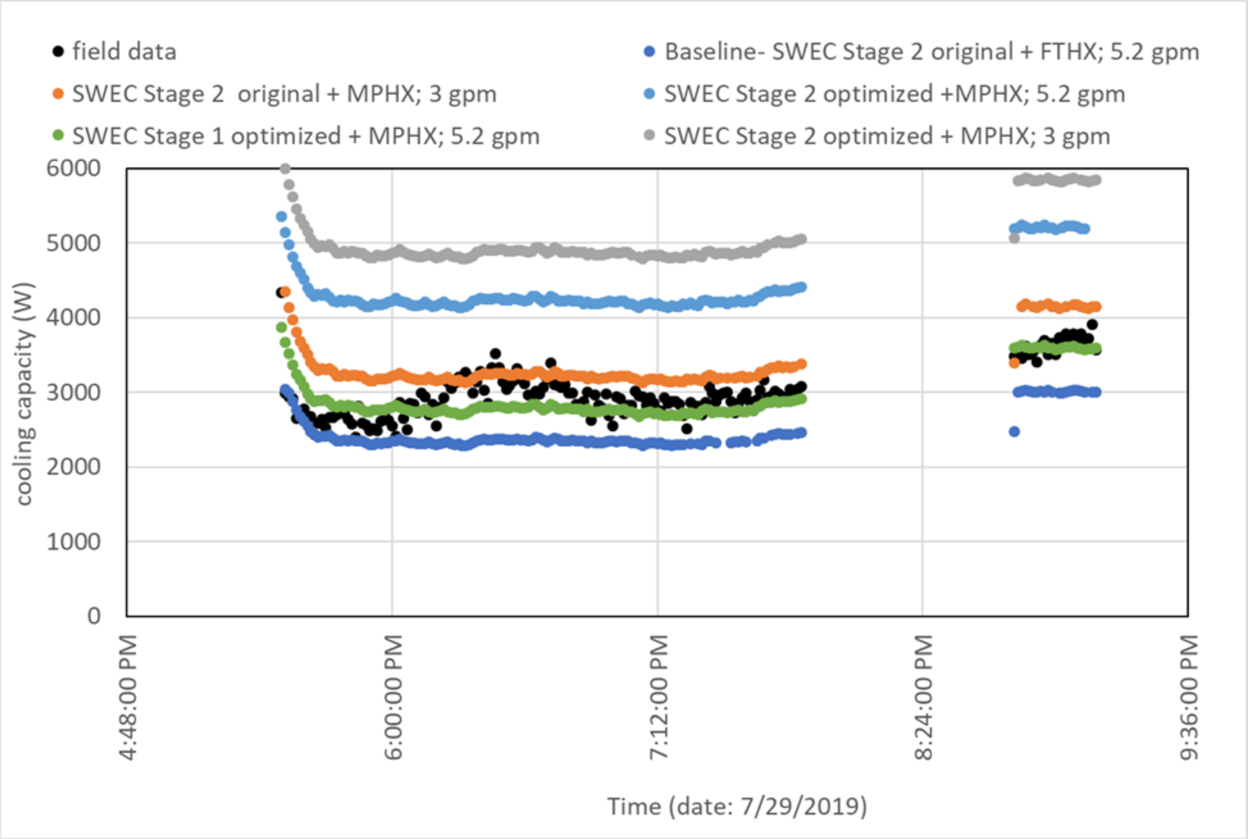
[5] Rasouli, E., Strong, A., and Narayanan, V., 2020, High Efficiency Microchannel Polymer Heat Exchangers for Heating and Cooling Applications," Paper number 31230, 2020 ASHRAE Virtual Summer Conference, June 29th-July 2nd 2020.

Figure 61: Sub Wet-Bulb Evaporative Chiller Stage 2 Cooling Capacity for Each Modeled Scenario Compared With Field Data Over a Week in July/August



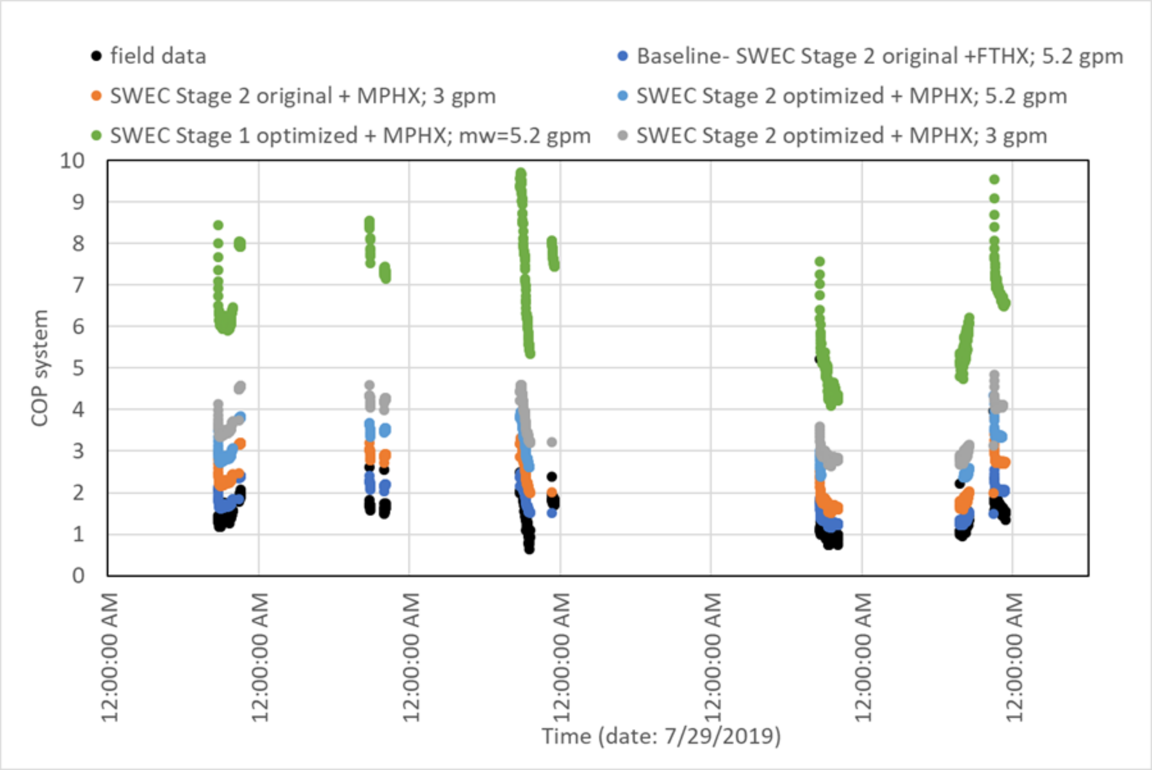
Source: University of California, Davis

Figure 62: Sub Wet-Bulb Evaporative Chiller Stage 2 Cooling Capacity for Each Modeled Scenario Compared With Field Data Over a Day in July (Enlarged Single-Day Comparison)



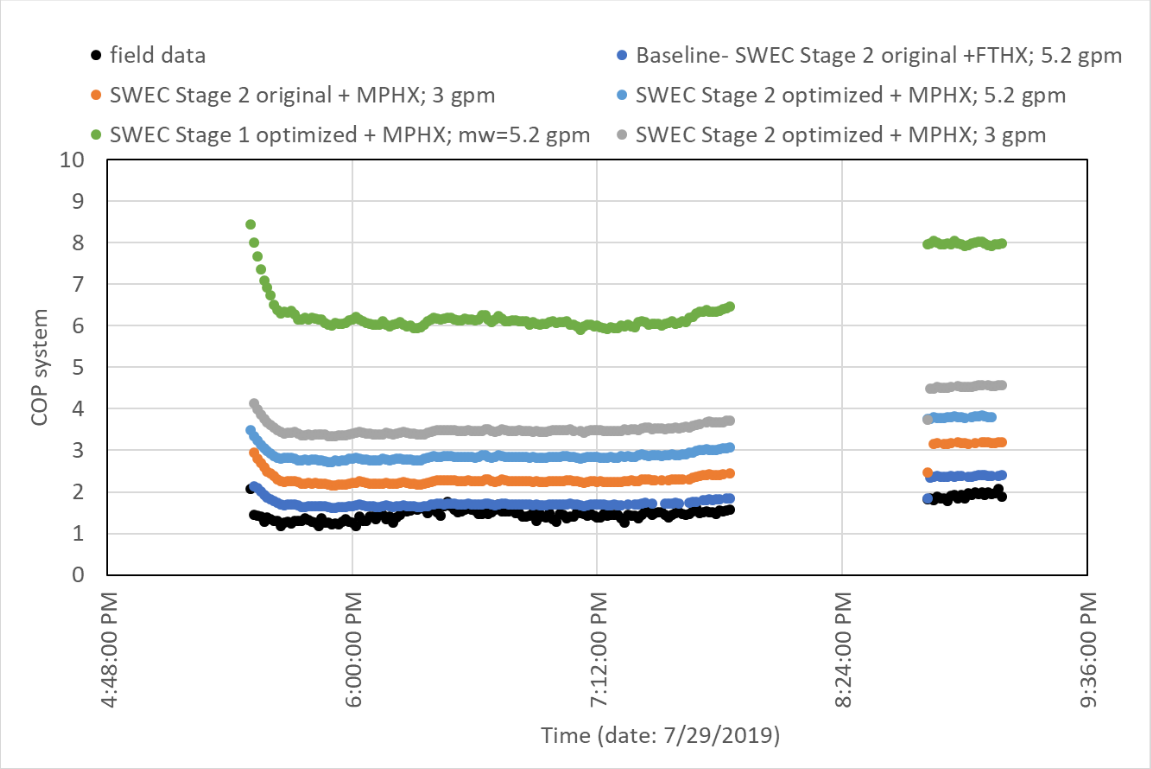
Source: University of California, Davis

Figure 63: Sub Wet-Bulb Evaporative Chiller Stage 2 System Coefficient of Performance Including Blower Fan Power for Each Modeled Scenario Compared With Field Data Over a Week in July/August



Source: University of California, Davis

Figure 64: Sub Wet-Bulb Evaporative Chiller Stage 2 System Coefficient of Performance Including Blower Fan Power for Each Modeled Scenario Compared With Field Data Over a Day in July (Enlarged Single Day Comparison)



Source: University of California, Davis

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Market Characterization

The objective of the market characterization was to assess the current market conditions for three types of technologies - aerosol sealing of building envelopes, ventilation cooling, and evaporative cooling - evaluated in the field demonstrations for this project. This section describes barriers to adoption in the California residential market and identifies strategies to overcome those barriers, drawing on multiple stakeholder perspectives. The market potential was estimated for the group of technologies (pre-cooling ventilation) that is closest to market-ready.

Market evaluation for the technologies identified in this project used multiple data sources and analytic methods to assess the market potential for the three key technologies studied. Data sources included relevant policies (such as California building energy codes, ASHRAE standard 62.2); existing reports on relevant technologies; public data sets on housing stock (existing and forecasted), prevalence of mechanical systems; climate conditions; manufacturers' websites and personal communications with their staff; and interviews with researchers and key industry stakeholders.

Technologies were investigated to varying degrees of specificity, as was appropriate given the technology's market readiness and prior research on the topic. In the case of aerosol sealing with Aerobarrier, that specific technology was explored because it is already commercially available and its performance verified. Whole-house ventilation strategies were considered more generally, including those that provide "free cooling" at night. Finally, interviewees were asked about mini-splits (or multi-splits). For some questions, mini-splits served as a proxy for room-by-room systems generally, while other questions focused on mini-splits specifically.

Barriers and opportunities were identified through a qualitative analysis of interview data. Market potential was estimated using a model that applied expected adoption rates with relevant markets based on a range of criteria, as later described.

Methodology

The results reported in this section reflect the input of two housing developers, one nonprofit developer, one installer/engineering firm, five staffers at three different affordable housing building owners/operators (including property managers), and two tenants. Feedback from the demonstration home participants was summarized from quarterly surveys completed during the project. Interviews were also conducted with two California developers as part of a DOE study on aerosol sealing.

Ten interviews were conducted to explore the barriers to and opportunities for adoption of specified technologies. Interviews were conducted over the telephone and were audio recorded to ensure accurate note taking. A series of questions was asked about respondents' perceptions of three technologies: aerosol sealing of building envelopes, whole-house ventilation, and mini-splits (or multi-splits).[6] Most had not worked with (or heard of) some of the technologies, so they were given a brief description of each technology at the outset. Building owners and operators reported from both their own perspectives and those of their residents.

Cooling

Background

This project focused on retrofit packages that would dramatically reduce the energy required for cooling a home. Cooling single-family homes is projected to consume more than 5,700 GWh per year in 2024 (Energy Commission, 2015). The retrofit packages tested in field demonstrations for this project were estimated to reduce residential cooling-energy use by 30 percent.

Sub Wet-Bulb Evaporative Chiller

Purpose and Need

Nexajoule's SWEC has many selling points as a tool to address California's cooling needs and climate goals. First and foremost, it is highly efficient. Although the field demonstrations did not demonstrate the efficiencies that the team had anticipated, a validated computer model identified design improvements for future work. In addition, the SWEC can in some cases provide sufficient cooling capacity without refrigerants, where traditional air conditioners contain refrigerants that contribute to climate change. The low peak-power draw also reduces strain on the electrical grid and avoids the need to upgrade the electric service in buildings that would otherwise require it.

Market Assessment

Barriers

Evaporative cooling has posed several technical challenges that have prevented its widespread adoption in California. One barrier is that direct evaporative systems are limited by the wet-bulb temperature of the air, which seldom drops below 70°F during hot days. Direct evaporation cooling also adds significant moisture to the space, which can reduce occupant comfort. Indirect evaporative cooling, like that employed in the SWEC, can provide cooler temperatures below wet bulb, but at the expense of higher fan power. Both of these evaporative cooling technologies rely on 100 percent outdoor air, which also increases the overall cooling load required by the system. But given their high efficiency there are still opportunities for using these systems as energy-efficiency resources. Lastly, mineral deposits can lead to reliability concerns by reducing effectiveness over time as deposits build up. Evaporative cooling systems commonly have water-management strategies in place for mitigating those issues, in addition to easily replaceable heat exchanger cores.

The SWEC system differs in that it chills water instead of cooling air. Chilled water can be pumped into the house to a hydronic fan coil so that the system more closely resembles a typical air conditioning system that operates with recirculated indoor air rather than 100

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[6] Interviews did not cover the evaporative cooling system tested because it was not successful. Instead, a brief exploration into the distributed nature of mini-splits was conducted, to understand how the room-by-room approach to heating and cooling is perceived by the industry.

percent outdoor air. The addition of the hydronic fan coil does have an impact on performance since there are inherent efficiency penalties with running a secondary water loop (pumping power and heat exchanger effectiveness). So, while the SWEC system offers new opportunities for evaporative cooling, different technical challenges still remain.

Like any evaporative cooling system, climate conditions significantly impact SWEC performance. The ideal climate would be one that is hot and dry, which provides the greatest potential for evaporative cooling. The most challenging climates are those that are hot and humid, since building cooling loads are high and ambient wet-bulb temperatures are low. SWEC operation in cooler climates is not expected to achieve high cooling capacities but may have sufficiently low wet-bulb temperatures to chill water and provide adequate cooling to manage relatively low building loads. That said, within any climate there are variations in conditions that will impact SWEC efficiency and cooling capacity. To overcome some of the climate limitations of the SWEC and extend the useful range of climate conditions, the system was coupled with a small vapor-compression system to boost cooling capacity. The hybrid SWEC has two stages of cooling: evaporative only and evaporative cooling plus vapor-compression.

Relative to traditional vapor-compression residential A/C units, the SWEC unit is physically larger, which may be off-putting to customers. While the cross-sectional area is only slightly larger than a typical vapor compression unit, the height of the SWEC is a little over double, standing about 5 feet tall. The SWEC's energy and environmental benefits would have to be marketed to customers to overcome doubts about purchasing a larger and possibly noisier unit.

Opportunities

The SWEC struggled to provide the cooling required in the field demonstrations, which highlighted areas for further technical refinement. However, the team was able use a validated computer model to optimize SWEC design and performance. The optimized design developed showed the hybrid SWEC design capable of Stage 1 and Stage 2 cooling, suitable for homes in many California climate zones. Energy modeling with the optimized design showed substantial cooling energy savings of between 43-75 percent over a traditional vapor-compression air conditioner. The SWEC modeling results also show that with further development, the SWEC has market potential for residential customers.

Estimates

For the evaporative-only SWEC, the cost of materials is expected to go down relative to standard air conditioners. Traditional air conditioners contain a significant amount of copper or aluminum, as well as refrigerant. These are expensive materials that are not required for the evaporative SWEC. For the hybrid SWEC, more costly materials would be required, but to a lesser extent due to the reduction in capacity of the refrigeration system.

Ductless Space Conditioning

Purpose and Need

One of the ways to improve cooling efficiency is to decrease the size of the space being cooled. Mini- and multi-splits are designed to cool individual spaces (rooms) and ideally operate only when a room is occupied. California's push for decarbonization is increasing attention to heat pumps, one type of which is the mini- multi-split. Although this field demonstration did not test mini-splits, it did retrofit one of the homes with a system that provided cooling to individual rooms, controlled by individual thermostats. In this analysis, market barriers to and opportunities for adoption of mini-splits are explored, with a particular emphasis on the narrowly targeted conditioning they provide.

Market Assessment

Barriers

Concern about cost was cited by several interviewees. One builder stated that mini-splits are "not cost-effective." It is important to note, however, that this respondent's company is developing an alternative technology, which seems to have greatly influenced this perspective. Others interviewed were not similarly convinced that mini-splits are not cost-effective.

Another interviewee pointed out that for retrofits of older buildings, there may be other costs associated with installing mini-splits. Many were not designed to carry the electric load that mini-splits require, meaning that new wiring, and perhaps even a new transformer, may be required. Another consideration is making duct work obsolete. One interviewee said she would be loathe to switch to mini-splits unless they were also thinking of replacing water heating and completely electrifying. It is "hard to swap them out with previous equipment. Our whole mechanical systems aren't designed with mini-splits in mind, which makes installing them in existing buildings more complicated," she said.

Several interviewees also noted that the cost of maintaining mini-splits might be higher than a central system, with the need for residents or maintenance staff to change (or wash) multiple filters. Another thought that this might "be a wash" with other maintenance cost factors, while yet another said that other advantages outweighed this consideration. One building owner/operator noted that, as a group, they "vendor out" HVAC work anyway, so system repairs or maintenance would "be a service call whether it's a central A/C or a mini-split."

Another concern was negative customer perception. The space conditioning experience is quite different from that delivered by a central system since it is designed to condition a single room, and each room is controlled individually. A few interviewees thought that customers would not like it. To emphasize the point, one home builder noted that his company is currently developing a new cooling technology that would provide, in his words, "a much more conventional customer experience." This suggests that at least some in the industry think that the distributed-space conditioning approach is undesirable.

Several factors related to the remote controllers were also noted by multiple interviewees. Some had concerns about (or experiences with) occupants losing their remotes. Replacement costs are reported to be $200, which is too expensive for many low-income residents. Without the remotes, interviewees worried that occupants would not be able to control their mini-splits, or would continually call maintenance staff for help. Another was concerned that multiple devices would increase the number of maintenance calls to either reprogram or troubleshoot. Finally, one interviewee worried that replacement remotes might become unavailable in the future.

The participant in the demonstration home with the decentralized system reported that the new thermostats were, although "not difficult" to operate, "a little more inconvenient" than the previous thermostat since it was necessary to operate "five thermostats in the house," where "before just one button" controlled the space conditioning for the whole house. A builder that was interviewed had a different opinion: "I don't see individual unit control as any different than with a central system. Human input is required in either case." But some interviewees worried that older occupants might find the system overwhelming or confusing. As one put it: "Turning units on and off in multiple rooms could be too much for some residents." He concluded, however, that residents "would be receptive to multiple controls because they know they ultimately have the final say on what areas get cooled or heated and which do not."

On the technical front, two interviewees noted that mini-splits cannot provide heating and cooling at the same time in different rooms of the same house or the system will shut down. Their perception was that it would require maintenance staff to reset it. Though restarting the system is likely something occupants could do independently, the perception of potential problems could become a barrier for mini-splits. In addition, if preferences or ambient conditions vary widely enough within a household, mini-splits' inability to provide simultaneous heating and cooling might be a shortcoming – one that variable refrigerant flow systems do not have. However, it should be noted that typical HVAC systems cannot provide simultaneous heating and cooling either, so it's unclear whether this limitation has any practical significance.

Mini-splits also impact the aesthetics of a house by introducing equipment to the interior space, unlike many other types of systems. One interviewee noted that the wall units are rather large for the small bedrooms of older buildings. The visibility of mini-splits' indoor units may be viewed by some as a drawback. A few interviewees also reported that determining where to put them in each room can be challenging, since it can influence the subsequent layout of the furniture which should not block the indoor head unit of the mini-split. They quickly added that a similar determination must be made for duct work ("You don't want ducting dumping cold air on the couch").

Opportunities

Most interviewees were positive about mini-splits. Two building owners mentioned that they had retrofitted a building with mini-splits in the recent past. One said residents had been happy with them, while the other said there were no complaints so far. (A third had experienced problems with refrigerant leakage.) For many in the affordable housing arena, mini-splits are a large improvement over the status quo because they deliver conditioned air to multiple points within the home, instead of just a single one, which is a common setup in some of our interviewees' buildings.

Cost is an important consideration. One builder described a housing complex his organization is currently developing, and is in the process of comparing the upfront costs of installing mini-splits or central systems with duct work. The interviewee said he thinks the "mini-splits might be cheaper." In new construction, mini-splits can lower overall costs by avoiding the need for gas lines, as one builder pointed out. Mini-splits were also thought to be relatively low maintenance among several interviewees. One building owner said she would lean toward mini-splits when considering a total rehab or a switch to all-electric, but not if they were just looking to upgrade the efficiency of their HVAC units since a simple change-out would be easier.

Cost savings for occupants were also cited as very attractive. Interviewees cited both energy efficiency and the mini-splits' ability to scale down use. Several interviewees noted that allowing occupants to shut off conditioning to individual rooms would be a valuable energy-saving feature since many rooms are empty for (sometimes large) portions of the day. Furthermore, shutting down is a way of saving energy that does not compromise comfort.

More precise targeting of space conditioning could also allow occupants to align usage with their household budgets. One interviewee told us that some families use no heating during the winter to save money. He thought those families might appreciate being able to heat a single occupied room during day (such as the living room) or at night (bedroom). This method would be "better than an all or nothing approach" – "I think they'd be very receptive to that."

All interviewees noted that customized temperature control could be appealing to many occupants because it provides "the ability to adjust by room to match varying occupant preferences," useful since some individuals "run hot" (or cold). Mini-splits would allow everyone to be comfortable (albeit in separate areas of the home). This was echoed by one family in the field demonstration site that reported that temperature preferences among family members differed.

One interviewee cited the particular benefit for large units (3-4 bedroom apartments) where some rooms get solar heat gains. Mini-splits would help address those room differences by allowing for different temperatures by room.

Several interviewees agreed that the appeal of this feature may vary with the age of occupants. Households with teenagers who spend time alone in their rooms may like this feature, while families with young children may not.

It is also worth noting that many residents in California may have previously lived in homes or apartments that did not have central A/C. Residents of affordable housing in particular are likely to have lived in properties with window units. Room-by-room heating or cooling control would therefore be already familiar to many.

Co-benefits are vitally important, yet often overlooked, selling points for space conditioning equipment. In addition to more precise control of space conditioning, mini-splits offer a better acoustic environment because they are very quiet. Interviewees noted this as an attractive feature.

Estimates

Mini-splits highlight an important tradeoff between upfront cost and efficiency. While many would like to embrace them for their energy-saving potential, the specific goals, priorities, and financial capacities of individual organizations (builders, building owners and operators) influence whether or not mini-splits are a feasible choice.

There is an important open question as to whether room-by-room space conditioning will be embraced for its advantages (efficiency, greater control) or rejected for its drawbacks (unfamiliarity, greater requirement for engagement).

There appeared to be more openness to mini-splits in the context of new construction than for retrofits. From the interviews there emerged a sense that, for existing buildings, the adoption of mini-splits is not a stand-alone decision. It is bound up with decisions about solar photovoltaics (PV), water heating, heating, and ducting since the systems are interconnected. As a result, the most palatable case of retrofitting with mini-splits seemed to be when it is part of a larger building electrification project.

Aerosol Sealing

Purpose and Need

The residential sector is responsible for about 23 percent of energy use in the United States, and 43 percent of that is due to heating and cooling (DOE 2014). For homes, 29 percent of space conditioning use is due to air infiltration, which means that about 12 percent of total use, or 2.85 quads, is due to air infiltration (DOE 2014). In many parts of the United States, this unintended air infiltration results in excess space heating and cooling equipment energy consumption.

California alone accounts for 6.7 percent of total United States total residential consumption (U.S. Energy Information Administration, 2020). In 2018, the California residential sector consumed 1,439.2 trillion Btu of energy, accounting for 18.1 percent of total energy consumption in the state (U.S. Energy Information Administration, State Energy Data System, 2020). Per the U.S. Energy Information Administration (EIA), nearly 32 percent of residential energy use is attributed to space heating and air conditioning in the Pacific section of the West Census Region (U.S. Energy Information Administration, Residential Energy Consumption Survey, 2018), which includes California, Oregon, Washington, Alaska, and Hawaii (Geography Division, U.S. Census Bureau) .

A tighter building envelope reduces the cooling and heating load on an HVAC system. Additionally, a tighter building effectively reduces penetration of both particles and ozone into the building. Both substances are regulated under the Clean Air Act and are known to have adverse respiratory and cardiovascular health impacts. Achieving tighter building envelopes using traditional methods can be highly labor intensive, with variable success rates, especially when performed as a retrofit. By contrast, field testing of the aerosol-sealing technique has demonstrated excellent results in single and multifamily residential buildings, sealing up to 90 percent of the leaks in fewer than two hours. Reducing leakage can improve energy efficiency, comfort, and infiltration of pests, noise, and particulate matter.

Furthermore, aerosol sealing can potentially produce tight homes with reduced labor and material costs when compared with conventional sealing, in addition to reducing contractor training and quality control to ensure that target house tightness values are achieved.

Market Assessment

Barriers

Perhaps the most notable barrier to adoption of aerosol sealing is a lack of requirements in the *California Building Energy Efficiency Standards*, and, to a lesser degree, the relatively low performance credits gained when lower leakage targets are met. Several building owners, operators, and builders cited this issue. One explained that they only adopt strategies that are minimum code requirements because the upfront cost of “extras” is simply unfeasible for their (nonprofit) organization. Without a mandate, few building owners or builders set their own leakage targets or conduct leakage tests on their homes.

Several building owners and operators interviewed mentioned concerns about the cost of aerosol sealing (though they were not provided cost information). Some said it simply would not be feasible to seal their buildings unless doing so paid for itself through either energy savings or reduced construction or maintenance costs (though not all shared that view). A few builders interviewed shared that sentiment, stating that they have difficulty justifying the cost of sealing to their customers. The latter are commonly less concerned with air sealing than with more visible and tangible aspects of their home and are often willing to reduce overall costs by minimizing their investment in high-quality air sealing.

As with any new technology, lack of familiarity with aerosol sealing building envelopes is also a barrier to adoption. Most of the building owner/operators who were interviewed had not heard of this approach. Even when builders are familiar with this approach, marketing this service to their customers is difficult, according to several builders interviewed.

Interviewees had questions about the applicability of the aerosol sealing approach based on existing building conditions. In particular, they wondered whether Aerobarrier works on really old buildings with large gaps. If not, that would limit the market to a certain vintage of building (namely those that are not too old, but not too new). Another interviewee said: "It doesn't make sense to seal an apartment that has a large fresh air vent with no active control."

Several building owners and operators who were interviewed noted that many of their residents keep their units closed up, rarely opening either windows or doors. Sealing the building envelope alone could in these cases exacerbate existing problems like moisture build-up. The solution is to ensure that the mechanical ventilation system provides adequate fresh air to safeguard indoor-air quality. As one interviewee put it, after sealing the building you have to "supply a little more air to the unit." Buildings that have inadequate or inoperable mechanical ventilation systems might need to upgrade them in conjunction with sealing the building envelope. This would raise the cost of sealing the building and potentially introduce technical challenges. As one building owner/operator reported, there are sometimes existing conditions that limit the ability to add louvers or vents. It can be challenging and costly. "That might deter us from taking that approach. It opens up another can of worms. We don't always know what the existing conditions are so sealing the building adds a level of uncertainty."

Other practical barriers included several inconveniences involved in sealing existing homes. Preparations for sealing the two demonstration homes involved moving out all of the households' belongings and covering soft furnishings such as rugs. This was an expensive and time-consuming process. In addition, there were challenges in scheduling the aerosol sealing since it required the families to move out for several days. When occupants returned they had to spend time returning their belongings to their rightful places and one found that the surfaces were sticky from the aerosol treatment. The other household, however, had no issues (mess, dust) with the sealing procedure. Even in new construction, scheduling aerosol sealing can be burdensome since the house must be empty of workers, as several interviewees noted.

Opportunities

Changes to the building code present perhaps the greatest opportunity for broader adoption of aerosol sealing. Several builders interviewed predicted that as regulations become increasingly stringent, more builders may come to rely on aerosol sealing. This, in turn, would help the technology achieve greater scale and ultimately reduce costs to customers.

But the technology must also stand on its own merits. Sealing building envelopes with the Aerobarrier approach has many advantages, as the interviewees noted. Builders cited energy efficiency or less air leakage, utility incentives or credits, and reduced rooftop solar costs in net-zero energy homes since envelope sealing reduces heating and cooling loads. One stated that "if the goal was to make the home as tight as possible, this product would be far superior to the method we use," citing far greater cost effectiveness for comparable results. The greatest opportunities for aerosol-sealing technology are in climates with extremely hot or cold temperatures (or both) as they would likely see the greatest impact (and cost-effectiveness), relative to more temperate regions.

Most building owners and operators interviewed were unfamiliar with the concept of aerosol sealing of building envelopes, but all found it interesting, intuitively appealing, and practical. Responses included: "The concept seems valid," "I only see advantages," and "It sounds cool." Another who had been involved in the field demonstration said that the residents, after sealing, did not feel drafts or anything else coming into their homes. He said: "It works. It makes the building weather-tight, sealed."

One building owner interviewed noted the particular appeal of its applicability to existing buildings. She said: "It's really exciting that this is applicable to retrofits. When we rehab a building, we typically can upgrade the mechanical systems, but we lose efficiency because we can't seal up the building." In this way, aerosol sealing fills a gap among available retrofit solutions.

Cost is another important consideration. On this factor the building owners/operators split. One reported needing a 7 to 10 year payback to make it a "slam dunk," a "no-brainer." He went on: "If it's much longer than that, or you never catch up, then it would be a little more problematic. We would be waiting for the industry to catch up to give a suitable repayment timeframe to become widely used." By contrast, another interviewee said her organization does not consider payback or return on investment, per se. "In non-profit affordable housing we're not really looking at the bottom line. We're just making sure it pencils out – it's financially feasible – as long as it's not increasing ongoing costs over time. We're not looking for the project to make money, just sustain itself." In that case, sealing the building envelope would be considered part of an overall package that might include energy upgrades as well as cosmetic ones, the latter of which do not have a direct return on investment.

Interviewees noted several ways that cost-effectiveness could be improved. First, if aerosol sealing enables builders to eliminate other sealing measures (especially spray foam), the cost challenge will be greatly reduced. (though there was no consensus among builders on which current air sealing techniques [such as sill seals] - could be eliminated if using aerosol sealing.) Cost-effectiveness could also be improved by leveraging scale economies. Sealing jobs could be batched to spread set-up costs over multiple units. Locations with large and predictable seasonal turnover (like college towns) would be good targets since there are typically many vacant units at the same time.

Making performance data accessible is critical to promoting adoption. Building owners and operators who were interviewed reported that access to an objective and credible performance evaluation would be a critical precursor to adoption. One builder also suggested that more accurate home-energy-use modeling technology would make it easier to evaluate cost effectiveness by providing a better comparison of performance relative to other efficiency measures. Along similar lines, the sealing process provides immediate transparency in the outcome by generating pre- and post-sealing leakage data. As one interviewee put it, anyone who is interested in the technology would be interested in the data that's generated during installation, which can equate with lower energy bills.

The many benefits of aerosol sealing of building envelopes contribute significantly to its appeal and value. Air sealing can reduce noise, pest, and odor transmission between units in multi-family buildings. Noise reductions from aerosol sealing were extensive in the case of a building with uninsulated walls between tenants, though the building with insulation between tenants showed that the sealing had little impact (Bohac et al., 2016). Several building owner/operators interviewed remarked that those were very attractive selling points. The reduced need for pest control, in particular, would be of huge benefit to property managers. In addition, sealing the building envelope would help "protect the asset," improve resident health, and generate savings that could be applied to the sealing cost. Another interviewee pointed out that there were further health benefits from increased replacement air after sealing the building envelope. On balance, he said "the pros outweigh the cons."

Interviewees told us that the application process itself is critically important to the appeal of this technology. For example, sealing the units during "turn" (while vacant and being prepared for the next tenant) would be convenient because it would avoid the need for coordinating with residents. Installers would also not need to work around household contents. Alternatively, when done as part of a larger building renovation project, the fact that a unit can be sealed in a matter of hours is highly desirable. One building owner reported that they are moving away from relocating residents (for up to four weeks) during rehabilitation projects and instead are adopting a new approach where residents vacate units only during the day (between 9 am and 5 pm, for example), but otherwise remain in place amidst renovations. The aerosol sealing approach would fit well with that approach, she noted.

In that same vein, another interviewee said that, in the case of new construction, it would be useful to provide a list of specifications upfront that reduce man-hours after sealing. For example, the organization could require its sheetrock contractors to seal up penetrations ahead of time. In addition, timing the sealing strategically with the construction schedule to minimize downtime would enhance the appeal of the approach. Note, however, that builders had mixed opinions about the precise point in the construction process during which it would make the most sense to do the aerosol sealing.

Estimates

Aerobarrier is suitable for most residential construction, with applicability for both single and multi-family homes. Its technical potential, therefore, is limited mostly by the rate at which new homes are constructed. Forecasts for new construction are very uncertain, especially in the wake of the COVID-19 pandemic. The manufacturer of Aerobarrier reported that the company conservatively expects a minimum of a 5 percent market share in the next 5 years, representing 5,675 units per year, assuming that 115,000 residential units are built each year. The company is targeting a 25 percent market share after 10 years, representing 28,375 units per year (Aerobarrier representative, personal communication, 10/14/20). Based on the manufacturer's projections, total installations could range from 56,750 to 283,750 in the next 10 years, depending on where the actual adoption rates fall (between 5 and 25 percent), and assuming constant construction activity.

Precooling Ventilation

Purpose and Need

To meet California's building codes and standards (Title 24), newly constructed houses and additions to existing houses (over a certain square footage) are required to have mechanical ventilation. Ventilation improves indoor air quality by removing contaminants generated inside the house, and, in some cases, filters the outdoor air brought into the house. As houses are increasingly built with tighter building envelopes, resulting in less passive air flow through the building shell, mechanical ventilation has become increasingly important to ensure that indoor air quality is maintained. Moving from passive to active ventilation has the advantage of facilitating better filtration in some cases, but also increases energy use through greater fan usage and an increased need to condition the air. Striking a balance between providing fresh air while minimizing electricity consumption is a critical challenge.

Title 24 mandates that new homes have mechanical ventilation with air-flow rates in accordance with ASHRAE Standard 62.2, *Ventilation and Acceptable Indoor Air Quality in Residential Buildings*. Several different types of systems meet these code requirements for mechanical ventilation, which creates flexibility when meeting the needs of diverse house constructions.

There are three primary types of residential ventilation systems: exhaust, supply, and balanced. An exhaust ventilation system depressurizes the house by exhausting air while make-up air infiltrates through building leakage or intentional passive vents. These systems are best in cold climates versus warm, humid climates where depressurization can draw moist air into the building and lead to moisture damage. The most common exhaust ventilation strategy is to rely on a kitchen or bathroom exhaust fan running continuously to provide the necessary whole house ventilation rate.[7] A disadvantage of exhaust systems is that incoming air cannot be filtered, allowing contaminants to enter the house. It is also difficult to evenly distribute outside air throughout the house with exhaust systems.

A supply ventilation system pressurizes the house by forcing outdoor air into the house, while indoor air leaks out of the house through building leakage, bath and range fans, or intentional vents. This system consists of a fan and ductwork that supply fresh air into one or more rooms in the house. This can be a separate fan from a central air system or it can use the blower fan in a central air system in combination with an outdoor-air vent. Supply ventilation systems allow outdoor air to be filtered but may require conditioning of outdoor air to prevent bringing in air that is either uncomfortably hot or cold. Supply ventilation works well for hot or mixed climates; in cold climates the system can potentially create condensation issues when warm, humid indoor air condenses on cold surfaces in a wall cavity, causing mold or mildew. Supply systems are relatively inexpensive to install but can cost slightly more to operate than exhaust systems when an additional fan must be installed (versus using an existing exhaust fan).

Balanced ventilation systems combine both supply and exhaust systems. These systems introduce and exhaust approximately equal amounts of outdoor air and indoor air. Similar to supply-ventilation systems, balanced systems allow the use of filters for outside air entering a house. Balanced systems are well suited for all climates since they don't rely on building

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[7] Whole house fan systems also exhaust indoor air; however, they are not installed as code-compliant ventilation systems. These systems are typically used to cool the home with fresh outdoor air during optimal conditions through open windows and an exhaust fan installed in a central location in the house. Whole house ventilation attempts to ensure a certain air exchange rate to improve air quality and is intended to run continuously or semi-continuously.

leakage for pressure relief. Because balanced systems require two fans and two duct systems, they are more expensive than either supply or exhaust systems alone.

Balanced ventilation systems have the distinct advantage of recovering energy from the exhaust stream to temper the supply air, reducing the thermal load introduced by the ventilation air. There are two types of energy recovery systems: heat-recovery ventilation (HRV) and energy-recovery ventilation (ERV). Both systems reduce heating costs in the winter by transferring heat from warm indoor air exhausted to the fresh (cold) supply air. Similarly, in the summer, the systems transfer heat between the cool indoor air being exhausted and the warm outdoor air being brought into the home. HRV and ERV systems both exchange heat between incoming and outgoing air streams, but ERV systems also exchange moisture between the two air streams and reduce the latent load introduced by the ventilation air. Energy (and heat) recovery ventilation systems are typically more expensive than either supply or exhaust ventilation systems, but save on space conditioning costs.

While different types of ventilation systems can be compared by average system cost, there are other factors that go into the cost of installing a ventilation system in an existing home. These include the size of the house (e.g., floor area, number of rooms), whether the house has existing ductwork (e.g., central heating and air), or if ventilation fans already exist (bathroom or kitchen exhaust). The size of the house and the number of bedrooms determine the required ventilation rate for proper ventilation. How the air is distributed in the home also influences installation cost, whether it's to a central location in the house or distributed throughout (in each room). Having existing ductwork may lower installation costs if the ventilation system can be easily integrated into the existing system. In addition to system type and size, costs are also incurred from required equipment that may include fans, ductwork, and system controls.

Products

Traditional ventilation systems introduce outdoor air without regard to the temperature differential between indoors and outdoors. While improving indoor air quality, this can introduce an "energy penalty" by increasing the amount of air that requires conditioning to achieve desired set points. Recent innovations in mechanical ventilation have mitigated this issue by either improving fan efficiency (for all system types), recovering heat from outgoing exhaust air, or optimizing the timing of ventilation to reduce conditioning load in the building.

The latter approach, sometimes called ventilation cooling, is chosen when supply ventilation systems use advanced controls that minimize heat loss or gain. They measure outdoor conditions and precool the home during warm summer days by over-ventilating the home with cool nighttime air. Cooler daytime indoor air temperatures then delay when an air conditioner must take over to reach a desired set point, saving energy. In addition, by restricting outdoor air when the temperature is not optimal, these systems avoid increasing heating and cooling loads during peak periods, which could in turn strain heating and cooling equipment, jeopardize occupant comfort, and increase space-conditioning costs.

Two technologies were evaluated through field demonstrations in this project: NightBreeze and the SRV. Both are supply-ventilation systems that connect to the supply side of existing central-air ductwork and supply outdoor air when controls signal a call for ventilation.

Comparative Analysis

NightBreeze and SRV are both designed to work as supply-ventilation systems, installing fans in-line with supply ducts that provide outdoor air through the ductwork. This is not the typical setup for NightBreeze since it normally utilizes a central fan. The controls for both the SRV and NightBreeze operate the ventilation fan to "over-ventilate" the home to meet ventilation requirements when outdoor conditions are optimal. The home is then precooled to reduce use of mechanical cooling while meeting ventilation needs. There are some minor differences in how each controller operates. The SRV controller uses the forecast for the following day to anticipate heating and cooling loads and energy loads to set an optimal time to "over-ventilate." The NightBreeze system uses measured temperatures and a statistical function to predict next-day temperatures and varies ventilation fan speeds for the amount of cooling required, then adjusts the temperature settings to maximize comfort and reduce air-conditioner and fan-energy use. Another difference in the two systems is fan speed. The NightBreeze system uses a fan with higher flow rates, requiring a relief damper to prevent over-pressurizing the home.

In this project, both ventilation systems were installed in-line with existing ductwork. They both could, however, also be installed in a house that does not have existing ducts since both systems use an independent fan to introduce outdoor air; but this would require that ductwork be added. This may not be the most cost-effective approach, depending on the size of the home, which determines how much new ductwork would be needed for the ventilation system. The NightBreeze system utilizes an existing central fan and ductwork so it would generally not be considered for a home without a duct system. Another limitation on installing these systems is space availability for fan equipment or dampers; there is, however, the potential for alterations in the system design to fit either system in most houses, as was done for this project.

Other Ventilation Cooling Technologies

There are several other commercially available ventilation-cooling technologies that are commercially available, which may compete for the same market as NightBreeze and SRV. Table 14 provides an overview. All of the systems monitor outdoor conditions to optimize when to introduce outdoor air, though there are some notable differences in how they operate.

One such product is called *VentCool Automated Free Cooling*, by Field Controls, L.L.C. Similar to the two technologies evaluated in this project, this system is a supply-ventilation system that provides free cooling. VentCool is Title 24 compliant and includes a smart thermostat that works with most forced-air systems. The system monitors indoor and outdoor conditions and when outdoor conditions are favorable, the system circulates fresh air in the home. When outdoor conditions are not favorable, the system will switch to normal cooling mode, using the house A/C system. The system also includes a filter to clean and purify incoming air when the central fan is operating. Because the controls for operating the ventilation system are adjustable for different outdoor conditions, it can be installed across many climate zones. However, ideal temperature parameters would be down to 60°F at night or in the early morning to optimize precooling capabilities where the home is cooled more aggressively at night to reduce the next day's cooling load. VentCool's Automated Free Cooling system has been available for over five years and costs around $1,000. Although the system helps save energy, it is not as frequently installed as the company's whole-house fan ventilation systems.

Although whole-house fans do not filter incoming outdoor air, they are less expensive to install and are a well-established technology.

Another product similar to NightBreeze and Ventcool is Villara's *SmartVent* ventilation system. This ventilation system uses a controller that integrates with a home's heating and cooling systems to introduce outdoor air through existing ductwork when outdoor conditions are favorable. The controller monitors outdoor and indoor temperatures and brings in fresh outdoor air when the outdoor air temperature is lower than indoor air to help cool the home, reducing the use of the home's next-day air conditioning system. Occupants can set a minimum temperature that ensures the home is not overcooled at night. SmartVent is Title 24 compliant and has been in production since 1989. The system costs about $650, excluding installation costs.

Another ventilation cooling technology is the CoolMizer by Arzel, which has been on the market just over 10 years. This product is not certified as Title 24 compliant, and its primary purpose is as an economizer. The CoolMizer uses controls that deliver fresh outdoor air when outdoor conditions are favorable and uses the blower fan in the home's central air system to introduce air through the duct system. The system monitors both outdoor temperature and humidity to provide "free" conditioning by selectively introducing outdoor air through the home's distributed duct system, which is based on a set operation mode. Because the controller is customizable, it can be used across most climate zones. Depending on the size of the project, the CoolMizer system costs around $700 in addition to the dampers installed, which can range from $100 to $500. It has been on the market since 2007.

A similar product is the FAMCO Zip Economizer. This system is similar to the CoolMizer in that it functions primarily as an economizer, introducing outdoor air into the house when conditions are favorable to reduce the use of a mechanical cooling system. This system can also be used with an indoor air quality/CO_2 sensor, or with an alarm input from a carbon monoxide alarm. This system costs around $1,300.

Table 14: Overview of Selected Ventilation Cooling Technologies

	NightBreeze	**Smart Residential Ventilation**	**Villara Smartvent**	**Field Controls VentCool**	**Arzel CoolMizer**	**Famco Zip**
Current Market Status	Prototype system. Controls from previous product (no longer available).	Prototype system and controls.	Available for over 20 years	Available for over 5 years	Available for over 10 years	Available for over 5 years
Operates per Title 24 requirements	Satisfied in Winter mode Summer mode using relative exposure procedure in Normative Appendix C	Yes	Yes	Yes	No	No
Controller Input	History of indoor and outdoor conditions to predict next day conditions	Weather forecast for next day and predicted energy use	Real time outdoor weather data	Real time outdoor weather data	Real time outdoor weather data	Real time outdoor weather data
Operation	Minimizes fan energy use by varying fan speed according to amount of cooling needed	Minimizes energy consumption from calculated heating/cooling loads and energy consumption	Ventilates during favorable outdoor conditions	Ventilates during favorable outdoor conditions	Introduces outdoor air during favorable conditions	Introduces outdoor air during favorable conditions
Cost	$2300	$2000	$650	$1000	$1000	$1,299

Source: University of California, Davis

Market Assessment

Drivers

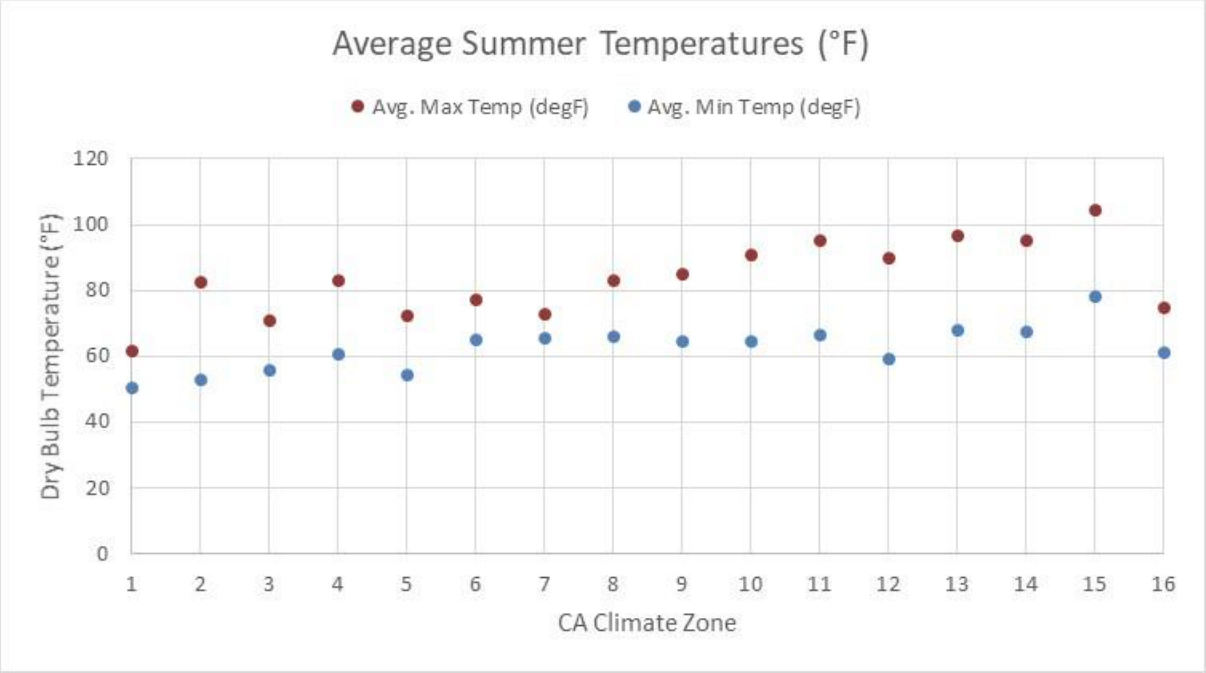
There are several key market drivers for ventilation strategies that can also deliver precooling in California homes. The primary driver is Title 24 ventilation code requirements. This will drive adoption in both new and existing homes constructing permitted additions that trigger code requirements for mechanical ventilation (additions over 1,000 square feet and new dwelling additions to existing buildings). Drivers of voluntary adoption of precooling ventilation products will include potential savings on cooling (and possibly heating) costs, improved indoor air quality, increased cooling needs, and environmental concerns. The former will be influenced by factors such as potential changes in electricity prices, equipment efficiency, and macro-economic conditions. An increasing emphasis on building tightness to improve efficiency drives a greater need for mechanical ventilation. At the same time, concerns about outdoor air quality (particularly given the severity of recent fire seasons) is increasing the need for and attention to air filtration. The precooling ventilation products profiled in this report have an advantage over whole-house fans in this respect since the latter does not have filtration capabilities, while the former does. In addition, rising temperatures mean that hot areas of the state will need ways to curb rising electricity consumption from air conditioners, while more mild areas will, for the first time, need new options for cooling that do not exacerbate peak loads and subsequent grid instability. Finally, environmental awareness will spur some households to seek efficient alternatives to air conditioning.

Code-compliant precooling ventilation technologies are suitable for both existing homes and new construction, though their technical feasibility and cost effectiveness vary by climate zone and existing HVAC systems.

Suitability by Climate Conditions

Precooling ventilation systems can deliver benefits in many climate zones. Those that can be programmed by customers to ventilate at set outdoor temperatures are especially beneficial because they can help reduce use of mechanical cooling systems. However, this precooling control strategy may yield more energy savings in some California climate zones than in others. For example, locations with larger daily fluctuations may result in more savings. To classify each climate zone, the average maximum and minimum summer temperatures across California's 16 climate zones are shown in Figure 65**Error! Reference source not found.**.

Figure 65: Average Maximum and Average Minimum Temperatures for Each California Climate Zone for June Through August



Data from the California Building Energy Code Compliance (For Commercial/Nonresidential Buildings) Software was used in this data analysis.

Source: University of California, Davis

As shown in Table 15, based upon changes in average summer (June, July, August) maximum and minimum temperatures for a given climate zone, each of the 16 zones was grouped together (California Building Energy Code Compliance [For Commercial/Nonresidential Buildings] Software) and classified as "best," "better," "good," or "N/A" in relation to market applicability for precooling ventilation.

Table 15: Criteria and Classification of California Climate Zones for Benefitting From Installation of Pre-Cooling Ventilation System

ΔT (max-min)	Classification	Climate Zones
>20°F	Best	2,4,9,10,11,12,13,14
20°F >ΔT>15°F	Better	3,5,8
15°F >ΔT>10°F	Good	1,6,16
	N/A	7, 15

Source: University of California, Davis

These classifications were assigned based on two criteria. The first is that the average minimum summer temperature must be low enough to truly benefit from precooling the house; it is estimated that 70°F is an appropriate cutoff.[8] For that reason, Climate Zone 15 has

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[8] Although a nighttime temperature of 75°F may feel like a relief after a 100°F day, introducing nighttime air to precool is not likely to provide enough cooling to substantially reduce the use of air conditioning the next day.

been excluded from Table 15; those with relatively warmer average minimum summertime temperatures are not ideal candidates.

Secondly, more energy savings can be realized from greater temperature fluctuations throughout a 24-hour cycle. Climate zones without much variation from daytime highs and nighttime lows have little need to precool. For this reason, Climate Zone 7 is excluded.

It is worth noting that in cooler climates such as in climate zones 3 and 5, many existing homes do not have air conditioning. Summer temperatures in these regions do not reach the high temperatures of inland climates zones, though nighttime temperatures often still drop. Precooling ventilation systems in this type of climate zone could offer an alternative to A/C systems, resulting in substantial energy savings, with the added benefit of a ventilation system that can filter incoming outdoor air.

While the SRV and NightBreeze systems have some notable technical differences – both from each other and from other precooling ventilation products – they essentially serve the same purpose and are suitable for the same types of homes and climates.[9] As a result, it is expected that this class of products would collectively compete for the same potential market. In the calculations that follow, the potential market size for precooling ventilation products is estimated, conditional on being Title 24 code-compliant.[10]

Summary of Drivers and Trends

Several trends are expected to drive demand for ventilation cooling products. The most important are building codes. Increased standards for building envelope tightness will continue to drive the need for mechanical ventilation in both new homes and existing homes with qualifying conditions, or major renovations. At the same time, there is increasing attention on indoor-air quality. Wildfires and Covid-19 have increased awareness of the need to filter outdoor air coming in as well as removing indoor-air pollutants. Mechanical ventilation now seems to be on the minds of many California residents.

Another factor that could drive demand for ventilation cooling is an emerging emphasis on electric-grid strain, which will increasingly demand greater load flexibility. California's utilities, grid operator, and others are searching for new ways to reduce peak load and improve reliability. On the consumer side, widespread adoption of time-of-use rates is expected to pique interest in ways that increase overnight precooling. Ventilation cooling offers benefits for both consumers and the electric grid.

As outdoor temperatures continue to rise, the need for mechanical cooling (and ways to save energy while delivering cooling) is growing. This applies to both already-hot areas of the state, as well as to those that have traditionally not required mechanical cooling, such as coastal

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[9] The notable exception to this is that the SRV is designed to optimize ventilation in heating season, too. However, since wintertime energy savings were not demonstrated as part of this project the market estimate is based only on the SRV's ventilation cooling mode. If heating season suitability were considered the market potential might be slightly higher.

[10] At this time, some products identified in this report are code-compliant while others are not. The project team estimate that all of them have the potential to meet code requirements, in which case they could target the same market.

areas. Ventilation cooling can serve as either complement or alternative to air conditioning, depending on the climate.

Of the various ventilation or cooling strategies common in California home construction and retrofits today, only ventilation cooling addresses all three of the trends to improve indoor-air quality, increase electric-load flexibility, and optimize ventilation delivery to reduce cooling loads. None of the standard alternatives incorporates controls that accomplish all three. Typical balanced ventilation systems and exhaust fans do not prioritize ventilation during cooler periods and are usually sized to run continuously, which means that they cannot shut off and make up the ventilation later (and the latter also do not filter outdoor air). Whole-house fans provide cooling but neither code-compliant mechanical ventilation nor filtration. Furthermore, whole-house fans require that occupants open windows (with the attendant safety and air-quality problems that may introduce) once the outdoor temperature is favorable, which may be after they have gone to bed. The NightBreeze and SRV systems begin ventilation cooling automatically when appropriate without any occupant input.

Integration of zone damper operation with HVAC-system speed and capacity can be provided by other products, but at very high cost. Western Cooling Efficiency Center research has shown that, without integrated zoning, multiple-speed systems substantially increase duct loss and reduce overall system efficiency. In light of COVID-19 circumstances, smart residential-ventilation systems could also reduce virus exposure by providing both consistent, reliable ventilation throughout the house and improved filtration using MERV 13 (or higher) filters.

On a related note, ventilation cooling automates ventilation, not just cooling. From a code perspective, that is very important because it suggests that the required amount of ventilation air is likely delivered to the space. By contrast, according to one industry expert, exhaust fans are frequently disabled by occupants. Similarly, whole-house fans are often not used at all since they require opening windows. Ventilation cooling is thought to be rarely usurped (especially if the minimum temperature setting is acceptable).[11] Thus, ventilation cooling is assumed to deliver more reliable ventilation, though this has not yet been verified. This is an important selling point for both consumers and policymakers for whom indoor air quality is critical.

Finally, there is intuitive appeal to ventilation cooling. The concept is a modern improvement on an old method to cool and refresh air in homes. In the simplest terms, the technologies bring in filtered fresh air at night to flush out the house, precooling and freshening it for the next day. One developer noted that it “doesn’t take people very long to understand and accept the value when they’re told it provides fresh air, and that it’s all automatic.” As another said: “There are a lot of folks that will appreciate ventilation cooling once they have it… it’s a way to get natural cooling back into their lives, and people are going to appreciate that.”

Considering the various drivers and trends together, there is reason for optimism that there could be a sizeable future market for ventilation cooling technologies like the NightBreeze and SRV.

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[11] ERVs/HRVs have this same advantage over exhaust and whole-house fans.

Barriers

While many homes in California would undoubtedly benefit from ventilation cooling technologies, there are several barriers to market adoption that are expected to dampen market uptake. In new construction, there are cheaper, easier, and more familiar alternatives available such as exhaust fans or balanced systems. Ventilation cooling technologies can be more difficult to both install and verify. Determining code compliance requires more detailed monitoring to ensure that the dynamic and intermittent ventilation they deliver will provide the code-required number of air changes. It is less complicated to install a bathroom fan, where air-flow rates can be easily verified.

On the precooling side, there were initially some advantages provided by Title 24. However, the calculation for energy savings has changed and those advantages have substantially diminished. In contrast, whole-house fans meet prescriptive requirements with a distinct advantage since they require no complex verification of energy savings.

Builders are generally very cost-conscious and typically look for the most cost-effective ways to meet code requirements. There is currently no incentive for builders to choose ventilation cooling technologies; they are simply more expensive and complicated than existing alternatives. Without major shifts in building codes or incentive policies, inertia will continue to drive the use of dominant technologies.

The retrofit market faces even steeper barriers. Aside from homes adding major additions (greater than 1,000 square feet), existing homes are not required to add mechanical ventilation under current building codes. A primary lever for adoption is therefore missing in the retrofit market. Voluntary adoption of ventilation cooling technologies (for purposes of ventilation) is expected to be low since newer homes already have mechanical ventilation (albeit inferior in terms of both energy use and air filtration), and older homes may realize limited value from air filtration given leaky building envelopes.

On the cooling side, the few households with the means to invest in energy-saving ventilation cooling technology are rarely motivated to reduce their utility bill, while less wealthy households that are motivated do not have the means to do so. At the same time, coastal customers looking to add cooling capabilities will find more familiar alternatives (e.g., packaged units or mini-splits) that their HVAC installers will more readily endorse. In addition, when cooling is required but outdoor air is unhealthy, during wildfires for example, ventilation cooling cannot be used, while traditional air conditioners cool indoor air without introducing outdoor pollutants.

On the comfort side, the technology's greatest benefit is driving down indoor temperatures ahead of the next day's cooling load. One builder reported that many customers have limited tolerance for low temperatures at night, which the NightBreeze and SRV rely on to save energy. By contrast, HRVs and ERVs deliver supply air closer to a desired set point; maintaining this narrower temperature range can deliver greater occupant comfort. Customers reportedly were also upset when ventilation was required while outdoor temperatures were especially high or low. For these customers, it seemed counterintuitive to bring in outdoor air when it is 100 (or 30) degrees outside. (ERVs and HRVs mitigate that concern by preconditioning ventilation air with captured heat and energy.) As one builder said: "It's always tough to have a product that some people like and some people really don't like." As a result of this and code changes, his company stopped offering ventilation cooling as a standard option when 2019 building codes took effect. Instead they have moved to ERVs and HRVs for "more customer-friendly" Title 24 compliance.[12]

NightBreeze is "not an easy retrofit" said one builder. Its path to market "needs to go through distribution and HVAC technicians."[13] The same is true for the SRV. Thus, as in the new construction market, suppliers would have to champion ventilation cooling technologies, both introducing them and educating their customers.

Based on its own experience with residential ventilation, Frontier Energy identified the following factors and barriers against increased adoption of residential ventilation systems:

- Thermostat manufacturers may not recognize the value of ventilation cooling and are focused on other "smart" control functions.
- HVAC equipment manufacturers similarly may not recognize the value of ventilation cooling. Other than allowing the use of non-proprietary thermostats, they do not allow the use of third-party products that control air flow or system capacity.
- Production builders may not have a vested interest in the long-term operating costs of the homes they build or the long-term health of their occupants.
- Other than whole-house fans, home buyers may not be able to purchase products that improve ventilation and indoor air quality beyond what is required by energy standards.

Finally, as California homes continue to become more efficient, air conditioners are required to run less. As a result, there is less benefit from ventilation cooling, which in turn lowers its cost effectiveness.

Under present circumstances, the adoption of ventilation cooling technologies is likely to remain limited to households and builders who pursue this alternative approach for reasons beyond solely the proverbial bottom line.

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[12] Note that ERVs/HRVs and ventilation cooling may be substitute goods or complementary goods. In fact, one builder interviewed said that the ideal ventilation approach would be to use ventilation cooling when conditions are favorable and run an ERV/HRV continuously otherwise when needed to meet ventilation requirements.

[13] Note that there is now a spin-off to NightBreeze, the EcoBreeze, which is designed as a window unit but serves a similar function. It does not require an HVAC installer but would simply be set in a window or sliding door. It is targeting a direct-to-customer path to market.

SmartVent Market History

SmartVent's market history, as summarized by the commercial home builder that developed it, provides an illustrative example of how uptake of ventilation cooling technologies responds to policy changes. Beginning in the 1990s, SmartVent was offered by Villara as a buyer option. In the early 2000s, an estimated 90 percent of homeowners who saw it in the builder showroom would choose it from among the other upgrade options. When the economic recession hit, it "hammered the industry" and many builders moved away from the SmartVent as they struggled to make their homes more affordable. Demand for SmartVent nearly vanished. Several years later, the 2013 update to Title 24 began offering a significant credit for night cooling, at which point it became a standard offering. The market picked up and was "really gaining traction" when the Energy Commission changed the protocols. They reduced the energy credits given to ventilation cooling and began giving whole house fans large credits. Despite SmartVent's notable advantages over whole house fans – such as filtration, automation – whole house fans have become the standard option because the energy credits they receive make them more affordable. Several builders continue to sell SmartVent because their customers like it, but in general builders are moving away from complex buyer options because it slows the construction process. Furthermore, customers seem to prefer non-energy upgrades, and ventilation cooling "can't compete against granite countertops." (Based on interview with Villara executive, 10/8/20)

Estimates

A potential market-size estimate for existing and new homes follows, based on the drivers, barriers and trends just identified, as well as characteristics of the homes themselves. Again, market potential is estimated for code-compliant, whole-house ventilation cooling technologies as a whole, such as those shown in Table 14.[14]

Of the state's 16 climate zones, Climate Zone 7 is the only zone that encompasses a portion of a single county; the remaining 15 climate zones span 2 or more of California's 58 counties (Energy Commission, 2020). Important to note is that most of the counties are split unevenly between 2 or more climate zones since climate zone and county boundaries were designed independently of one another (Energy Commission, 2020). Therefore, to determine which counties are the most promising market targets, it was necessary to assign each county a dominant classification.

A county was assigned a dominant classification under a "best," "better," "good," or "N/A" framework based on which area of the county was most densely populated, and in turn which climate zone most accurately reflected a climate zone's most densely populated areas. (population of California, 2018).

The market estimates considered ventilation cooling technologies both as an energy-saving complement to air conditioning in hotter climate zones and as potential alternatives to air conditioning in more temperate areas. Slightly higher adoption rates were applied to homes

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[14] The SRV actually consists of two components – the control algorithm and the low power fan – that can be deployed together, as in the demonstration project, or apart. The control algorithm could in fact be integrated into other ventilation cooling hardware options, such as ERVs/HRVs or transfer fans. There may be a separate market for the control algorithm itself, but the estimates here consider only the SRV as a package.

that do not have air conditioning since ventilation cooling would provide a new service for those homes.

Separate estimates were generated for existing homes built before the 2010 code cycle, prior to the requirement for whole-house ventilation, homes built between 2010 and 2020, which were subject to the new ventilation requirement, and new construction from 2021 to 2030. Table 16 shows this breakdown.

Table 16: Estimated Total Homes and Those with Ventilation Cooling Systems Installed by Home Vintage and Climate Suitability

	Best		**Better**		**Good**		**Total**
	Total	***Installing***	**Total**	***Installing***	**Total**	***Installing***	***Installing***
Pre-2010	4,643,897	*22,987 (0-0.5%)*	1,232,067	*0 (0%)*	285,471	*0 (0%)*	***22,987 (0.4%)***
2010-2020	152,557	*38 (0-0.5%)*	34,839	*0 (0%)*	5,885	*0 (0%)*	***38 (0.02%)***
2021-2030	152,557	*3,323 (0-4%)*	34,839	*379 (0-2%)*	5,885	*32 (0-1%)*	***3,734 (1.9%)***
Total	4,949,010	*26,348*	1,301,746	*379*	297,241	*32*	***26,759 (0.4%)***

Note: Totals may be slightly off due to rounding.

Source: University of California, Davis

In total it is estimated that roughly 27,000 ventilation cooling units may be installed in California homes in the next 10 years, though given current market conditions only this 0.4 percent of homes would be technically feasible candidates. The bulk of that demand would come from pre-2010 homes in the "best" climate zones where it is expected that 0.5 percent of homes will adopt a ventilation cooling technology to supplement their kitchen and bathroom fans (which provide inferior ventilation and no cooling benefits). Much less demand is expected in new homes where some builders continue to offer ventilation cooling to their customers as an upgrade option. In those cases, demand is expected to be higher among the small fraction of homes without air conditioning (4 percent adoption in the "best" climate zones) compared with those with air conditioning (2 percent adoption in the "best" climate zones in homes with ducts). Detailed assumptions and calculations are available, upon request from the Western Cooling Efficiency Center, and are in a separate (Excel) file.

Adoption rates were estimated based on input gathered from industry interviews. Experts noted that very low adoption rates (2 percent) have been observed for efficiency or ventilation technologies that were not heavily incentivized by building codes or utility rebate programs, even when builders encouraged them. Adoption rates in the retrofit market are expected to be even lower (0-0.5 percent) because there are virtually no HVAC installers that currently offer ventilation cooling options like NightBreeze or SRV. Thus, with cheaper, more convenient, and more familiar alternatives for "free cooling" and ventilation, ventilation cooling technologies will face stiff competition in both existing and new home markets.

Outlook

From the market potential estimates just described, it is clear that there exists a large gap between the technical potential for ventilation cooling and its market potential. To gain traction, policies have to change. As one industry expert put it, “Title 24 and utility rebates drive everything that’s going into a home when it comes to energy efficiency.” Ventilation cooling technologies will only be widely adopted when there are incentives for both builders and customers.

In addition, the technologies themselves need to be market-ready: code compliant, universally compatible, and commercially available. For NightBreeze, the former would require adjusting the algorithm to ensure that the technology delivers code-compliant ventilation year-round; it is currently considered to be a code-compliant strategy only in winter. More generally, control algorithms for ventilation cooling technologies need to defer to ventilation when setting priorities, optimizing space conditioning only when ventilation requirements have been met. This would be necessary to ensure code-compliant performance.

The interviews stressed the importance of ventilation cooling’s compatibility with a range of equipment that builders or installers may want to integrate it with, including various types of heating equipment and thermostats. While the field-tested versions of NightBreeze and SRV both had dedicated controllers, for market appeal it is important that the technologies be compatible with many types so that builders and homeowners can choose what they prefer.

Finally, it is worth noting that NightBreeze, SRV, and the other ventilation cooling technologies would need to have their manufacturing and distribution channels well established and reliable to be market ready. This is not a trivial matter as both those tested have experienced supply problems in these areas over the last several years.

Coastal areas of California where air conditioning is uncommon have experienced record high temperatures over the last few summers. Demand for air conditioning is growing in these areas, and unless customers are diverted to other cooling approaches, peak load will rise. Ventilation cooling could provide an attractive mitigation for this concern. In fact, as the developer of the NightBreeze said, “The original intent was to stop the march of air conditioners from the coast inland because coastal areas don’t really need A/C except for a few days per year.” Customers looking for a low-energy cooling option could be a promising niche market for these technologies. Utilities and the California Independent System Operator would both benefit from reliable peak-load management.

Another interesting trend is poised to align with ventilation cooling. The move towards decarbonization invites a more holistic approach to building systems. This could bode well for ventilation cooling, which now struggles because it does not fit neatly into either ventilation or “free cooling” boxes. Related to this is the notion that thermostats may evolve to become a hub for thermal comfort and air quality. Ventilation cooling technologies would dovetail into that approach very well since they are already designed to work with a home’s HVAC system while providing both ventilation air and thermal comfort benefits.

Three key recommendations emerged from research on the market potential for ventilation cooling. First, a certification process for hard-to-test dynamic ventilation technologies would be beneficial for market adoption. Currently, the hurdles involved in verifying complex ventilation systems pose a significant barrier to adoption by builders.

Second, incentive programs that encourage adoption of ventilation cooling technologies could have a large impact on market acceptance. For example, direct-install programs that provide ventilation cooling to low-income households without air conditioning would offer a triple benefit: healthier and more comfortable homes, relatively low utility bills, and peak load management. Rebates or direct-install programs in areas where air conditioning is prevalent could reduce peak loads and customers' electricity bills. Each of these outcomes aligns with the priorities of California's utilities and the California Independent System Operator.

Third, a more dynamic and holistic approach to ventilation would be beneficial. Several experts noted that policymaking on energy and air quality silos has resulted in building codes that do not adequately address tradeoffs. They note, for example, that while dominant ventilation strategies such as exhaust fans easily meet codes, little is actually known about their effectiveness, especially since they can be, and often are, disabled by occupants. Further research is required to understand how much ventilation is required to manage CO_2 and other indoor air pollutants. Some speculate that there is potential to reduce fan energy with a combination of air-quality monitoring (made possible by relatively low-cost sensors) and aggressive filtration. More research is needed to inform potential changes to ventilation requirements and achieve a better, more verifiable balance between energy and air quality. Credits for ventilation cooling could then be more properly calibrated to reflect their contribution to the holistic goals of indoor health and comfort.

CHAPTER 5: Conclusions and Recommendations

This project evaluated two energy-efficient retrofit packages on two existing homes in Davis, California. The packages included building-envelope sealing, mechanical ventilation, and a sub-wet bulb evaporative chiller (SWEC). These technologies all represent emerging technologies that currently have limited applications in actual buildings. Without evaluating their installed performance, they are unlikely to gain significant market share. This project helped identify both the benefits of these retrofit technologies and the barriers the technologies must overcome to expand into the commercial market.

The aerosol-sealing portion of the retrofit was completed successfully, reducing leakage in the West Home by 37 percent and in the East House by 64 percent. This process incurred additional costs from temporarily displacing tenants and their belongings, which could be avoided by sealing during periods between tenants. This notable increase in the amount of preparation time required for existing buildings, compared with new construction, was unavoidable but could be streamlined with more experience.

Neither home had an installed ventilation system. Both had range fans above the kitchen stove, but both occupants reported not using them because they were recirculating fans that were not vented to the outdoors. The measured indoor CO_2 and $PM_{2.5}$ values after the ventilation systems were installed resulted in values below regulatory levels. It is clear that these ventilation systems improved indoor air quality compared with the baseline, which had no ventilation equipment.

The installed ventilation system provided controls for ventilation flows based on outdoor-air conditions and ventilation requirements. Both retrofit mechanical ventilation systems provided more efficient cooling than standard air conditioners when outdoor-air temperatures were cooler, which both systems capitalized on with their corresponding algorithms and controllers. Next steps with the SRV system would require further refinement of the controller, as well as its integration with a thermostat that feeds outdoor ambient conditions to the SRV controller.

As an emerging product, the NightBreeze system demonstrated its efficacy with a higher air-flow capacity range for daily power consumption (~140 W for NightBreeze vs. ~4 W for SRV) since the NightBreeze system prioritizes cooling performance; SRV is designed primarily to meet whole-building ventilation requirements as efficiently as possible. This distinction creates significant differences in daily ventilation, ventilation loads introduced to the buildings, and energy consumption.

While the overall field performance of the retrofit cooling systems was lower than expected, the systems used less energy than the baseline and maintained relatively constant energy use in both homes with increasing outdoor-air temperatures. The capacity, however, was limited by the air-side distribution systems. The SWEC in the East Home, with a central-coil design, achieved higher cooling capacity than the West Home, which used distributed fan coils. Evaluating the results showed that the control scheme for both systems could be improved.

The SWEC lab testing showed that for Stage 1 cooling (evaporative only), the most beneficial water-flow rate was the medium setting of 3.5 gallons per minute (GPM). Depending on outdoor conditions, the most beneficial exhaust air-flow rate was at the higher settings of 1,100 or 1,500 RPM, respectively. These operating conditions provided the best balance of cooling capacities, coefficients of performance (COPs), and chilled water temperatures. For Stage 2 cooling (compressor), testing showed that high-water flow rates and high air-flow rates seemed to be the best operating conditions for all outdoor conditions tested. In the field evaluation, there were no controls for varying the speed of the SWEC to optimize performance. The system was instead set to the highest setting to prioritize cooling capacity since there was concern about meeting existing loads in the building.

Lab and field results used to validate the computer model further refined the SWEC design, including resizing the internal heat exchangers and the water- and air-flow rates. The two highest-cooling capacities were achieved with the optimized SWEC, using the MPHX fan coil, with the lower water-flow rate (3 GPM), which yielded the highest capacity. In some cases, the capacity was more than double what was observed in the field trials. The optimized SWEC in Stage 1 further achieved similar capacity to the original SWEC design in Stage 2. The hybrid SWEC designs showed substantial performance improvements over the system demonstrated in the field trials (with COPs in Stage 1 ranging between 6-14 and COPs in Stage 2 ranging between 2.5-5). The Stage 2 COP range is similar to the standard vapor-compression-cooling equipment used in residential buildings, which shows that the primary advantage of the SWEC system is when it operates in Stage 1 and achieves very high efficiencies.

Energy modeling for the optimized SWEC design, when operating both as a distributed system and as a central system, was performed to assess energy savings across California’s climate zones. The results showed that, when operating as a distributed system, the SWEC had no efficiency benefits over the central system. However, both the distributed and central systems showed significant performance improvements over the baseline air conditioner with 44 percent cooling-energy savings in California Climate Zone 12. While the two systems performed similarly, distributed fan coils provided greater comfort by tailoring cooling to particular zones in the house. By setting thermostat schedules according to occupancy in certain zones, it was possible to reduce cooling in unoccupied zones by setting higher thermostat set points. For example, the house can be split into sleeping zones and family zones where the set point for sleeping zones can be increased during the day and decreased at night. Another benefit of the distributed fan coil system is that these systems typically do not require ducts. This has implications for both fan power and thermal losses through duct walls. Neither of these impacts was modeled for this report but should be considered when choosing a thermal distribution system.

Two of the technologies evaluated in this project ─building-envelope aerosol sealing and ventilation cooling ─improved air quality in the homes. However, their paths to broad market acceptance remain uncertain. AeroBarrier is currently offered by only a few providers throughout California and few home builders are even aware of it. Under current market conditions, AeroBarrier’s penetration is expected to grow very slowly, in tandem with the organic growth capacity of the manufacturer itself. Ventilation cooling technologies, including the NightBreeze and SRV tested for this project, are in a slightly different position. The few products in this category that are both commercially available (excluding NightBreeze and the SRV) and code compliant could potentially be adopted by home builders and HVAC installers who promote them with their customers. However, as expressed in interviews with builders and others, that scenario seems unlikely given that cheaper, easier, and more familiar alternatives exist.

While the approach for building-envelope aerosol sealing and ventilation cooling proved successful, project results strongly suggest that both technologies are best suited for new construction. There are practical challenges in retrofitting existing homes that new construction avoids. The structure of the HVAC market is also such that both technologies would likely find easier paths to market with new construction. This is not to say that the technologies are inappropriate for retrofits, but simply that with existing market barriers only the most promising paths should be considered.

Turning then to new construction, adoption of technologies that both improve building energy efficiency and indoor air quality are nearly always driven by code. Builders face increasing pressure to make homes more efficient while controlling costs. As a result, they have little flexibility to install technologies that require greater investments of time or money. These constraints further tighten in times of economic uncertainty.

Policymakers have powerful tools to incentivize adoption of building-envelope sealing and ventilation cooling. Developing a certification process for ventilation cooling products would make their verification easier. Providing rebates or direct-install programs would reduce costs for consumers. Finally, using a holistic approach for calculating energy savings that offers significant energy credits for building-envelope sealing and ventilation cooling, as well as for other building energy-efficiency technologies, could make them more cost-effective. Greater demand would drive down prices, improve cost-effectiveness and adoption, save energy, reduce peak electric loads, and improve both occupant comfort and indoor air quality.

CHAPTER 6:
Benefits to Ratepayers

The goal of this project was to evaluate potential energy savings for two retrofit packages in existing California homes. Single-family homes make up over 10 million of the buildings in California, nearly half of which were built before 1970. Retrofit packages like the ones evaluated in this project could potentially upgrade a large percentage of homes across the state. They would increase energy savings with more efficient equipment and increase indoor air quality with improved ventilation and tighter building envelopes.

Indoor Air Quality

Indoor air quality can be improved through better filtration, tighter sealing of the building shell, and increased ventilation of filtered air. Indoor pollutants that adversely affect respiratory health include particulate matter, oxides of nitrogen, volatile organic compounds, and ozone. Two technologies evaluated in this project improved indoor air quality in homes: aerosol envelope sealing and ventilation. While aerosol sealing the building envelope can decrease unwanted outdoor pollutants from entering a home, ventilation is also needed to bring in fresh outside air. By combining building envelope sealing and mechanical ventilation that meet Title 24 requirements, air quality in existing homes across California can be significantly improved. Once the homes in this project were retrofitted with both sealing and ventilation systems, indoor CO_2 levels fell substantially to near outdoor levels (typically in the 400-500 ppm range). Particulate matter levels were also reduced in both homes after sealing and ventilation. With California wildfires increasing each year, envelope sealing technology and ventilation filtration systems are excellent solutions for improving indoor air quality.

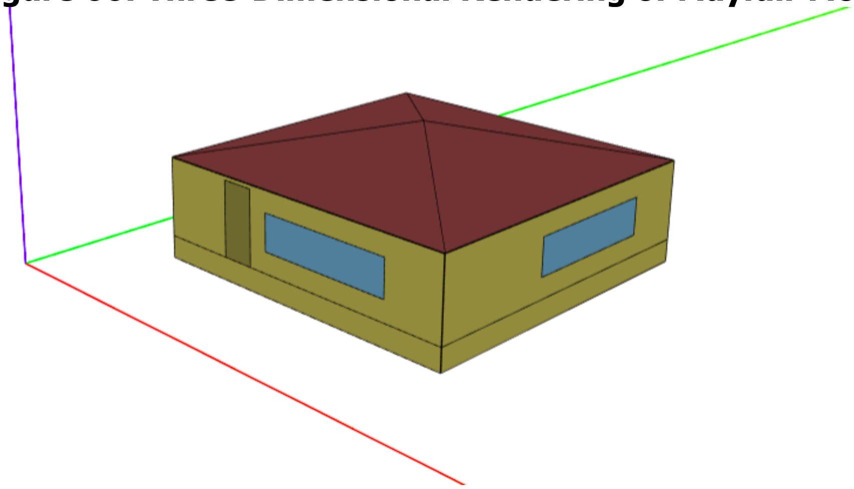
Energy Savings

While field measurements showed that SWEC performance was lower than expected, lab results showed energy-saving potential by replacing older homes' less efficient air conditioners with evaporative chillers. The most notable finding from the lab tests showed that by reducing fan and pump speeds, the SWEC provided cooling with lower power consumption and a higher coefficient of performance (COP) than what was observed in the field testing. The lab tests were also essential for calibrating a SWEC model paired with a whole-building energy simulation software (EnergyPlus) program to determine the overall potential of an optimized SWEC system in each of California's 16 climate zones. The following describes two house simulations used to illustrate energy savings from the optimized SWEC system.

Sub Wet-Bulb Evaporative Chiller Central System Performance Modeling for a Smaller House

To assess the benefits of the optimized SWEC for residential customers, cooling loads for a smaller single-family home (872 ft^2) were created in EnergyPlus (Figure 66). The model was simulated in each of the 16 California climate zones to generate annual cooling loads for different climate conditions around California.[15]

Figure 66: Three-Dimensional Rendering of Mayfair Model



Rendering of smaller house model used to evaluate energy savings in each California climate zone.

Source: University of California, Davis

The model's baseline air conditioning system was based on performance data from a seasonal energy-efficiency ratio (SEER) 14 unit. Performance data included the supply air-flow rate, capacity, sensible heat ratio, and power draw of the unit (Goodman Model: GSX140181), at the rated condition input for the modeled DX system. The default EnergyPlus curves scaled capacity and the EER across different outdoor-air conditions. The system capacity and air flow were auto-sized for each climate zone, with a 1.25 cooling-scaling factor.

The modeled performance of the baseline air conditioner was then compared with the performance of the hybrid SWEC system. The optimized hybrid SWEC, coupled with a central MPHX fan coil, was used for the analysis. The central MPHX fan coil had similar dimensions to the central fan coil applied in the East House field test, which measured 24″x 21″x 10.″ Stage 1 was modeled with the 5.2 gpm water-flow rate, while Stage 2 was modeled with the 3 gpm water-flow rate. Since the SWEC tends to provide higher air temperatures and is unlikely to provide large, latent cooling, only sensible cooling loads were modeled. Baseline system energy use was adjusted by multiplying by the sensible heat ratio (ratio of sensible cooling to total cooling) to account for the sensible portion of the load. The hybrid SWEC was then simulated using the loads for the smaller house, along with associated climate data and indoor air conditions. Figure 67 shows the percentage of cooling energy savings and associated electricity cost savings for the hybrid SWEC system when compared with the baseline system. Electricity cost savings were based on $0.18/kWh energy cost. Note that California Climate Zone 1 is not included due to negligible cooling loads in that zone.

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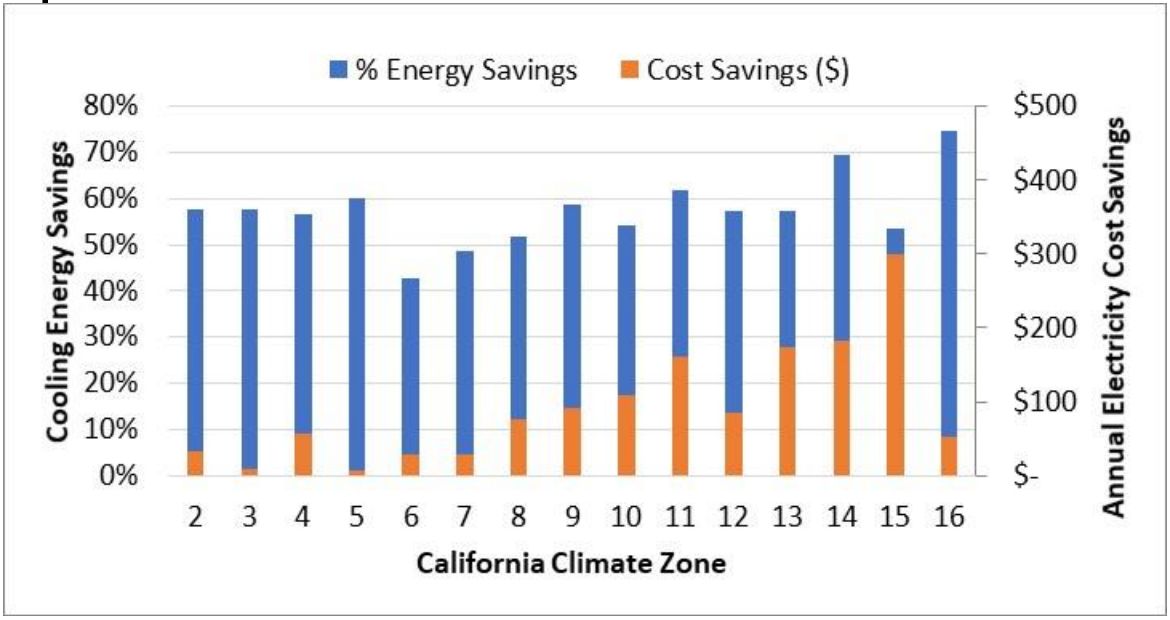
[15] California Climate Zone 1 showed negligible cooling loads so was omitted from the analysis.

Figure 67: Cooling Energy and Electricity Cost Savings for the Hybrid Sub Wet-Bulb Evaporative Chiller Versus the Baseline Air Conditioner for a Smaller House



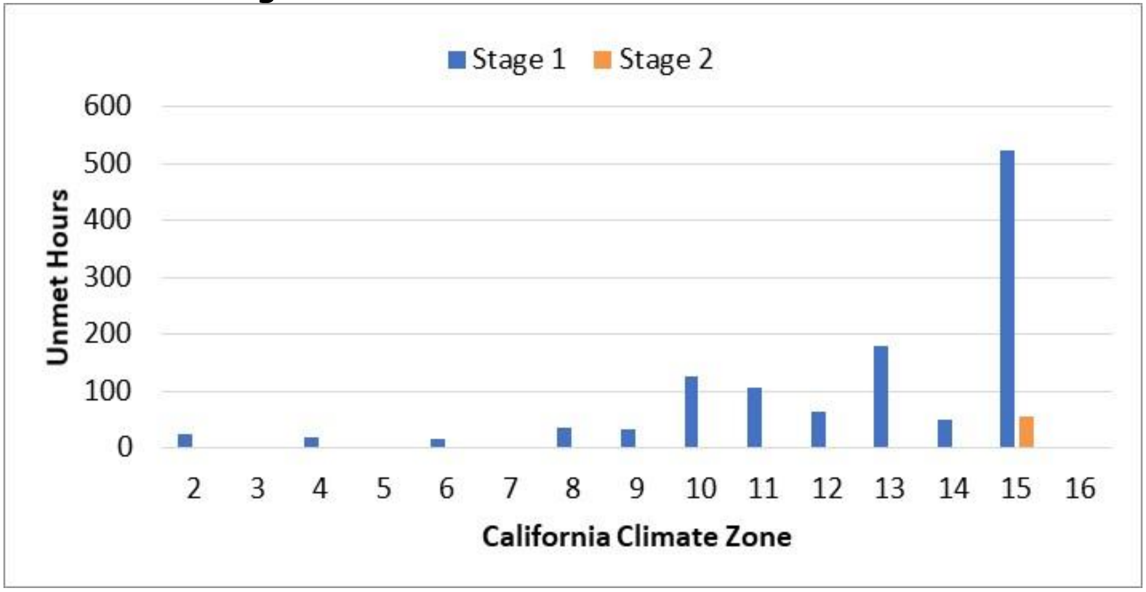
Assuming $0.18/kilowatt-hour electricity cost.

Source: University of California, Davis

The energy savings potential for the optimized hybrid SWEC were significant, with average savings of 57 percent across all climate zones simulated. Cost savings of cooling loads in each zone can be relatively small in some of the cooler climate zones. Climate Zone 15 had the highest electricity cost savings at $299 per year while Climate Zone 5 saved only $8 per year. The lowest percent energy savings were in zones 6, 7, and 8, which are all coastal climates. The highest percent energy savings were in more arid climates, including zones 14, 15, and 16.

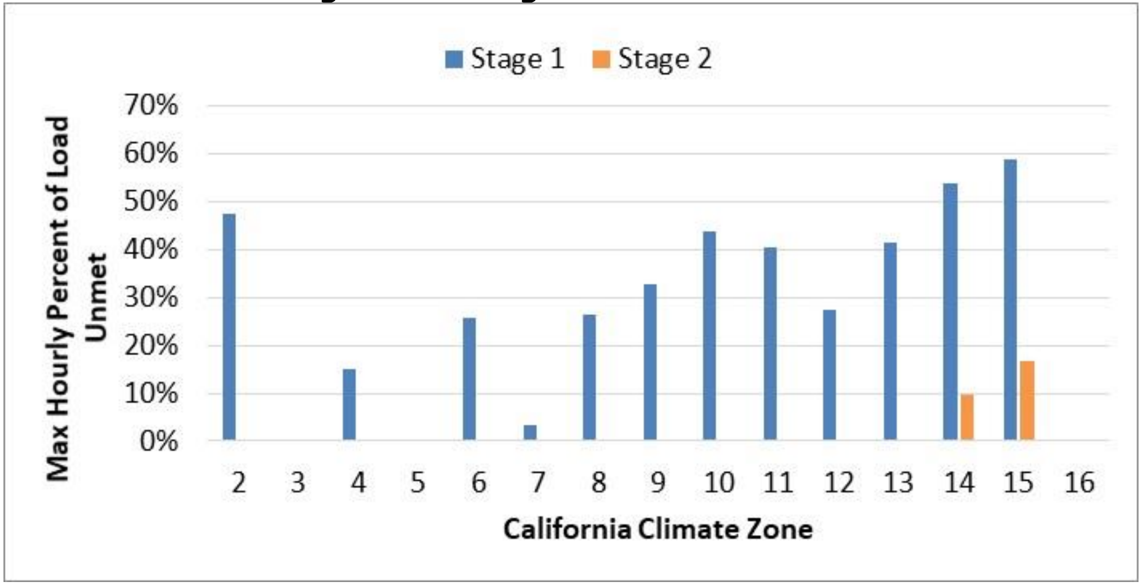
Because the same building was simulated in each of California's 16 climate zones, the capacity for the optimized hybrid SWEC system was oversized in many cases. The results showed that the optimized SWEC in Stage 1 easily met the load in a majority of the climate zones, but Stage 2 was required in Climate Zone 15. Figure 68 and 69 show both the number of unmet hours and the maximum unmet load during a single hour of simulation.

Figure 68: Unmet Hours for a Hybrid Sub Wet-Bulb Evaporative Chiller in Stage 1 and Stage 2 for a Smaller House for Each Climate Zone



Source: University of California, Davis

Figure 69: Maximum Hourly Percent of Load Unmet for Hybrid Sub Wet-Bulb Evaporative Chiller in Stage 1 and Stage 2 for Smaller House in Each Climate Zone



Source: University of California, Davis

ASHRAE 90.1 provides guidance on an acceptable number of unmet hours, by a system. This standard is for non-residential building but was used to determine an allowable number of unmet hours for a system. Typically, systems are sized based on a design day that does not consider the worst case; some unmet hours are acceptable for a system. Based on the ASHRAE 90.1 recommendation of reducing unmet hours to below 300, the optimized SWEC in Stage 1 can achieve the necessary capacity for all climate zones except Climate Zone 15. During peak conditions in Climate Zone 15, the maximum percent load that was unmet for a single hour in Stage 1 was 59 percent, whereas in Stage 2 this drops to 17 percent. Removing the hybrid vapor-compression function would significantly reduce peak power draw for the system, reduce the overall cost of the system, and remove the need for refrigerants.

Table 17 presents the summary of results for the optimized hybrid SWEC modeling when compared with the baseline air conditioning system for a smaller house.

Table 17: Results Summary for an Optimized Hybrid Sub Wet-Bulb Evaporative Chiller and a Baseline Air Conditioner for a Smaller House

Climate Zone	Annual Cooling Energy Use		% Energy Savings	Cost Savings ($)	Unmet Hours		Max % Load Unmet	
	Hybrid SWEC (kWh)	Baseline (kWh)			Stage 1	Stage 2	Stage 1	Stage 2
2	137	324	58%	$ 33.68	23	0	47%	0%
3	33	77	58%	$ 7.99	0	0	0%	0%
4	236	546	57%	$ 55.76	18	0	15%	0%
5	28	71	60%	$7.75	0	0	0%	0%
6	220	384	43%	$ 29.51	15	0	26%	0%
7	167	325	49%	$ 28.44	1	0	3%	0%
8	391	813	52%	$ 75.84	35	0	26%	0%
9	357	863	59%	$ 91.17	32	0	33%	0%
10	507	1108	54%	$ 108.21	126	0	44%	0%
11	556	1453	62%	$ 161.46	106	0	40%	0%
12	353	826	57%	$ 85.27	65	0	27%	0%
13	724	1691	57%	$ 174.02	180	0	41%	0%
14	445	1461	70%	$ 182.85	51	2	54%	10%
15	1443	3105	54%	$ 299.06	523	56	59%	17%
16	98	389	75%	$ 52.32	0	0	0%	0%

Source: University of California, Davis

Sub Wet-Bulb Evaporative Chiller Central System Performance Modeling for a Larger House

The previous section shows the results for the optimized SWEC system when compared with a baseline 14 SEER air conditioner for a relatively small home in each of California's climate zones. The hybrid SWEC system was in many cases oversized relative to house cooling loads, and in 14 of the 16 climate zones the hybrid function of the SWEC refrigeration system was not required. To further evaluate the hybrid SWEC system for a larger house, a two-story home was simulated using EnergyPlus for a scenario where the hybrid system was appropriately sized for the cooling loads. The model represents a new construction single-family home (2,400 ft^2) with a 2019 Title 24-compliant building envelope. This model was a modified version of the residential prototype developed by Pacific Northwest National Laboratory (PNNL), shown in Figure 70.[16]

The same baseline air conditioning system (SEER 14 Goodman Model: GSX140181) and sizing process just described for the smaller house was also used in simulations for the larger house. Similarly, the same SWEC system modeled for the smaller house was used again and consisted

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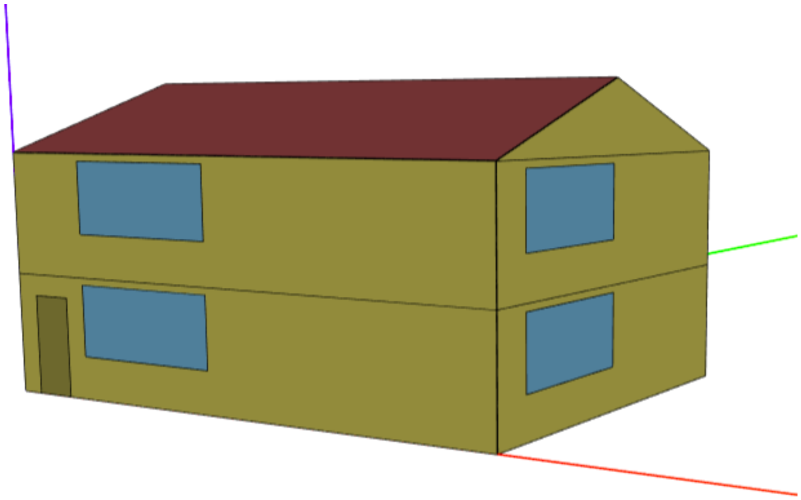
[16] US Department of Energy, "PNNL Residential Prototype Building Models," 2018. [Online]. Available: https://www.energycodes.gov/development/residential/iecc_models.

of the optimized SWEC, coupled with a central MPHX fan coil with Stage 1 operating at a 5.2 gpm water-flow rate, and Stage 2 operating at a 3 gpm water-flow rate. The SWEC fan-flow rate was fixed at 1,100 CFM for Stage 1 and increased to 1,800 CFM for Stage 2.

Figure 70: Larger House Model Used to Evaluate Energy Savings in Each California Climate Zone

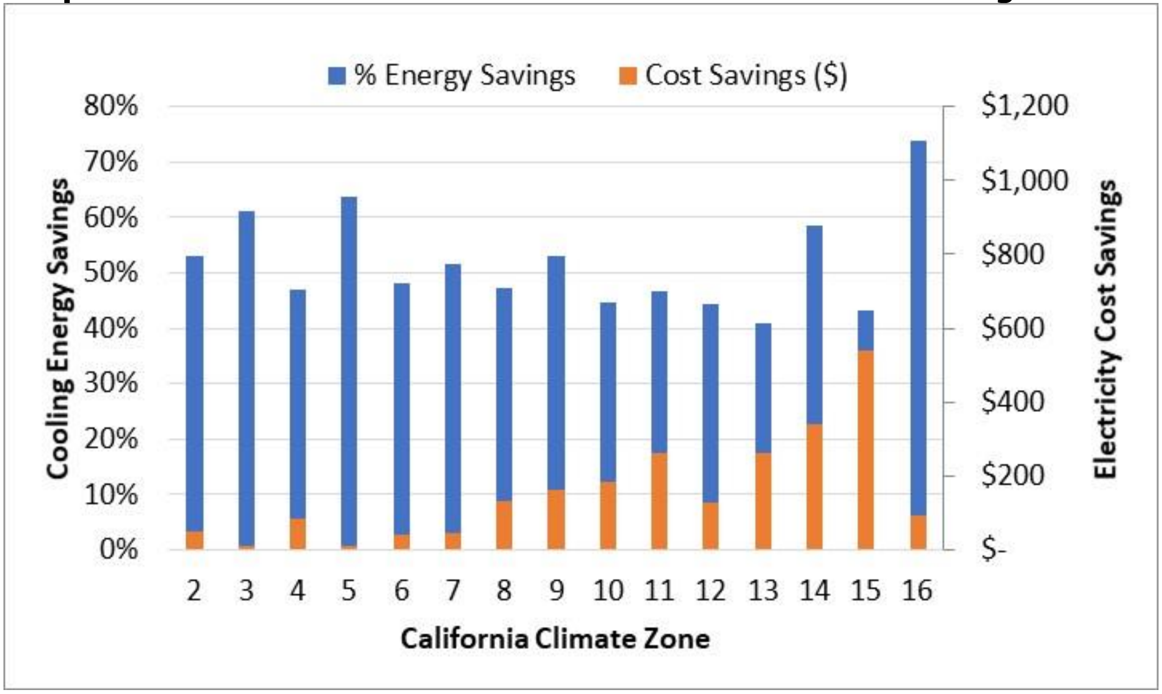


Source: University of California, Davis

Figure 71 shows both the cooling energy and electricity cost savings for each California climate zone. Again, Climate Zone 1 was omitted due to a lack of cooling loads. The average air conditioning energy-use savings were 52 percent over the baseline. The percent savings were slightly lower than results for the small house due to the amount of time the system operated in Stage 2; however, the annual electricity cost savings were on average 59 percent higher than the smaller house due to higher cooling loads.

The cooling loads for the larger house were more appropriate for the hybrid SWEC capacity, with a high number of hours required for Stage 2 operation. Figure 72 and 73 show both the number of unmet hours and the magnitude of the maximum unmet load for a single hour during the simulation.

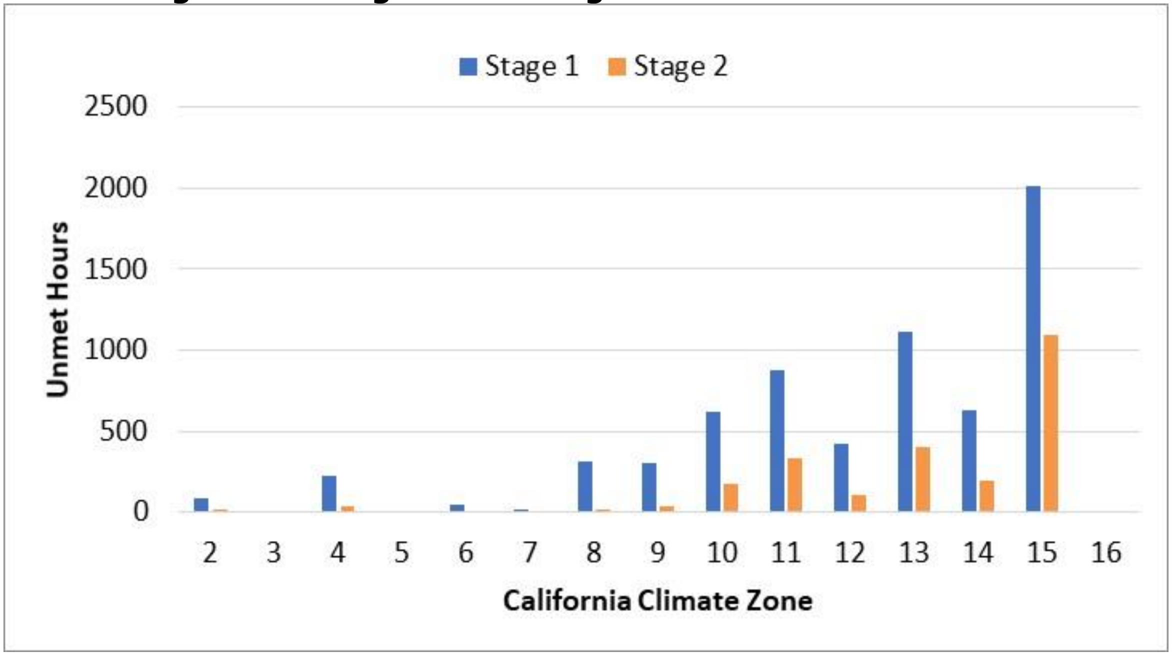
Figure 71: Cooling Energy and Electricity-Cost Savings for a Hybrid Sub Wet-Bulb Evaporative Chiller Versus a Baseline Air Conditioner for a Larger House



Assuming $0.18/kWh electricity cost.

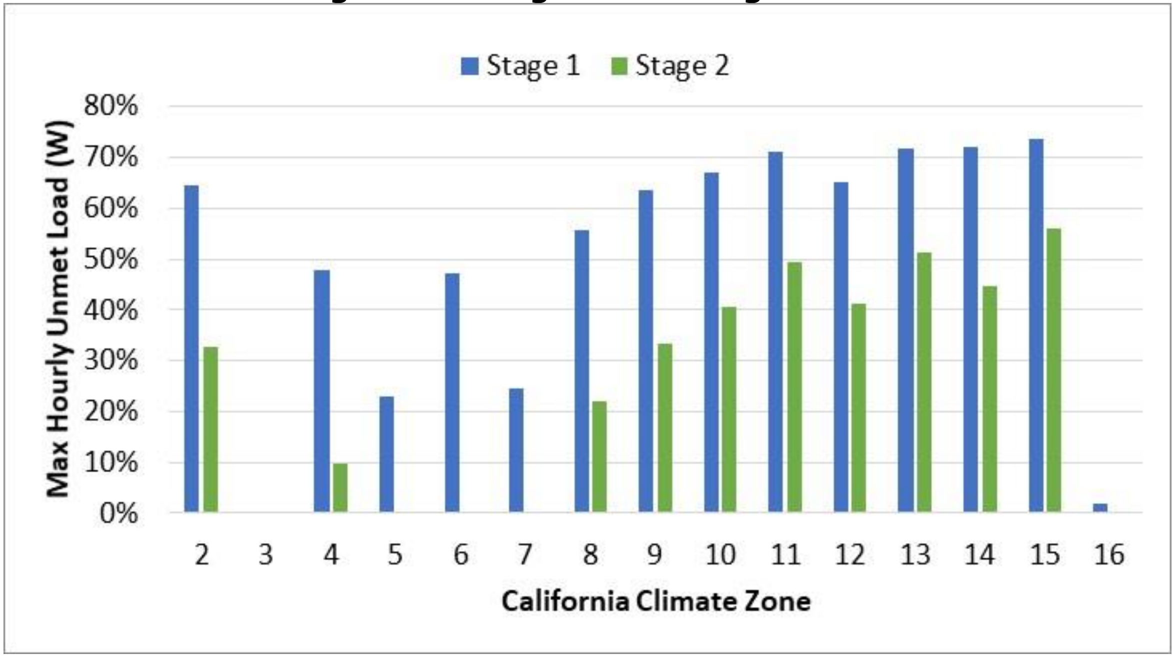
Source: University of California, Davis

Figure 72: Number of Unmet Hours for a Hybrid Sub Wet-Bulb Evaporative Chiller in Stage 1 and Stage 2 for a Larger House in Each Climate Zone



Source: University of California, Davis

Figure 73: Maximum Hourly Percent of Load Unmet for a Hybrid Sub Wet-Bulb Evaporative Chiller in Stage 1 and Stage 2 for a Larger House in Each Climate Zone



Source: University of California, Davis

Based on ASHRAE 90.1 guidance allowing up to 300 unmet hours, the results show that the hybrid SWEC can meet loads in all but three of the climate zones simulated. The hotter Central Valley climate zones 11 and 13 show the capacity of the optimized hybrid SWEC to be slightly too small to comfortably meet the loads, in contrast to Climate Zone 15, which had over 1,000 unmet hours throughout the year. The maximum-percent load that was unmet for a single hour in Stage 2 was about 50 percent in zones 11 and 13, and 56 percent in Climate Zone 15. The hybrid SWEC can be scaled up to meet loads in Climate Zone 15 by increasing the height of the evaporative medium pad by a few inches or increasing the capacity of the vapor-compression system.

Table 18 summarizes results for the optimized hybrid SWEC modeling when compared with the baseline air conditioning system for the larger house.

Table 18: Results for Optimized Hybrid Sub Wet-Bulb Evaporative Chiller and Baseline Air Conditioner Modeling for Larger House

Climate Zone	Annual Cooling Energy Use		% Energy Savings	Cost Savings ($)	Unmet Hours		Max % Load Unmet	
	Hybrid SWEC (kWh)	Baseline (kWh)			Stage 1	Stage 2	Stage 1	Stage 2
2	246	525	53%	$ 50.16	82	15	65%	33%
3	35	89	61%	$ 9.81	0	0	0%	0%
4	519	980	47%	$ 82.96	224	40	48%	10%
5	32	88	64%	$ 10.08	3	0	23%	0%
6	253	489	48%	$ 42.43	47	0	47%	0%
7	237	491	52%	$ 45.71	13	0	25%	0%
8	819	1,557	47%	$ 132.78	310	20	56%	22%
9	807	1,713	53%	$ 163.07	307	33	63%	33%
10	1,,256	2,272	45%	$ 182.89	616	174	67%	41%
11	1679	3,140	47%	$ 262.98	877	331	71%	49%
12	870	1,567	44%	$ 125.49	420	105	65%	41%
13	2,078	3,522	41%	$ 259.88	1,,111	399	72%	51%
14	1,352	3,250	58%	$ 341.64	632	193	72%	45%
15	3,963	6,961	43%	$ 539.62	2010	1,091	74%	56%
16	180	686	74%	$ 91.01	2	0	2%	0%

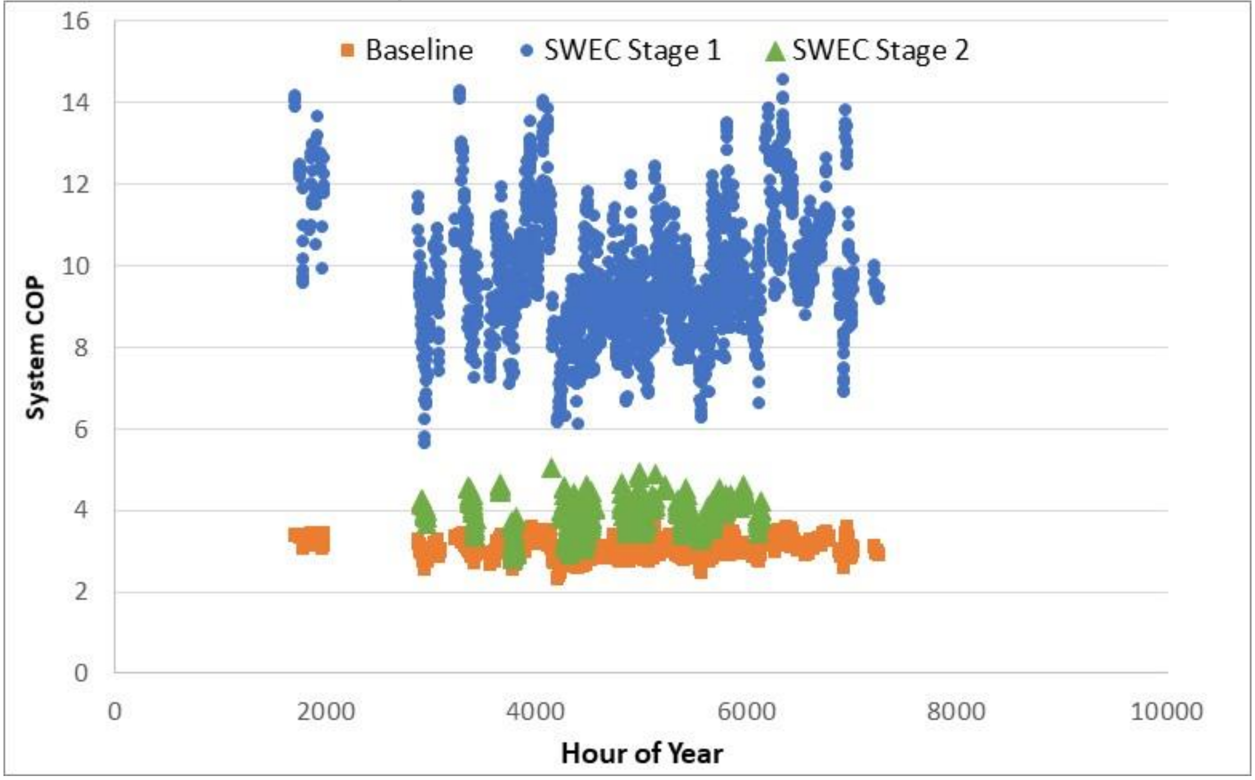
Source: University of California, Davis

To better understand the efficiency of the SWEC system when compared with the baseline, the efficiency for each hour of the simulation for Climate Zone 12 was compared in Figure 74. The plot shows a wide variation in SWEC Stage 1 efficiency throughout the year, where the baseline and SWEC Stage 2 show a much more consistent efficiency. When looking at the same data plotted against outdoor wet-bulb temperature, the relationship between outdoor moisture levels and SWEC Stage 1 performance becomes clearer, as shown in Figure 75. The SWEC in Stage 1 performs at much higher efficiencies when outdoor wet-bulb temperatures are lowest (with COPs of 14), while at the highest wet-bulb temperatures the COP drops to 6. Similarly, the efficiency of SWEC Stage 2 also shows a dependence on wet-bulb temperatures with a noticeable, albeit shallower, downward slope as wet-bulb temperature increases. The efficiency of the baseline system shows very little dependence on outdoor wet-bulb temperatures. The stronger dependence of the SWEC Stage 2 upon the wet-bulb temperature, when compared with the baseline system, was due to the fact that the condenser in the SWEC Stage 2 unit was cooled by moist air exiting the SWEC heat exchangers.

Outdoor wet-bulb temperatures fluctuate throughout the day as dry-bulb temperatures change, which is why the SWEC efficiency varies so much when plotted against time. Wet-bulb temperatures are generally highest during the hottest part of the day and lowest when temperatures are cooler. Figure 75 shows that Stage 2 of the SWEC is needed when wet-bulb temperatures are highest, with no Stage 1 operation above 69°F. The impact on COP is directly related to capacity in Stage 1 since the power draw from the SWEC fan and water pump is basically constant in that mode. Therefore, Stage 2 is needed in the larger house in

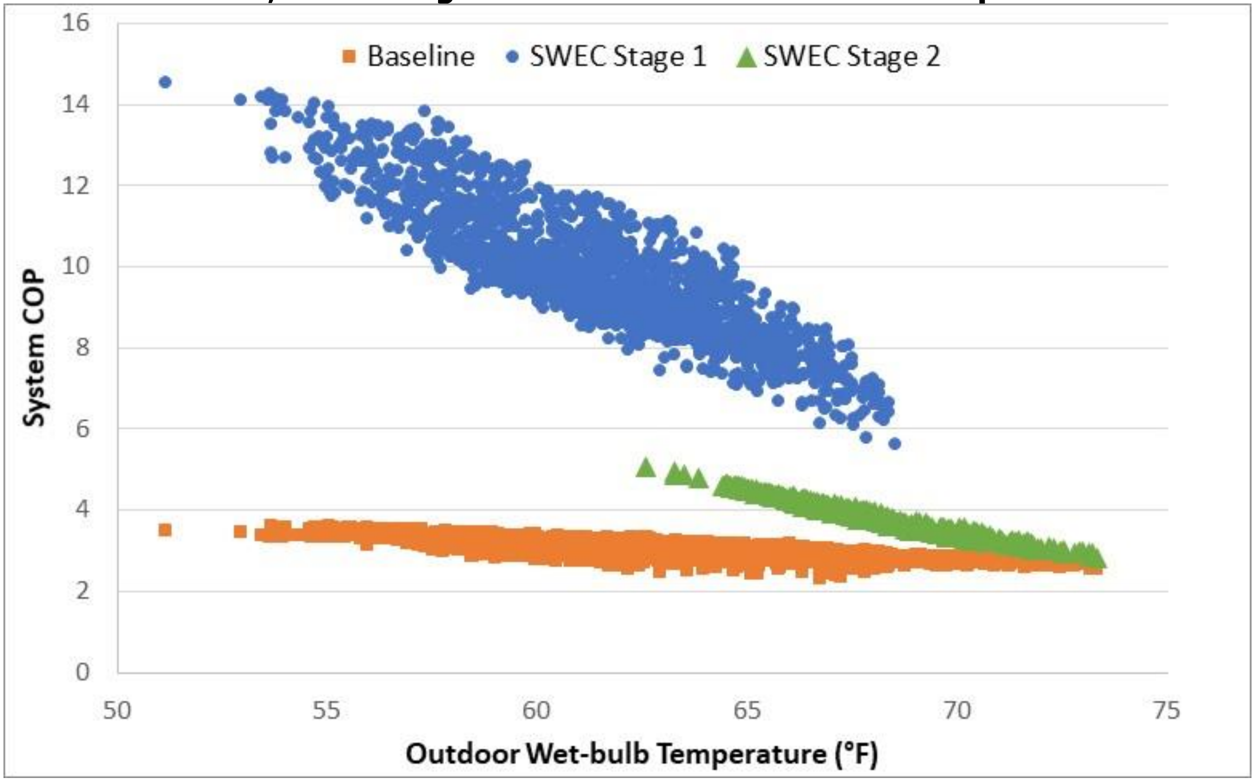
Climate Zone 12 when outdoor temperatures are highest not only to meet the largest loads in the building but also because of the reduced capacity of the SWEC in Stage 1.

Figure 74: Efficiency Comparison for Baseline System Versus a Sub Wet-Bulb Evaporative Chiller in Stage 1 and Stage 2 for a Larger House in California Climate Zone 12, Plotted for Each Hour of Simulation



Source: University of California, Davis

Figure 75: Efficiency Comparison for a Baseline System Versus a Sub Wet-Bulb Evaporative Chiller in Stage 1 and Stage 2 for a Larger House in California Climate Zone 12, Plotted Against the Outdoor Wet-Bulb Temperature



Source: University of California, Davis

Distributed Fan Coil System Performance in Climate Zone 12

The previous analysis considered the central fan coil application of the SWEC. The field testing evaluated both central and distributed systems, so this section considers optimization strategies for a distributed fan coil system in Climate Zone 12. The larger house model just described was split into four zones, two on the top floor and two on the bottom floor. This was similar to the setup at the West Home, which had five fan coil units. The thermostat schedule for the EnergyPlus model was identical for each of the four zones to limit differences in the total building loads between the central and distributed models. Each of the four fan coils modeled was MPHX and about one-quarter the size of the central coil, which measured 12” x 10” x 10” and operated at 212 CFM.

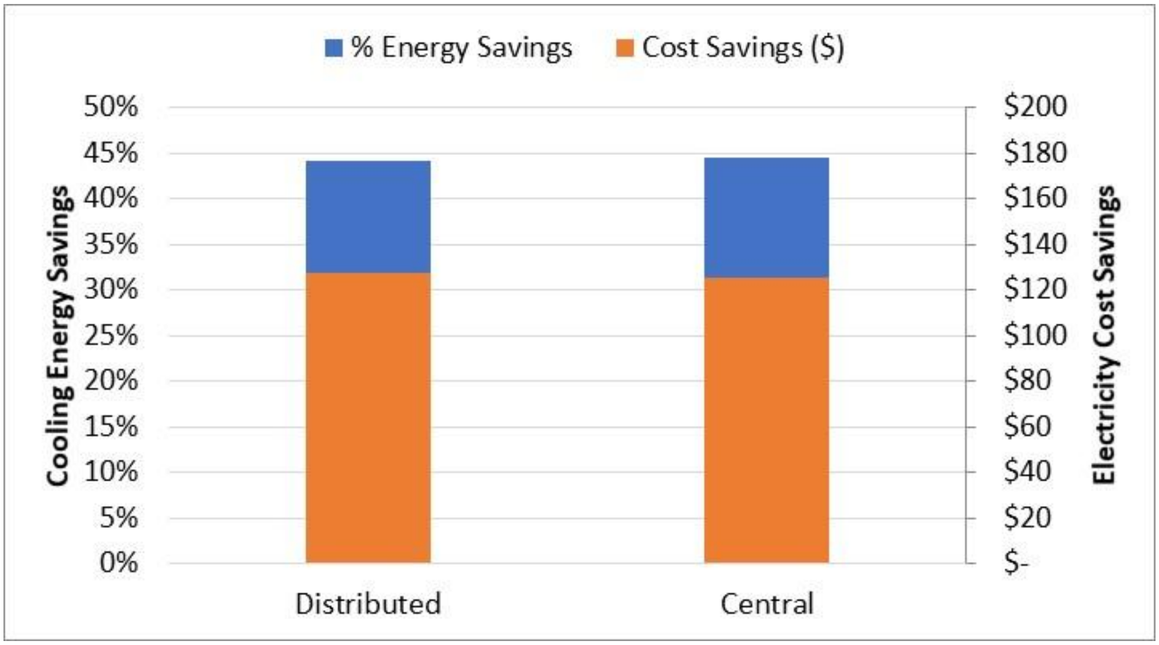
The SWEC controls were set up so that each individual coil had a valve that would open when cooling was requested, allowing chilled water to flow to that coil. For Stage 1, the SWEC pump and exhaust fan were variable speed and would step up or down depending on the number of coils requesting chilled water, with a maximum flow of 5.2 gpm and maximum SWEC fan flow rate of 1,100 cfm. This differed from the field test, which did not control the varying speed of the SWEC components and lacked the ability to turn the water flow on and off to individual fan coils.

Since the SWEC Stage 2 utilizes the compressor system, reducing water flow through the evaporator can lead to freezing of the coil; therefore, the SWEC only operated in Stage 2 at optimized pump and exhaust-fan flows (3 gpm and 1,800 cfm), with water distributed to all coils. While chilled water was delivered to each coil, the fan only operated when cooling was required for that zone, so no cooling was delivered to zones without any load. It turned out that for Climate Zone 12, SWEC Stage 2 was only needed during periods of higher load when all zones had some cooling demand.

The loads in each zone differed slightly from hour to hour. To avoid over-cooling the zones, the average cooling demand for all active zones during each time step was distributed evenly to each active zone. This allowed both the baseline and SWEC systems to deliver an equivalent load throughout the year. In an actual application, the zones would turn on and off more frequently to maintain comfort in each zone.

Figure 76 shows the percentage of cooling energy savings and associated electricity cost savings for both the distributed fan coil system and the central fan coil system in California Climate Zone 12. Note that the loads were slightly different for the two baseline models, as well as about 2 percent higher for the distributed baseline when compared with the central baseline. The results were similar, with 44 percent energy savings over the baseline air conditioning system. There appeared to be no significant impact when operating the SWEC with distributed fan coils when compared with a single central fan coil.

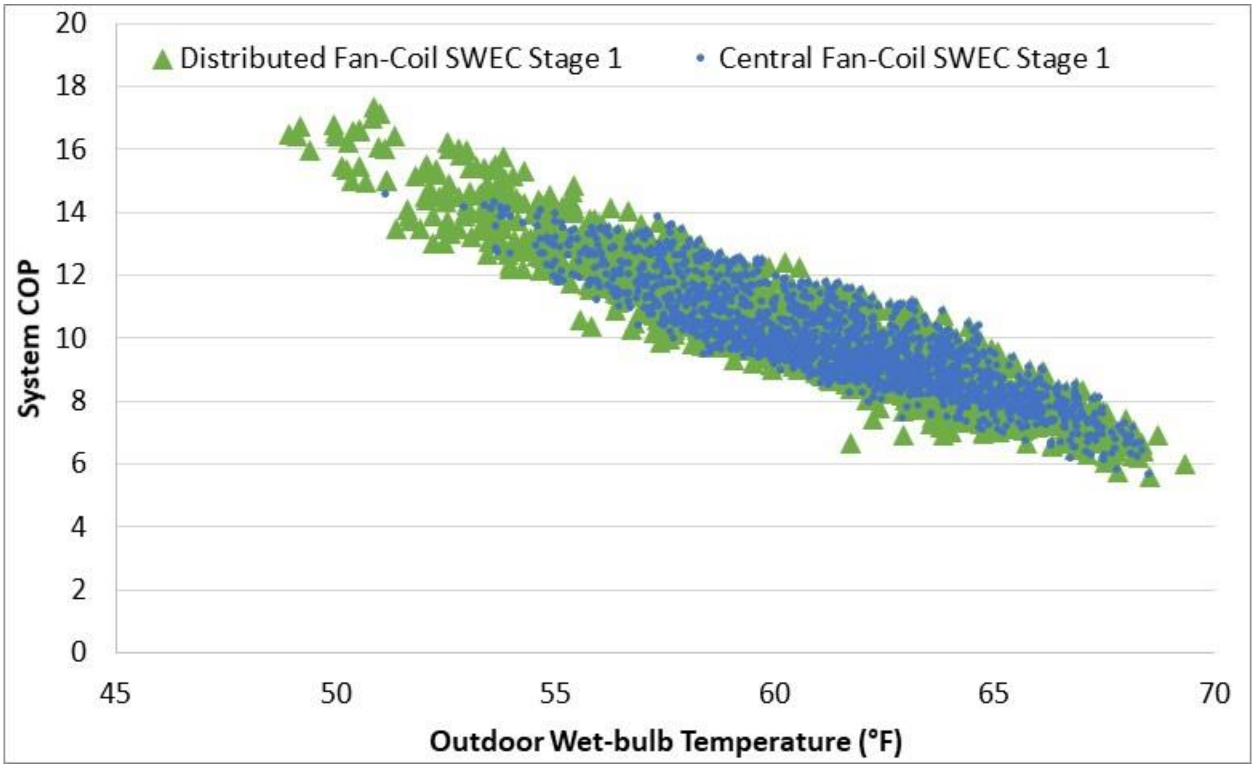
Figure 76: Cooling Energy and Electricity Costs Savings for a Hybrid Sub Wet-Bulb Evaporative Chiller Using Distributed Fan Coils Versus a Central Fan Coil in California Climate Zone 12



Source: University of California, Davis

Figure 77 shows the efficiency of the optimized hybrid SWEC in Stage 1 over the course of year, with both distributed and central-thermal distribution strategies. The results show a similar efficiency trend when plotted against outdoor wet-bulb temperatures. The distributed system operates at a wider range of outdoor wet-bulb temperatures due to differences in the thermal zones applied in the EnergyPlus model; however, the performance overall is comparable.

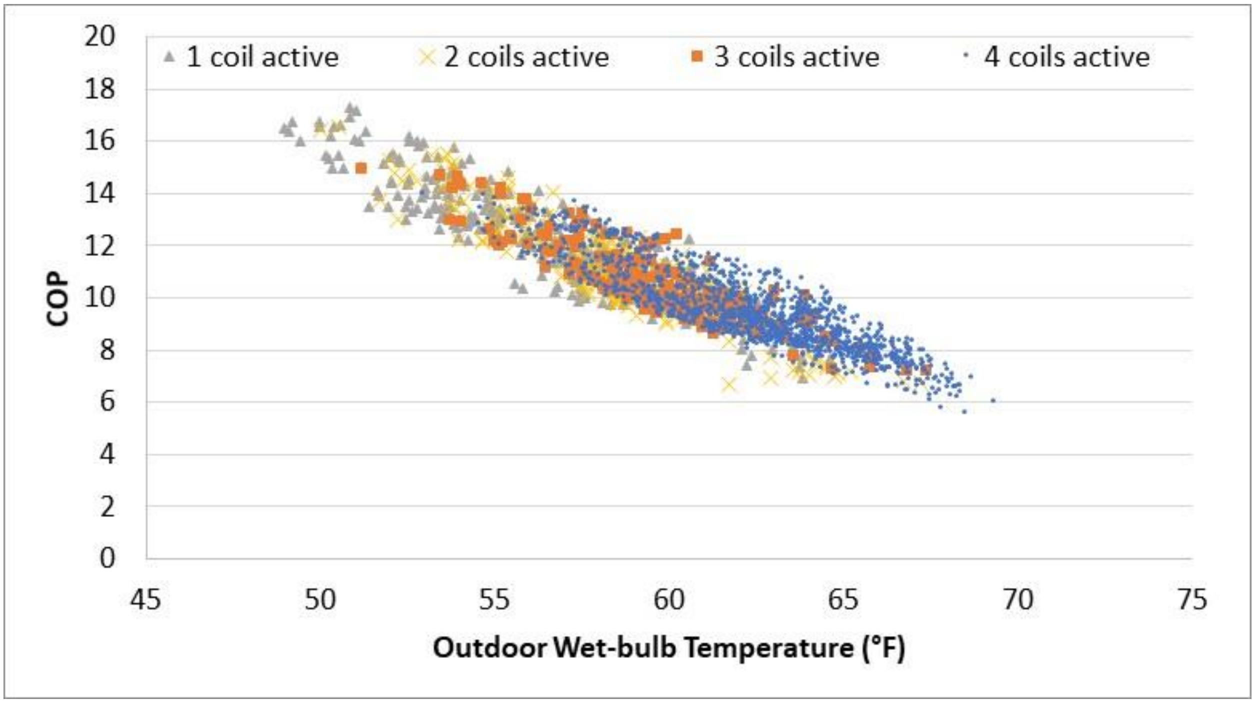
Figure 77: Efficiency Comparison of Optimized Hybrid Sub Wet-Bulb Evaporative Chiller in Stage 1 with Distributed Fan Coils and Central Fan Coil in California Climate Zone 12



Source: University of California, Davis

To further evaluate the performance of the optimized SWEC when operating with distributed fan coils, Stage 1 efficiency was compared with different combinations of active coils, shown in Figure 78. This essentially shows the performance of the SWEC in Stage 1 at each of the four speeds simulated. The results show very little difference in efficiency at each of the four speeds. The efficiency trends are similar when plotted against outdoor wet-bulb temperatures.

Figure 78: Efficiency Comparison of Optimized Hybrid Sub Wet-Bulb Evaporative Chiller Efficiency in Stage 1 when Operating with Different Combinations of Active Coils in California Climate Zone 12



Source: University of California, Davis

The modeled results of the optimized hybrid SWEC, when operating as a distributed system, showed no efficiency benefit over the central system; however, both the distributed and central systems showed substantial performance improvements over the baseline air conditioner, with 44 percent cooling energy savings in California Climate Zone 12. While the systems performed similarly, distributed fan coils provided greater comfort by tailoring cooling to specific zones in the house. By setting appropriate thermostat schedules based on varying occupancy of certain zones, it was possible to reduce required cooling in unoccupied zones by setting higher thermostat set points. For example, the house can be split into sleeping zones and family zones, where the set point for sleeping zones can be increased during the day and decreased at night. Another benefit of the distributed fan coil system is that these systems typically do not require ducts. This has implications on fan power and thermal losses through duct walls. Neither of these impacts was modeled for this report but should be considered when choosing an optimal thermal distribution system.

LIST OF ACRONYMS

Term	Definition
°F	Degrees Fahrenheit
µg	Microgram
A	Amps
AC	Air conditioning
ACH 50	Air changes per hour at 50 Pascals
ASHRAE	American Society for Heating, Refrigeration and Air-Conditioning Engineers
Btu	British thermal units
CEC	California Energy Commission
CF	Cubic feet
CFM	Cubic feet per minute
CFM50	Cubic feet per minute at 50 Pascals
Cm^3	Cubic centimeters
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DB	Dry bulb
EER	Energy efficiency ratio
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
ERV	Energy recovery ventilation
FTHX	Conventional hydronic coil
GPM	Gallons per minute
GWh	Gigawatt-hours
HERS	Home Energy Rating System
HRV	Heat recovery ventilation
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
ICI	Integrated Comfort Inc.
I/O	Indoor/outdoor ratio
m^3	Cubic meters

Term	Definition
MAE	Mean absolute error
MPHX	Microchannel polymer heat exchanger
N/A	Not applicable
NAAQA	National Ambient Air Quality Standards
Pa	Pascals
PM2.5	Particulate matter with diameter 2.5 microns or less
$PM_{2.5}$	Particulate matter with a diameter of less than 2.5 micrometers
PNNL	Pacific Northwest National Laboratory
ppm	Parts per million
QA/QC	Quality assurance/quality control
Rpm	Revolutions per minute
SRV	Smart Residential Ventilation
SWEC	Sub Wet-Bulb Evaporative Chiller
T_{supply}	Supply Water Temperature
USDOE	United States Department of Energy
VOCs	Volatile organic compounds
W	Watts
WB	Wet bulb
WC	Water column
WCEC	Western Cooling Efficiency Center
Wh	Watt-hours

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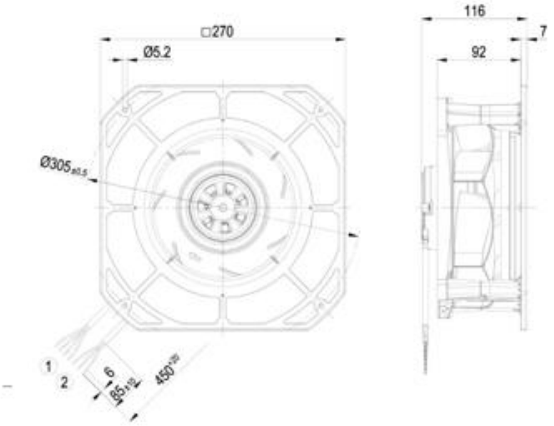
APPENDIX A: Ventilation System Installation and Functionality

The following describes both the Smart Residential Ventilation (SRV) and NightBreeze (NB) systems' installation and operation in the field at both homes.

Smart Residential Ventilation System Installation

Occidental Analytical Group (OAG), who is EPRI's subcontractor for field coordination was assigned to develop a sheet metal box to incorporate the Epm-Papst fan and necessary duct transitions. OAG worked with Mission Aire to fabricate the sheet metal in multiple sections so that the unit could be transported to Davis. The fan box was constructed by a subcontractor, Mission Aire and was transported from southern California as multiple sections, as shown in Figure A-2, for ease of install. The box was built with a provision to slide in a MERV filter.

Figure A-1: Schematic of Variable Speed Fan Specifications from MEpm-Papst (Units in mm)



Source: Electric Power Research Institute

Figure A-2: Components of Smart Residential Ventilation Built in Modular Format for Ease of Install

Source: Electric Power Research Institute

In addition to the fan box installation, several control and sensing devices had to be installed. They include the following.

Pitot Tube Pressure Sensor

A pitot tube was inserted through the side of the fan box. It was installed downstream of the fan and filter (6-8 inches after). The pitot tube was positioned towards the center of the box to ensure that it is reading from even air flow. Tygon tubing was connected between the ports of the pitot tube with the pressure transducer to read static pressure in the fan box.

Instrumentation Box

The instrumentation box housed the pressure transducer and custom-built Raspberry Pi controller. There was a single power supply going into the box, which powered a power strip.

Pressure Transducer

The pressure transducer was installed within the power box. The tubing connected to the L port of the pitot tube also connected to the + port on the pressure transducer. The transducer also connected to the Raspberry Pi controller.

Controller (Raspberry Pi)

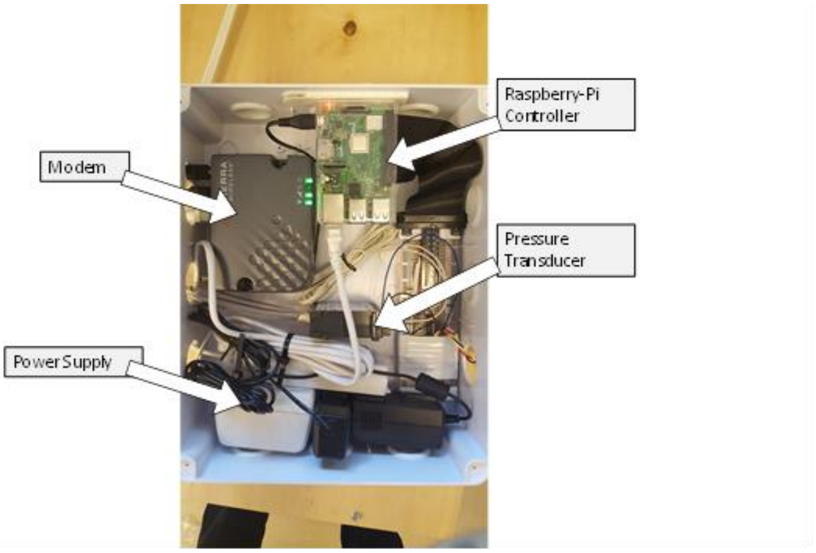
The Raspberry Pi was installed within the power box. It connects to the pressure transducer as well as the fan. It was powered by the power strip and requires an ethernet cable (or Wi-Fi).

Power Scout Power Meter

The Power Scout was used to measure fan power and is installed outside of the power box. It connected to the UC Davis Western Cooling Efficiency Center (WCEC) Datataker data logging system.

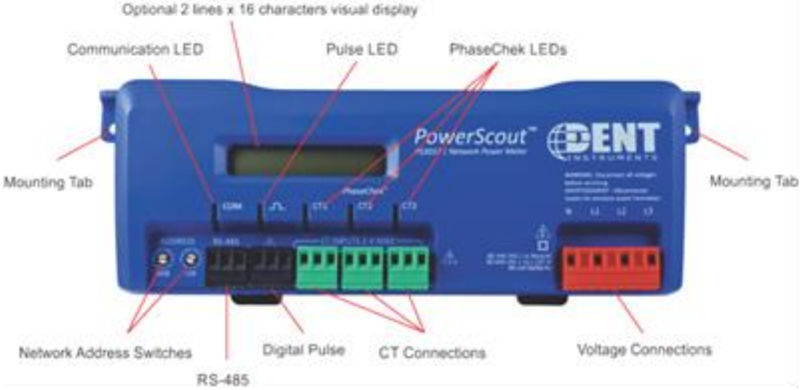
Figure A-3**Error! Reference source not found.** shows the instrument box as assembled with each of the above parts identified. **Error! Reference source not found.** shows the Power Scout power meter.

Figure A-3: Instrumentation Box for Smart Residential Ventilation that Includes Controller



Source: Electric Power Research Institute

Figure A-4: Power Meter for Fan Measurements



Source: Electric Power Research Institute

In preparation for installation, WCEC, EPRI, OAG and Villara Building Systems (contractor for the installation) met to review the installation of the SRV box and ventilation monitoring equipment. A site visit was scheduled with OAG, Villara and WCEC to inspect the home HVAC equipment and the duct system in the attic.

The existing ducts entering and leaving the HVAC system in the attic were too short and cramped within the room to allow installation of a fan. Since the SRV would require certain distance of straight runs both before and after the fan to allow for proper sensing of the pressures within the duct, it was virtually impossible to install it in the vertical run of the supply air duct in the equipment enclosure.

The big challenge was in finding a location for the fan in the main supply air duct in the attic. The supply air duct, after entering the attic from the equipment room below, has the branch duct into the master bedroom. The SRV fan had to be installed in a very short run of the main supply duct between the point of penetration and the first branch duct into the master bedroom. Thus, the Villara team completed the adjustments using the original sections of the SRV fan box to enable the installation of the SRV setup given the space and duct sizing constraints. Accordingly, one or more connector components shown in Figure A-4 were not used.

While the fan box construction and installation were completed, the EPRI project team developed the control schema, procured the control and monitoring devices, then wrote the code for the fan controller operation based on static pressure and flows, and developed the back office data collection system.

The installation of the fan box and ducts took place on May 6th, 2019, in the West Home host site upon completion and coordination amongst the various parties and the tenants' schedules. OAG contracted with Villara Building Systems, a residential installing contractor located in northern California to do the installation. Villara had two installers available for the installation. Installation took approximately eight hours because the SRV fan had to be brought into the attic thru the narrow attic access in piece by piece and then assembled. In addition, a roof penetration had to be done for the fresh air intake into the fan.

The installation of the monitoring and control box had to be scheduled for a subsequent visit as their programming and bench testing was not complete. EPRI discussed and coordinated with WCEC to complete the system algorithm design and operational testing. Once this was completed, Villara and WCEC went back to the site to complete the installation of the monitoring and control equipment.

Other than the restricted workspace in the attic which was not amenable for two workers working together to install the fan box and ducts, the installation of the ducts and fan box went smoothly.

Figure A-5 and Figure A-6 show the installed fan box and associated duct sections and the duct connection from the fan box to the roof for the fresh air intake. The insulated black duct to the right of the SRV fan section in Figure A-5 is the fresh air duct that penetrates the roof. Figure A-7 is a picture of the roof vent.

The EPRI team established remote access to the SRV controller (raspberry-pi). Thus, the team was able to log into the fan controller and confirm that the monitoring and controls were working and online. EPRI collected fan air flow (cfm) and static pressure data, while the power data is collected through WCEC's DAQ. Data collection was started when the ventilation monitoring equipment (power meters and pitot tube with pressure transducer for each home's ventilation system) was installed.

Figure A-5: Smart Residential Ventilation Installed Fan Box and Associated Duct Sections

Source: Electric Power Research Institute

Figure A-6: Smart Residential Ventilation Duct Connections from Fan Box to Roof for Fresh Air Intake

Source: Electric Power Research Institute

Figure A-7: Roof Vent for Smart Residential Ventilation System

Source: Electric Power Research Institute

Smart Residential Ventilation Optimization Algorithm

The optimized controller for the SRV is developed to minimize the energy consumption of the HVAC system. Since any fresh air brought into the space will need to be conditioned, doing so when the ambient temperature is closer to the conditioned space's temperature will reduce cooling or heating load energy consumption. This controller will be compared against the baseline system performance, which assumes the fan operates at a minimum average constant speed to ventilate the house. The problem can be stated mathematically as,

$$\min_{Q_{fan,k} \text{ for } k=1,\dots,N} J = P_{fan,k} + P_{thermal,k}$$

$$\text{such that}$$

$$R_k \leq 5$$

$$\sum_{k=1}^{N} Q_{total,k} \leq 1800^{17}$$

where J is daily energy consumption (kWh), k is the stage, N is the number of stages in the optimization period, Q_{fan} is the mechanical ventilation rate (CFM), P_{fan} is the energy consumption of the SRV fan (kWh), $P_{thermal}$ is the energy consumption of the thermal load due to ventilating fresh air (kWh), R is the relative exposure for each time step, and Q_{total} is the total ventilation rate (CFM) calculated according to ANSI/ASHRAE Standard 62.2 using,

$$Q_{total,k} = Q_{fan,k} + \varphi Q_{inf,k}$$

$$\varphi = \frac{Q_{inf,k}}{Q_{inf,k} + Q_{fan,k}}$$

where φ is the additivity coefficient, and Q_{inf} is the effective annual average infiltration rate (CFM).

The decision variable of this problem is the mechanical ventilation rate Q_{fan}, which determines how much fresh air needs to be conditioned by the cooling/heating system of the house. For the additional cooling load due to ventilation, the COP of a single speed 14 SEER heat pump is

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[17] In the case of the demonstration sites specifications, the minimum infiltration for the day required is 24hours X 75 CFM / hour = 1800 CFM / day. 75CFM is based on Table 4.1a in ASHRAE Standard 62.2-2016.

used to estimate the energy consumption. For the additional heating load due to ventilation, a 0.8 AFUE natural gas furnace is used instead. The optimization problem assumes that all the air brought into the house is cooled down to 55°F from the ambient temperature during the cooling season and heated up to 105°F from the ambient temperature during the heating season. These assumptions were set as lower and upper bounds for the steady-state model. In the next updated iteration of the SRV controller, it would interface with the home thermostat and both the thermostat setpoint and outdoor-air temperatures would be inputs to the controller instead of the initial assumption setup for the preliminary version of the controller.

There are two constraints for this optimization problem, and both are derived from the ANSI/ASHRAE Standard 62.2 on Ventilation and Acceptable Indoor Air Quality in Residential Buildings.[18] This first constraint concerns the relative exposure of the house, which is calculated by the ratio of total ventilation to mechanical ventilation as well as the relative exposure of the previous stage (following Section C1.3 Peak Exposure Limitation in the standard's normative appendix C[2] , $R_i \leq 5$). The second constraint is on the total ventilation air requirement of the house, which is calculated by the ratio of exterior envelope surface area not attached to garages to the total envelope surface area and the ventilation due to infiltration.

$$R_k = \begin{cases} 1, if\ k = 1 \\ R_{k-1} + \dfrac{Q_{tot}\Delta t}{V_{space}}, if\ Q_{fan,k} = 0 \\ \dfrac{Q_{tot}}{Q_{total,k}} + \left(R_{k-1} - \dfrac{Q_{tot}}{Q_{total,k}}\right) e^{-\frac{Q_{total,k}\Delta t}{V_{space}}}, if\ Q_{fan,k} > 0 \end{cases}$$

$$Q_{tot} \leq 5$$

where Q_{tot} is the ventilation rate requirement from the ASHRAE standard in cfm (cubic feet per minute), V_{space} is the volume of the house, and t is the duration of each stage.

The optimal controller requires the weather forecast of the next day in the form of hourly ambient temperatures (°F). Based on the ambient temperatures, the controller calculates the heating/cooling loads due to ventilation throughout the day and the corresponding energy consumption based on a correlated COP, as well as the associated fan power to ventilate a certain amount of fresh air. The controller then minimizes the total energy consumption using the fmincon function in Matlab.

The demonstration site is a house with three bedrooms, around 1000 ft^2 and 8500 ft^3, and requires 75 cfm ventilation air requirements according to Table 4.1a of the ASHRAE standard[2]. The air changes per hour at 50 pascals (Pa) pressure differential (ACH50) of the site pre-seal is 5.54 which gives a total air change of $Q_{tot,ACH50}$ = 47,090 ft^3/hr. The post-seal ACH50 in setting up the model was assumed to be 2, which is a conservative estimate compared to the measured post-seal ACH50 of 3.47, which gives a total air change of $Q_{tot,ACH50}$ = 17,000

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[18] ANSI/ASHRAE Standard 62.2-2016, Ventilation and Acceptable Indoor Air Quality in Residential Buildings, ISSN 1041-2336

ft^3/hr, which shows how a tighter seal of the conditioned space will require higher ventilation requirements since the rate of air changes is greatly reduced. This total air change has to take the reference pressure of the ASHRAE standard (4 Pa) into account using the following equation.

$$\frac{50}{{Q_{tot,ACH50}}^2} = \frac{4}{{Q_{tot,ASHRAE}}^2}$$

Where the subscript *ACH50* represents the actual ACH50 readings and subscript *ASHRAE* represents the infiltration according to the standard's reference pressure.

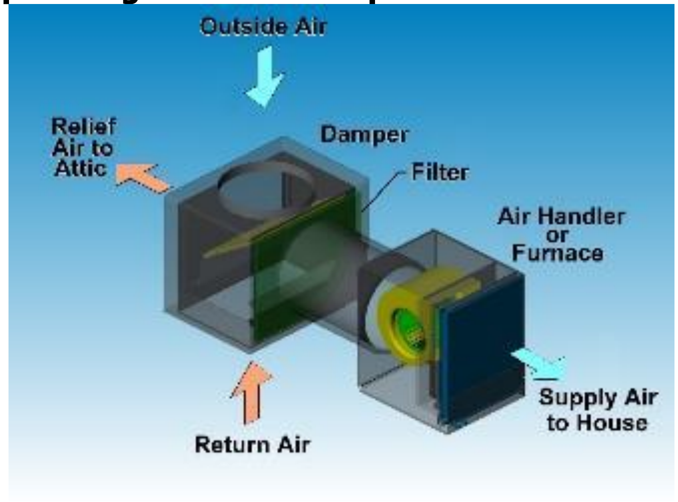
This gives an infiltration of 80 CFM with the assumptions above, which can be used to calculate the required fan ventilation[19] with a 0.75 assumption for the reduction factor A_{ext}. A_{ext} is defined as the ratio of exterior envelope surface area that is not attached to garages or other dwelling units to total envelope surface area for single-family attached homes. For single-family detached homes, A_{ext} = 1.

$$Q_{fan} = Q_{tot} - (Q_{inf} A_{ext})$$

NightBreeze Ventilation System Setup

The NightBreeze ventilation cooling system (NB)was installed and operational in the East Home by April 2019 by Frontier Energy. In a typical installation, NB controls integrate operation of the heating, cooling, and ventilation systems and optionally operate zone dampers. The damper pictured below normally directs indoor return air to the air handler. When ventilation cooling or fresh air ventilation are called for, the damper changes position to draw air from outdoors and also allows indoor air to be vented to the attic.

Figure A-8: Typical NightBreeze Damper and Air Handler Configuration



Source: Frontier Energy

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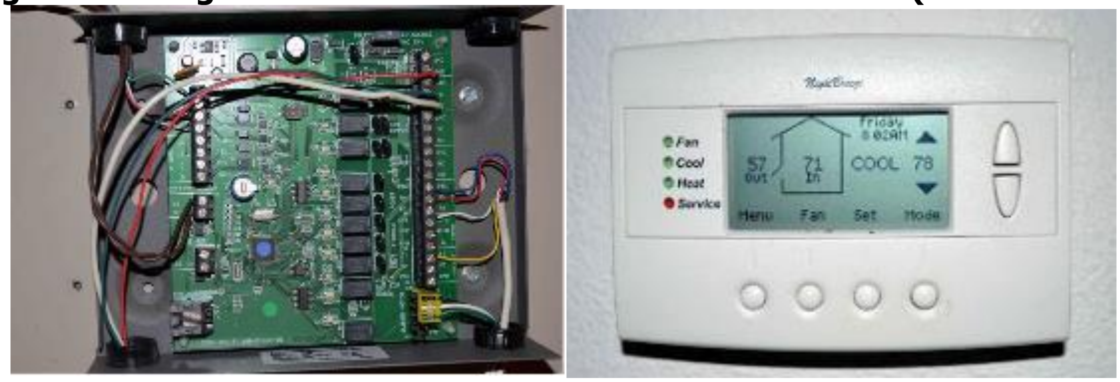
[19] Equation 4.6 in ASHRAE Standard 62.2-2016.

Figure A-9: NightBreeze Control Board and User Interface ("Thermostat")



Source: Frontier Energy

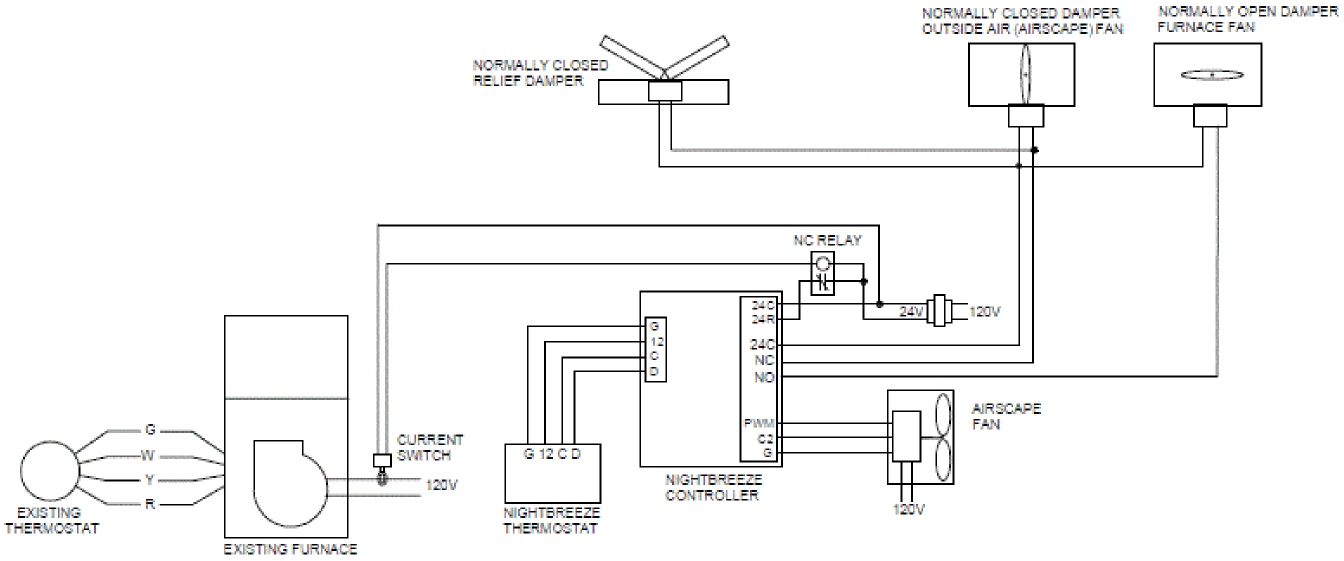
The furnace in the test house could not be converted to variable speed nor did it have enough air-flow capacity, so a second fan manufactured by Airscape was installed. The in-line Airscape fan uses an electronically commutated motor, the speed of which can be varied using the pulse-width modulation (PWM) signal produced by NB controls. Since the standard NB damper could not be used in this application, a wye-branch was installed in the main supply duct from the furnace and the branch was connected to the whole house fan. Two duct dampers were installed to control air flow and prevent backdrafting the furnace. The damper in the main supply duct is normally open and the damper in the ventilation duct is normally closed. When the NB control calls for ventilation, both dampers are actuated allowing the Airscape fan to deliver outside air through the supply registers. A third (Airscape) damper with insulated shutters was installed in the ceiling and also opens during fan operation to allow indoor air to be exhausted into the attic. A filter in the ventilation duct filters outside air.

Control modifications were required to manage the operation of the duct and relief dampers and to prevent the Airscape fan from operating at times that either the air conditioner or furnace are operating. As shown in Figure A-11, a current switch and relay were installed to disable NB controls whenever current is sensed in the 115V lines serving the furnace blower.

Figure A-10: Filter Box Installed in Outside Air Ducting in East Home

Source: Electric Power Research Institute

Figure A-11: NightBreeze Ventilation System Wiring Schematic



Source: Frontier Energy

NightBreeze Control Algorithm

NB ventilation cooling operation is as follows: When the thermostat is set to cooling mode and the outdoor temperature drops below the indoor temperature by 5°F, the duct dampers and fan operate to draw outdoor air and the ceiling damper allows indoor air to be relieved to the attic. Ventilation is ceased when the outdoor temperature rises above the indoor temperature or if the indoor temperature falls below the low limit temperature set on the thermostat. The control also discontinues ventilation at 7 am.

The fan speed varies with respect to current weather conditions (higher cfm during hotter weather). The low limit temperature is a user setting but is automatically adjusted upward during mild weather to prevent over-cooling. If the outdoor temperature is below the indoor temperature (by 0-1°F) while the air conditioner is operating, the damper will switch, causing the fan to draw in return air to using outdoor air (economizer function). In this test there was no economizer operation because a separate fan was used. It is capable of delivering up to 2000 cfm, but in this project's application, the system delivered a maximum of about 1100 cfm.

A predictive function uses a history of outdoor and indoor temperature conditions to predict the next day's temperatures. On very hot days the fan operates at maximum speed and on mild days it runs at lower speeds. The controller also attempts to cool the house to lower temperatures by modifying the indoor low limit temperature on hotter days. To determine what fan speed to run for ventilation cooling, the controller measures outdoor and indoor temperatures over the day and uses temperature trends to predict what the next day's temperature conditions will be. The "Low" and "High" user settings are also inputs to the algorithm. The prediction is used in equations that adjust the fan speed and the low limit, or target temperature. These parameters are reset each night at midnight. For example, if a hot day is predicted, the fan speed is raised and the target temperature, or the indoor temperature at which fan operation is discontinued, is lowered.

In winter, the NB system provides fresh air ventilation by operating the dampers as it does in summer, but the fan operates at a low cfm and runs a fraction of each hour to provide the volume of fresh air that is selected in Technician Settings on the thermostat. When NB is used with a furnace, heat pump, or hydronic air handler, ventilation occurs only when there is a call for heating. However, if there is no call for heating during a particular hour or insufficient fresh air was provided during a heating cycle, the system will operate to deliver sufficient ventilation to meet the quota (ASHRAE 62.2 or Title 24 requirement). The controller can also be programmed to ventilate at other rates.

Since the system did not provide heating in this test, NB used the last segment of each hour to deliver the required amount of ventilation (provided settings were made correctly). The ventilation rate is selected in program settings. The program assumes an air--low rate of 200 cfm (at the lowest fan speed) and calculates how many minutes it takes to meet the hourly quota of ventilation air and runs the fan for that length of time. The controller has other functions, such as scheduled heating and cooling operation, using the air conditioner for precooling, and operation of zone dampers.

NightBreeze Air flow and Power Measurements

The speed of the fan motor is controlled by a pulse-width modulation (PWM) signal issued by the controller. Since the PWM signal is calibrated for a particular ECM (electronically commutated motor) and air handler, the accuracy is reduced when using an alternate fan such as the Airscape fan used in this test. Air flow for the Airscape fan was measured using a TrueFlow flow grid at several control settings.

Table A-1: NightBreeze Air-Flow Measurement Calibrations

Airflow Setting	500	900	1300	1700
Measured Airflow	502	724	1207	1675

Source: Frontier Energy

For the winter time period between Dec 2019 and Jan 2020, the NB controls were set to heating mode and configured to provide an average ventilation rate of 50 CFM. With the fan delivering approximately 200 cfm it needs to run 15 minutes of each hour. Due to the relatively low power consumption, the power readings were within the noise levels of the instrumentation and were not reliable. Frontier Energy measured fan energy during a winter ventilation cycle for another typical system that uses an air handler. Power measured during fan operation was 49 W and during standby was 6 W. Thus, this the system averages about 15 W during winter ventilation mode.

Equipment was installed to measure pressures with the intent of correlating pressure to airflow, however the team noted that there is poor correlation between power and pressure and that correlation between power and CFM is much more dependable. One-time measurements resulted in the data shown in Table A-2 and allowed estimation of air flow based on fan power.

Table A-2: Air Flow Map for NightBreeze System

CFM Setting	Fan Power, Watts	Measured CFM
2000	320	1537
1500	217	1322
1000	120	1064
500	45	743
100	7.3	n/a

Source: Frontier Energy

In July 2020, Frontier Energy installed additional power meters for the NB system. The new instrumentation was able to read the data with higher resolution. The current transformers used to measure power were placed so they were measuring parasitic power from monitoring equipment as well as NightBreeze controls, which amounted to about 19.7 W during standby. Therefore, that amount was subtracted from the power data for the analysis and used to adjust the correlation between “logged” power and cfm. Table A-3 shows the updated air-flow measurements and calibration of the NB system using the new instrumentation. A curve-fit equation was developed using CurveExpert© software (below) to calculate cfm from power measurements. The table compares the calculated air flow to the measured air flow and shows the error is insignificant. Figure 12 plots the measured data and results from the equation.

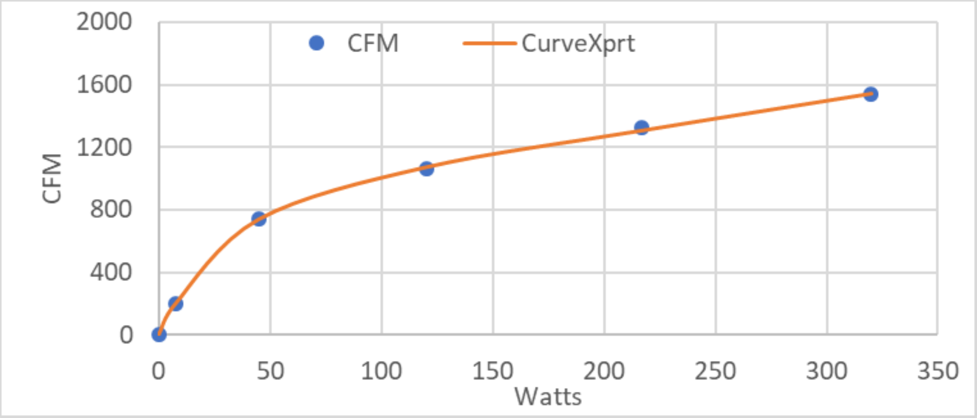
$$CFM = 767.76 - 1594.36(0.966)^{P} + 2.28P$$

Table A-3: Updated Flow Map for NightBreeze System

CFM Setting	Measured Watts	Logged Watts*	Measured CFM	CurveExpert CFM
2000	320	339.7	1537	1543
1500	217	236.7	1322	1308
1000	120	139.7	1064	1073
500	45	64.7	743	741
100	7.3	27	196	196
0	0	19.7	0	0

Source: Frontier Energy

Figure A-12: NightBreeze Ventilation System Air Flow Calibration



Data Reliability

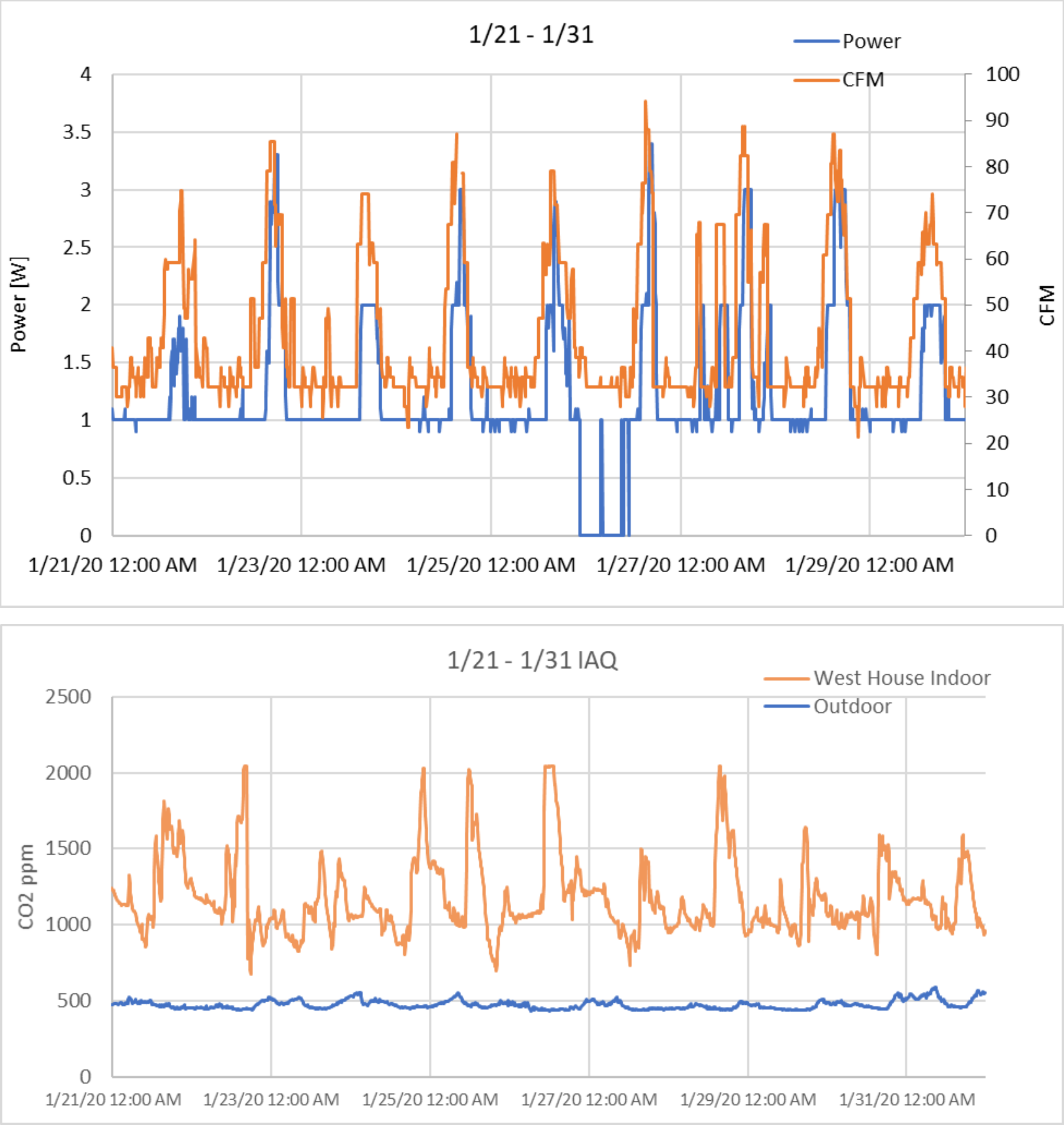
In the second project interim report analysis, the team identified that the resolution of the power measurements was not sufficient to capture the low-power operation due to reduced air flow during the heating mode for both ventilation systems. Thus, the team requested for WCEC team to replace the CTs for both the east and west house power meters to improve the power meter data resolution, especially for the lower fan speed operation.

- The CTs were updated in the East house (NB) in April 2020.
- The CTs were updated in the West house (SRV) on Jun 25th, 2020 (due to shelter in place restrictions).
- Additionally, the team coordinated with Frontier Energy who the provided airflow-power correlation for calculating cfm. Frontier also installed a separate data acquisition system which measured fan power and supply and relief air temperature, and relative humidity.
- System connectivity: The SRV controller box needed to be power-cycled occasionally due to the Raspberry Pi controller shutting down (power-cycled back on December 13th, 2019 and on July 15th, 2020). This mishap interrupted the scheduled testing with the SRV optimizer algorithm compared to the baseline case.

APPENDIX B:
Additional figures from Ventilation Analysis Results

Smart Residential Ventilation System

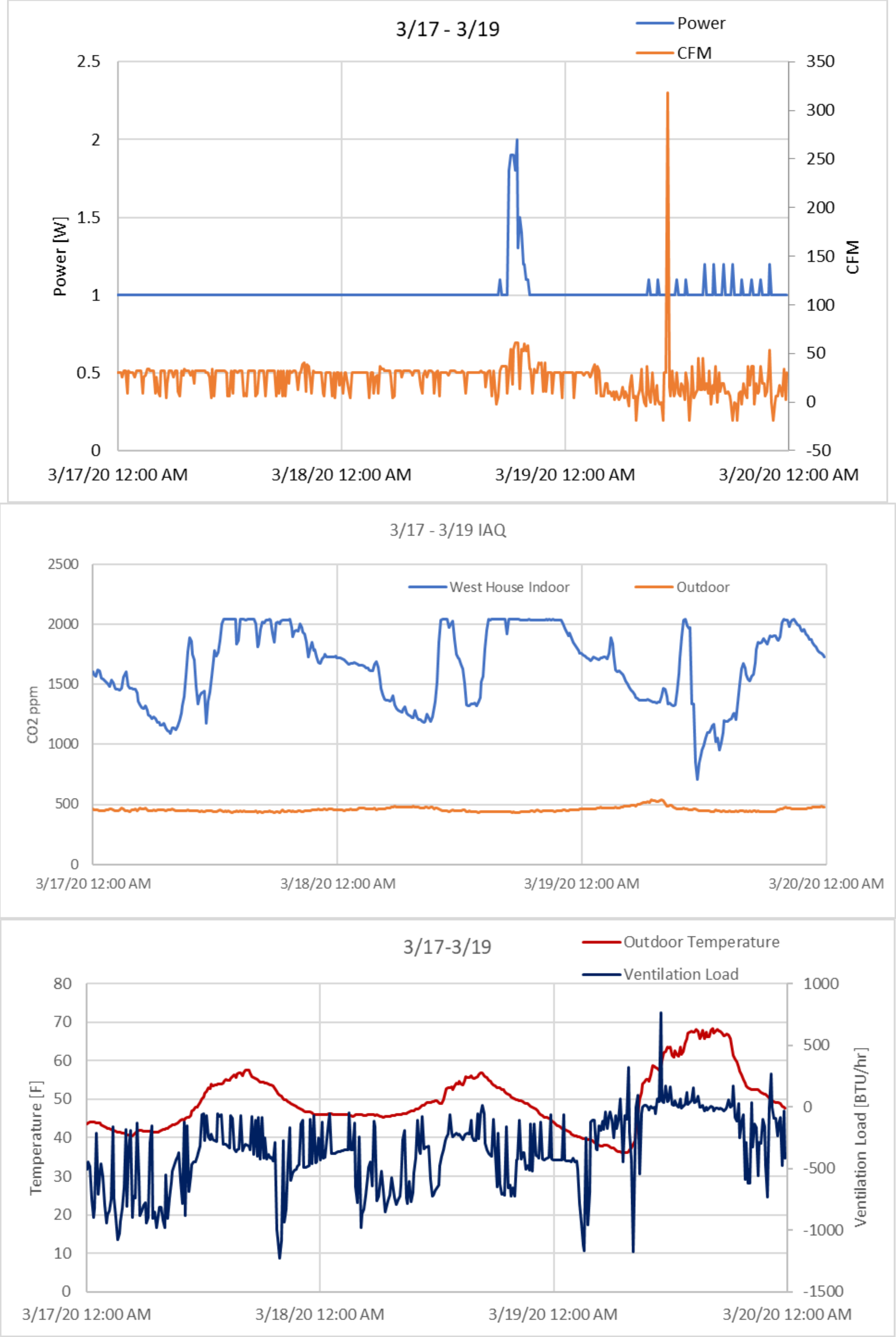
Figure B-1: Smart Residential Ventilation Performance in Optimized Mode on January 21-31, 2020



The first plot shows the ventilation rate and power consumption, the second plot shows the corresponding indoor and outdoor ai0r quality

Source: Electric Power Research Institute

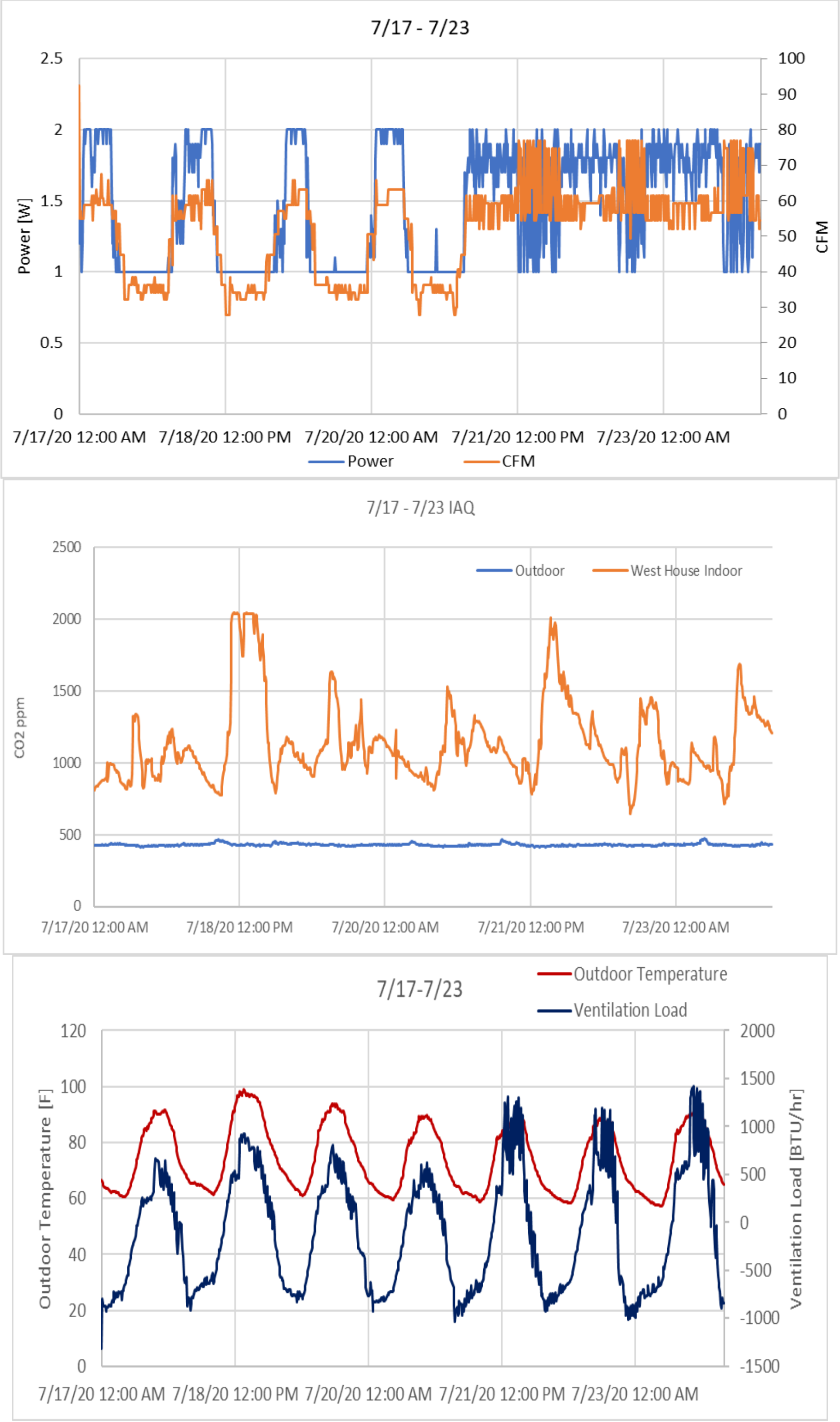
Figure B-2: Smart Residential Ventilation Performance in Optimized Mode on March 17-19, 2020



First plot shows the ventilation rate and power consumption, second plot shows the corresponding indoor and outdoor air quality, third plot shows the outdoor temperatures and corresponding ventilation load.

Source: Electric Power Research Institute

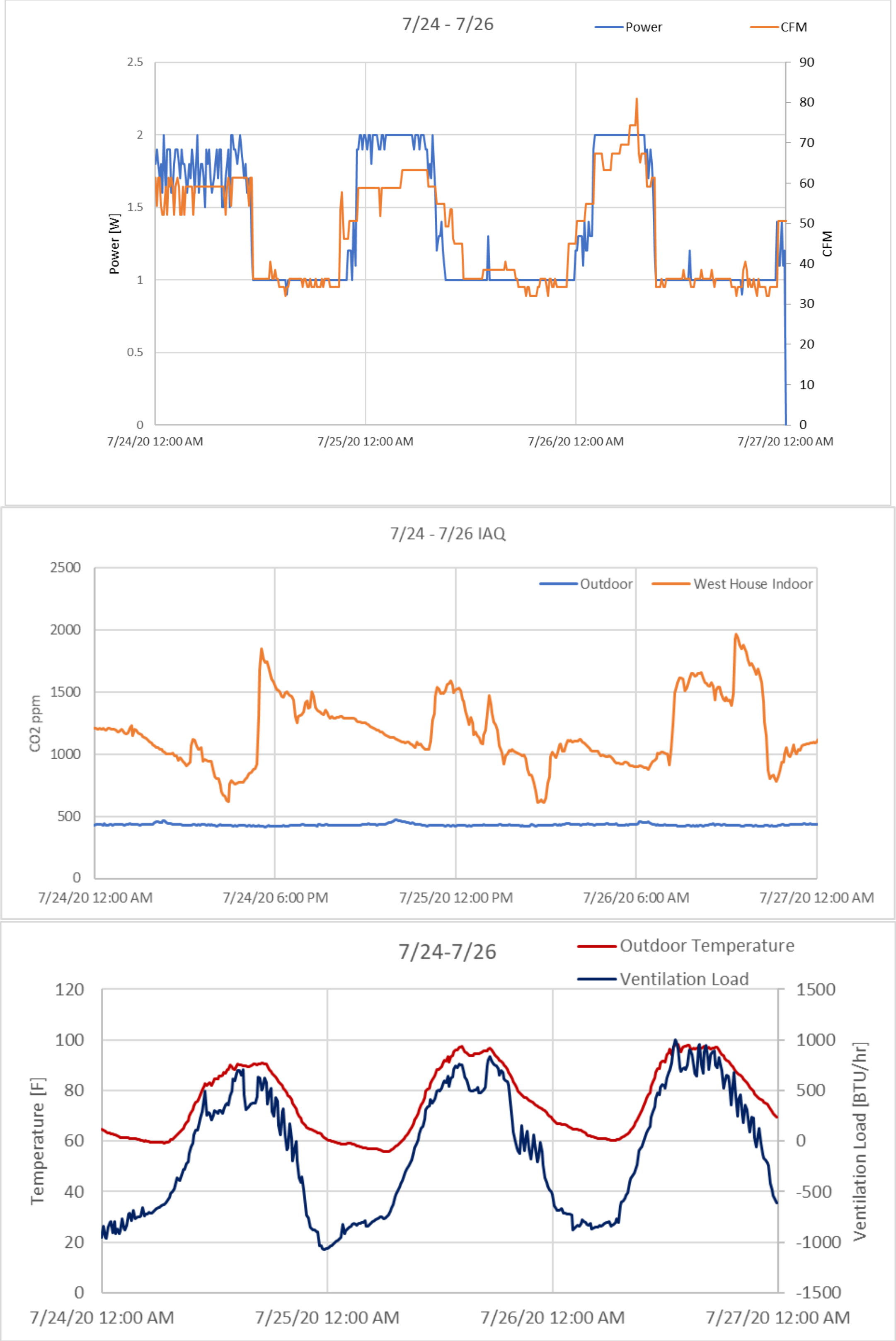
Figure B-3: Smart Residential Ventilation Performance in Optimized Mode on July 17-23, 2020



First plot shows the ventilation rate and power consumption, second plot shows the corresponding indoor and outdoor air quality, third plot shows the outdoor temperature and corresponding ventilation load.

Source: Electric Power Research Institute

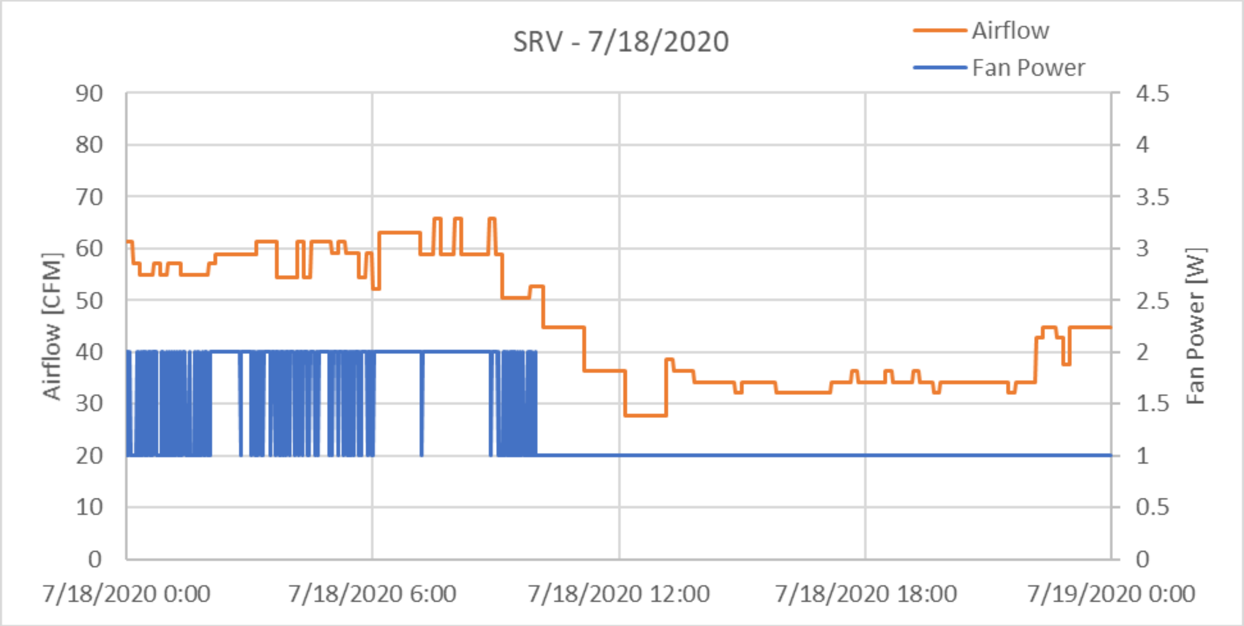
Figure B-4: Smart Residential Ventilation performance in optimized mode on Jul 24-26, 2020



First plot shows the ventilation rate and power consumption, second plot shows the corresponding indoor and outdoor air quality, third plot shows the outdoor temperature and corresponding ventilation load.

Source: Electric Power Research Institute

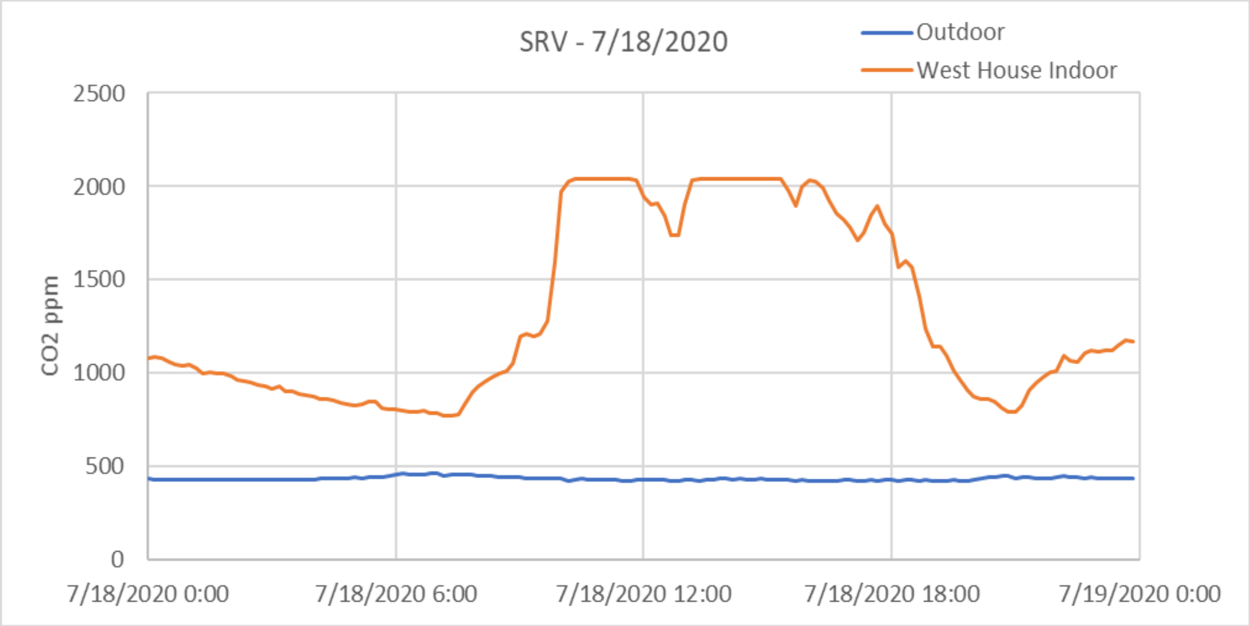
Figure B-5: Total Ventilation Delivered and Power Consumption on July 18, 2020 for Smart Residential Ventilation in Optimized Mode



Total Mechanical Ventilation for the day: 65,300 CF, Total Energy: 31 Wh

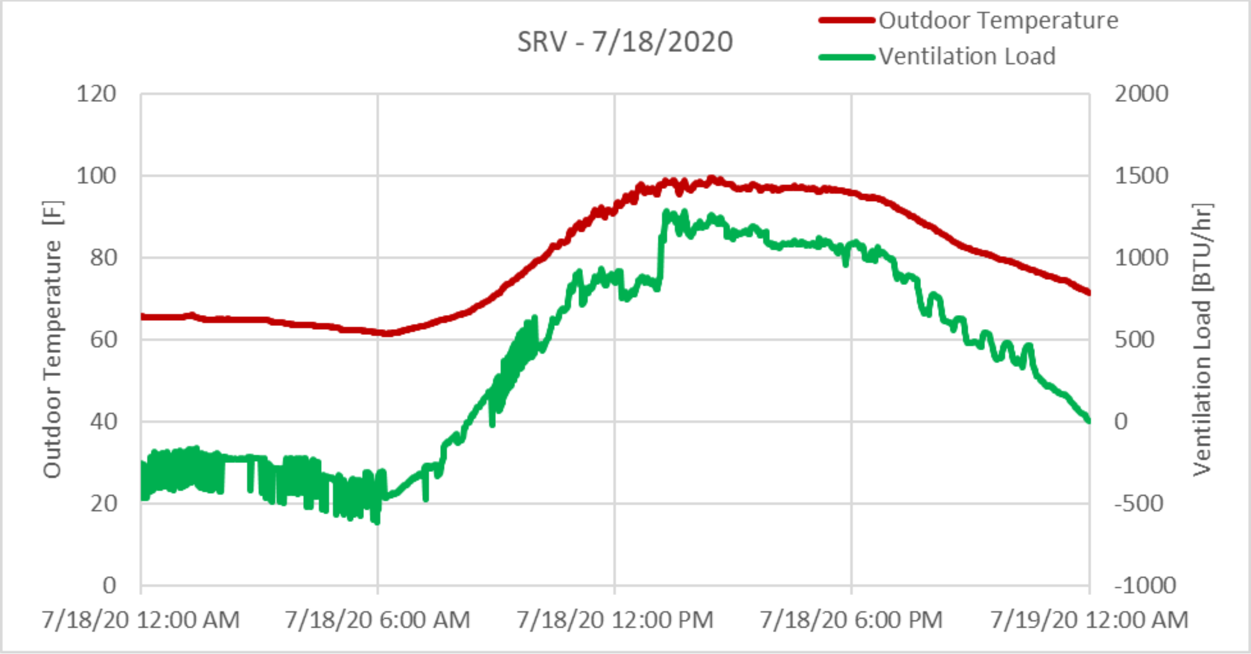
Source: Electric Power Research Institute

Figure B-6: Indoor and Outdoor Air Quality in Carbon Dioxide ppm Levels on July 18, 2020 for Smart Residential Ventilation in Optimized Mode



Source: Electric Power Research Institute

Figure B-7: Outdoor Air Temperature and Ventilation Cooling Delivered on July 18, 2020 for Smart Residential Ventilation in Optimized Mode

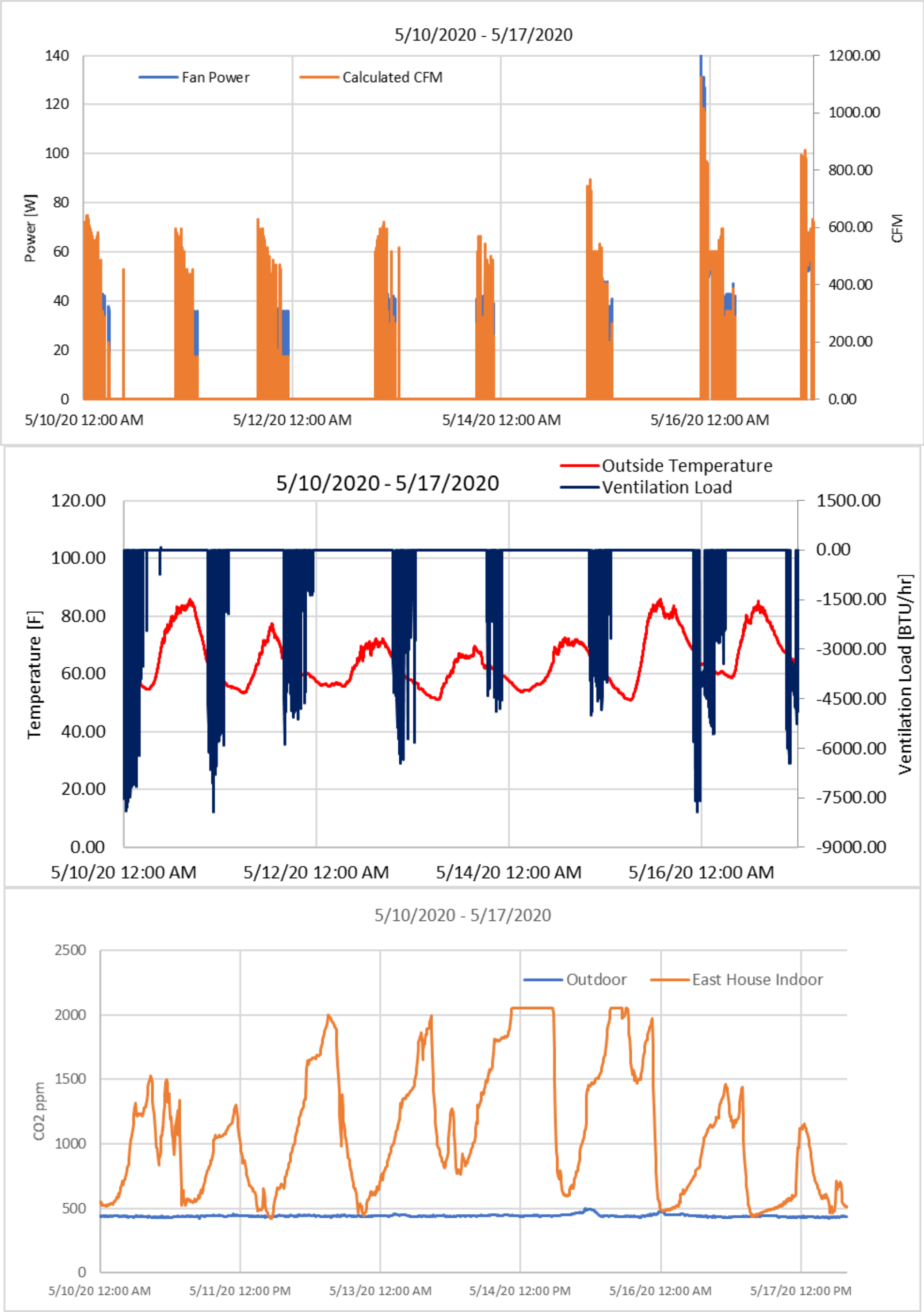


Total Ventilation Load: 9,178 BTUs

Source: Electric Power Research Institute

NightBreeze Ventilation System

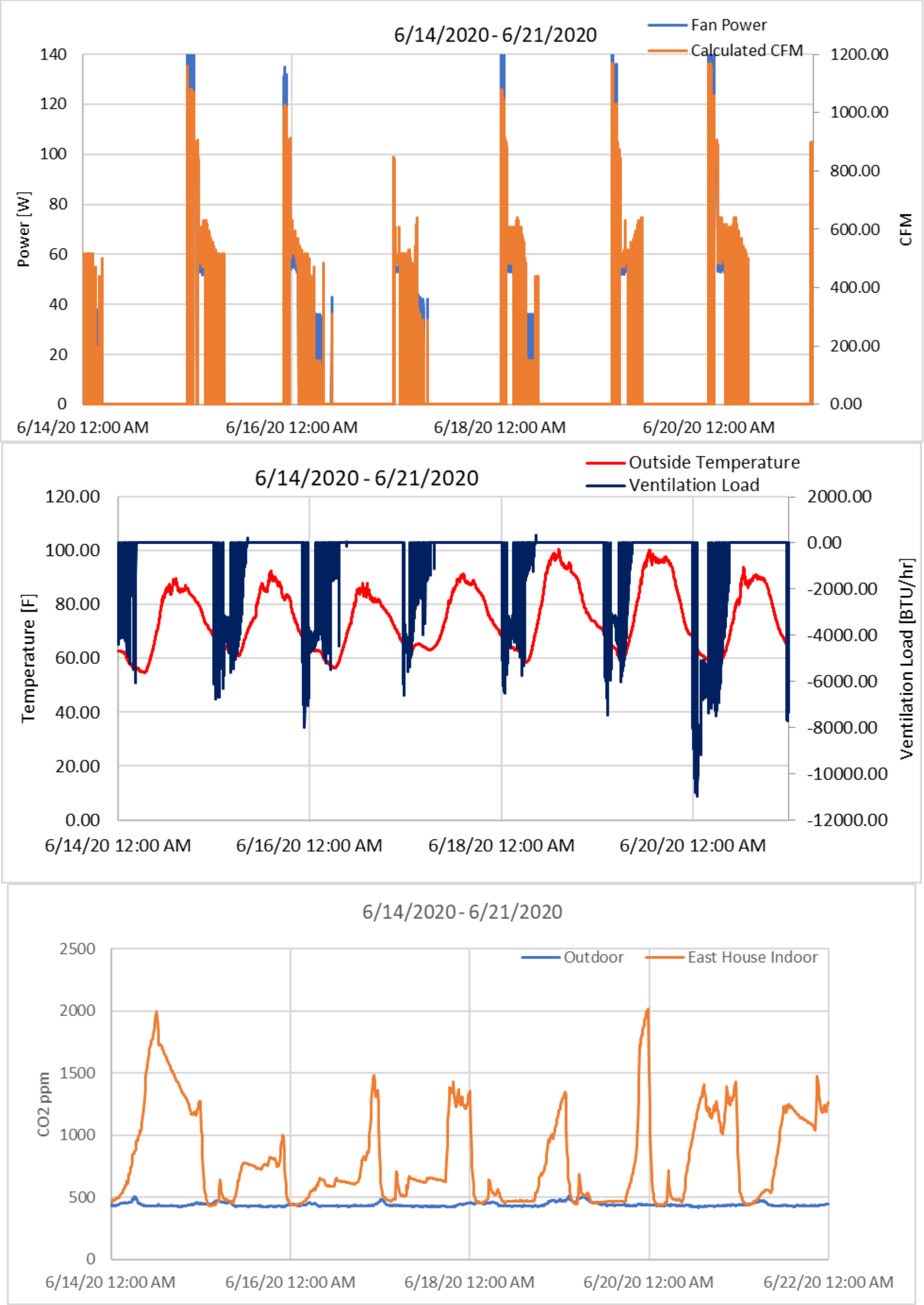
Figure B-8: NightBreeze Performance on May 10 –17 2020



first plot shows ventilation rate and power consumption, second plot shows the cooling from ventilation and outdoor temperature, and third plot shows the corresponding indoor and outdoor air quality

Source: Electric Power Research Institute

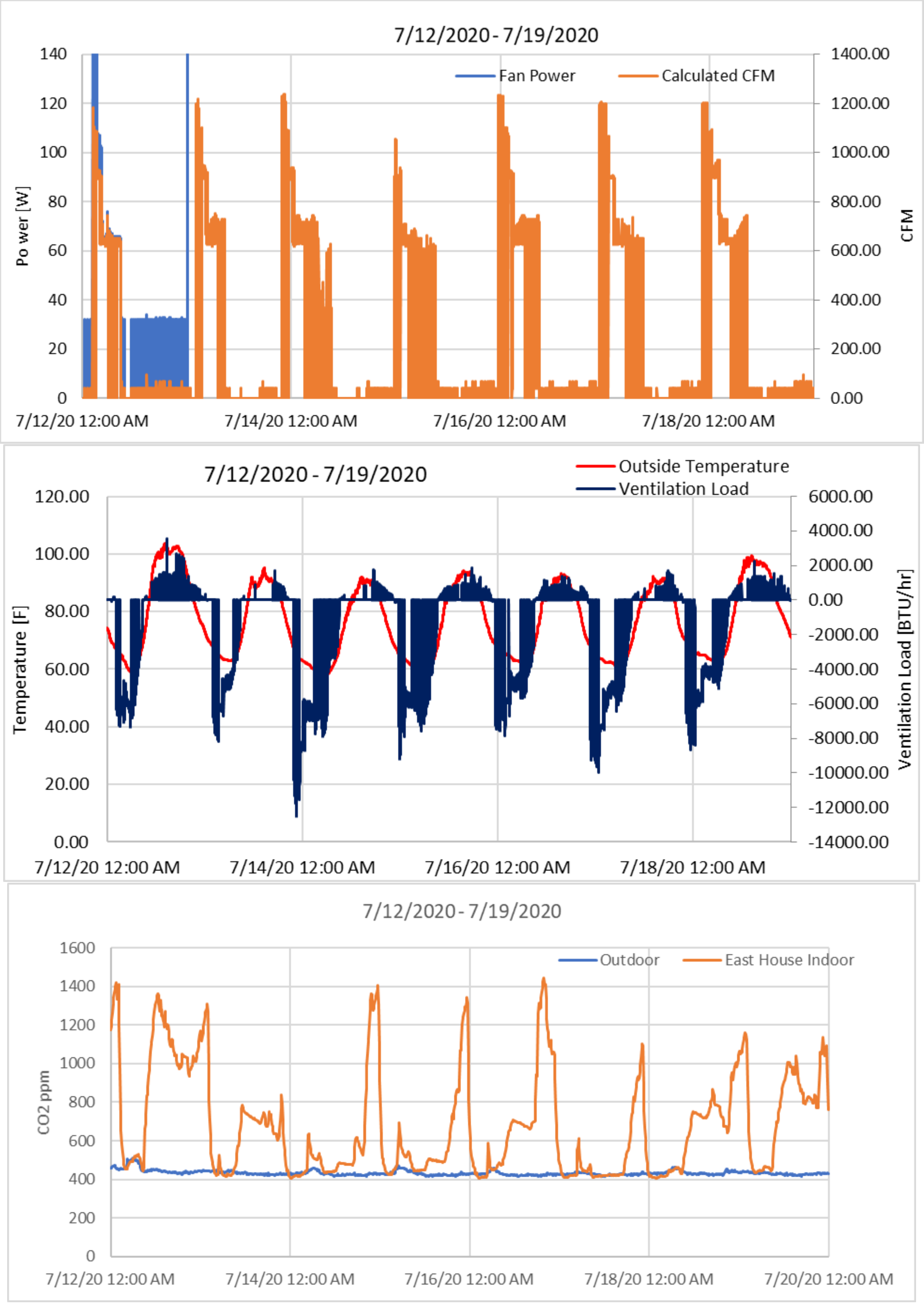
Figure B-9: NightBreeze Performance on June 14 – 21, 2020



First plot shows ventilation rate and power consumption, second plot shows the cooling from ventilation and outdoor temperature, and third plot shows the corresponding indoor and outdoor air quality.

Source: Electric Power Research Institute

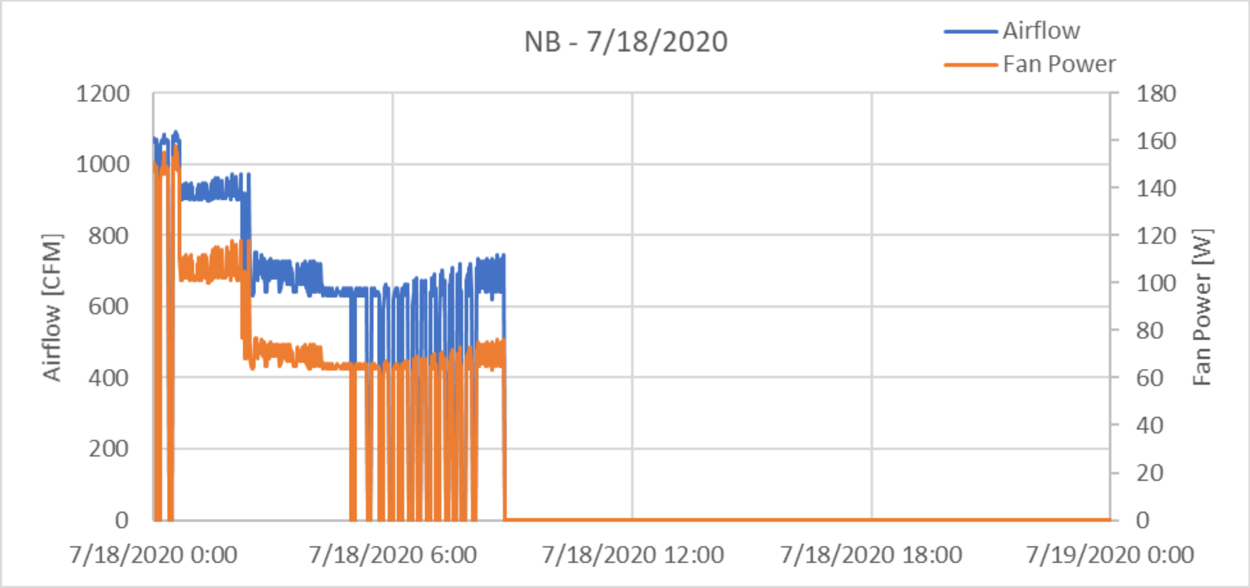
Figure B-10: NightBreeze Performance on July 12 – 19, 2020



First plot shows ventilation rate and power consumption, second plot shows the cooling from ventilation and outdoor temperature, and third plot shows the corresponding indoor and outdoor air quality.

Source: Electric Power Research Institute

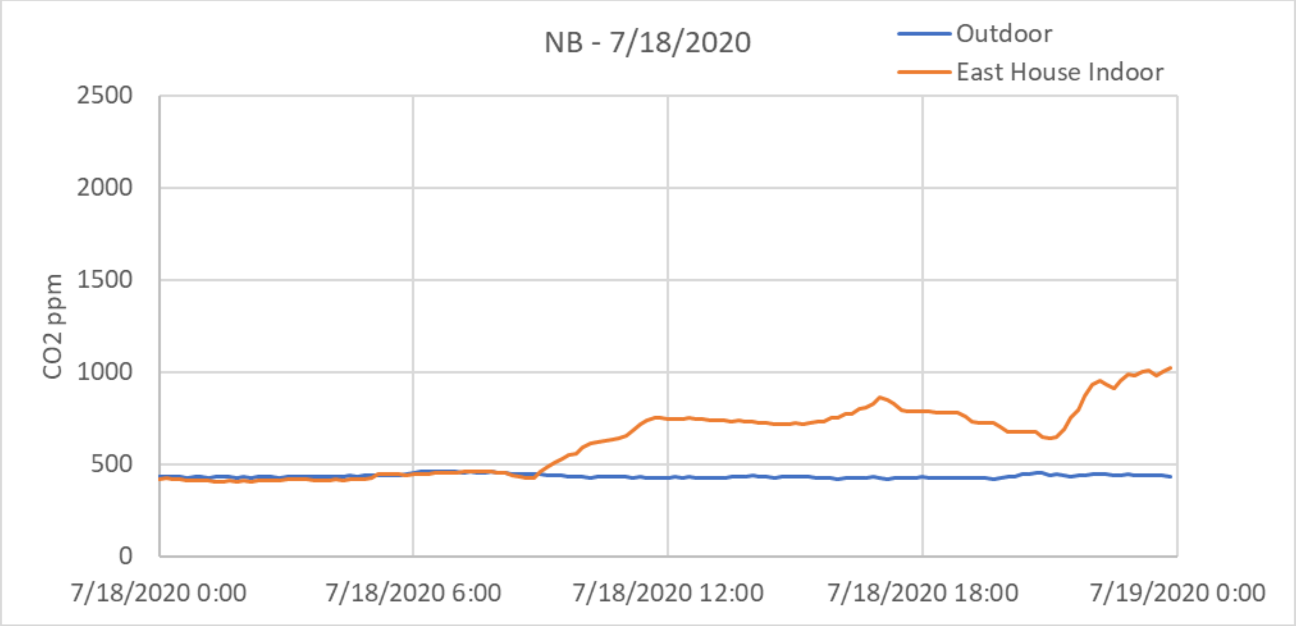
Figure B-11: Total Ventilation Delivered and Power Consumption on July 18, 2020 for NightBreeze System



Total Mechanical Ventilation: 342,738CF. Total Energy: 780 Wh

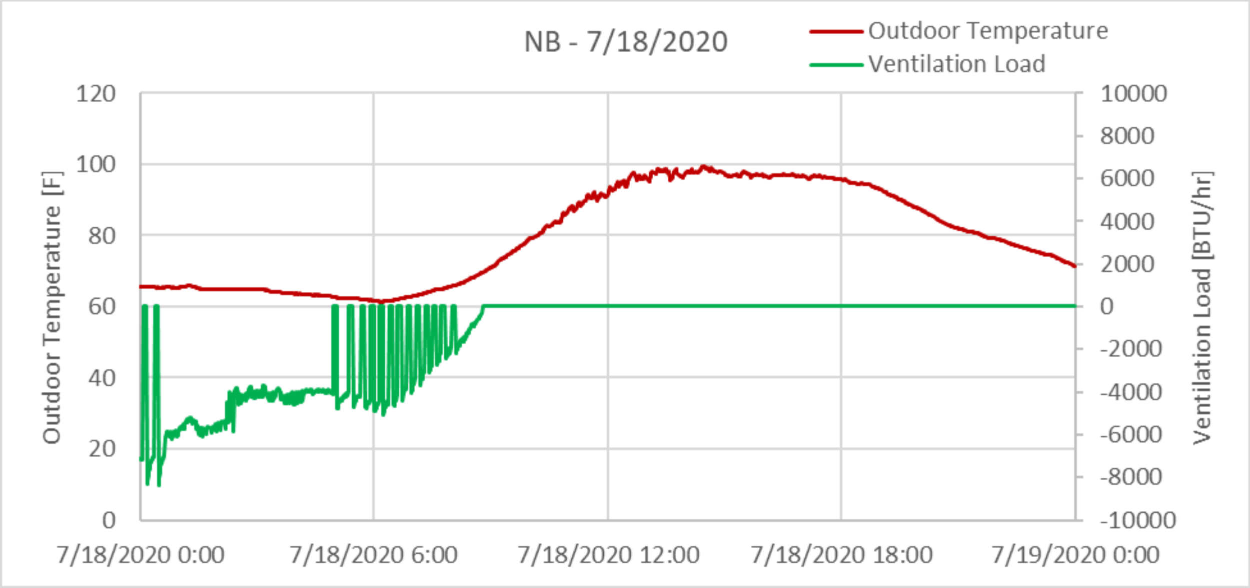
Source: Electric Power Research Institute

Figure B-12: Indoor and Outdoor Air Quality in Carbon Dioxide ppm Levels on July 18, 2020 for NightBreeze System



Source: Electric Power Research Institute

Figure B-13: Outdoor Air Temperature and Ventilation Cooling Delivered on July 18, 2020 for NightBreeze System



Total Ventilation Load: -31,416 BTUs

Source: Electric Power Research Institute

APPENDIX C:
Cooling Performance Methodology

The capacity of the SWEC cooling systems in both homes were measured through water-side measurements. Equation 1 shows the calculation for the water-side capacity calculation for the SWEC unit in both homes.

$$Q_{SWEC} = \dot{m}_{water} * c_{p\,water} * (T_R - T_S) \qquad \text{Equation 1}$$

Where,

T_R is the temperature of the water being returned to the SWEC from the home

T_S is the temperature of the water being supplied to the home from the SWEC

$\dot{m}_{water}$ is the flow rate of the water through the SWEC

$c_{p\,water}$ is the specific heat capacity of the water

This calculation will be the only water-side capacity for the East home cooling system, since the central coil and SWEC are in a closed loop. The west house cooling system, however, calculates the SWEC capacity using Equation 1, as well as the capacity being delivered to the coils distributed in the home. This capacity is calculated using the water temperature and flow rate measurements taken after the water-to-water plate heat exchanger, where the water loop for the SWEC transfers heat with the water being delivered to the fan coil units in the home. The capacity delivered to the water coils is shown in Equation 2.

$$Q_{HX} = \dot{m}_{water} * c_{p\,water} * (T_R - T_S) \qquad \text{Equation 2}$$

Where,

T_R is the temperature of the water being returned to the plate heat exchanger from the water coils

T_S is the temperature of the water being supplied to the water coils from the heat exchanger

$\dot{m}_{water}$ is the total flow rate of the water through all water coils throughout the house

$c_{p\,water}$ is the specific heat capacity of the water

The power consumption from the SWEC unit in both homes monitored the power of the pump, fan and compressor (when operating in Stage 2 cooling). The Coefficient of Performance (COP) was used to evaluate the overall performance of the cooling system in each home. The COP is the ratio of the total capacity of the system and the power consumed by the system.

$$COP = Q_{SWEC}/P_{System} \qquad \text{Equation 3}$$

where,

P_{System} is the total power used by the system as described above

The estimated uncertainties for the capacity and COP were calculated using typical conditions for retrofit cooling measurements. The following table show the conditions used and the estimated uncertainties for the SWEC capacity and COP.

Table C-1: Sub Wet-Bulb Evaporative Chiller Retrofit Conditions Used for Equipment Uncertainty Calculations

Parameter	Value
T_S (˚F)	63
T_R (˚F)	70
$\dot{m}_{water}$(gpm)	5
P (kW)	0.2

Source: University of California, Davis

Table C-2: Uncertainty Values for Sub Wet-Bulb Evaporative Chiller Capacity and Coefficient of Performance as well as System Capacity and Coefficient of Performance Measurements

	Metric	Uncertainty (%)
SWEC	Capacity (Btu/hr)	±7.3
SWEC	COP (Btu/hr/W)	±10.3

Source: University of California, Davis

APPENDIX D: Indoor Air Quality Results

This Appendix presents the detailed air quality data used in the analysis and discussion of the report.

$PM_{2.5}$ Concentrations

The data reported in the following tables are average concentrations by season, with seasons adjusted to match retrofit status.

Table D-1: Indoor PM$_{2.5}$ Concentrations (µg/m^3) in West House Calculated as Daily Means for Whole 24-Hour Period, with Values Averaged by Retrofit Status and Season

Pre-Retrofit							Post-Retrofit						
	N	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**		**N**	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**
Winter/Spring	121	11.36	5.45	8.76	15.66	20.31	**Winter/Spring-No Ventilation**	95	18.90	9.06	12.53	21.14	35.09
Summer/Early Fall	152	13.48	6.58	11.58	19.52	24.93	**Summer/Early Fall-SRV Installed**	107	6.31	3.52	5.49	8.22	12.47
							January 2020-Baseline mode	12	10.90	7.32	9.37	13.81	21.05
							January 2020-Optimized Mode	19	13.99	6.30	10.47	17.67	23.90

Source: University of California, Davis

Table D-2: Indoor PM$_{2.5}$ Concentrations (µg/m^3) in the East House Calculated as Daily Means for Whole 24-Hour Period, with Values Averaged by Retrofit Status and Season

Pre-Retrofit							Post-Retrofit						
	N	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**		**N**	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**
Winter/Spring	94	22.50	8.67	14.77	26.91	52.00	**Winter/Spring-NightBreeze Heating**	73	8.73	2.48	5.02	12.82	22.02
Summer/Early Fall	135	10.45	4.47	7.78	12.23	20.01	**Summer/Early Fall-NightBreeze Cooling**	105	4.17	2.43	3.81	5.46	7.44

Source: University of California, Davis

Table D-3: Summary Statistics for Outdoor $PM_{2.5}$ Concentration (µg/m^3) Calculated as Daily Means for Whole 24-Hour Period, with Values Averaged by Month

	2018						2019					
Month	**N**	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**	**N**	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**
Jan	17	17.68	7.51	16.58	25.18	29.37	0	.	.	.	.	.
Feb	16	12.31	7.94	11.73	15.53	20.61	13	11.55	6.98	10.49	13.66	15.27
Mar	20	6.63	3.11	6.10	8.38	12.84	23	5.74	2.55	5.14	7.76	9.17
Apr	19	4.83	3.57	4.81	6.18	8.34	25	5.20	2.61	4.48	6.68	9.99
May	18	4.94	3.53	4.37	5.33	9.16	28	5.32	3.38	4.58	6.81	8.76
June	29	6.15	4.57	5.94	7.93	9.20	5	6.11	5.32	5.65	7.28	7.93
July	31	10.67	5.11	7.83	17.14	20.04	29	6.75	4.83	5.80	8.12	12.78
Aug	31	27.96	21.01	27.73	36.06	41.83	30	6.12	4.63	5.78	7.34	9.98
Sept	30	9.10	4.24	6.99	12.20	19.42	27	4.05	2.03	2.85	4.89	10.36
Oct	25	6.65	3.03	4.74	9.54	13.41	23	6.75	2.35	4.30	10.00	14.23
Nov	0	.	.	.	.	.	24	19.42	16.83	20.11	22.73	24.04
Dec	0	.	.	.	.	.						

Source: University of California, Davis

Table D-4: $PM_{2.5}$ Indoor/Outdoor Ratios for the West House Calculated as Daily Means for Nonsource Period (Midnight to 5am), with Values Averaged by Retrofit Status and Season

Pre-Retrofit							Post-Retrofit						
	N	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**		**N**	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**
Winter/Spring	104	1.05	0.27	0.55	1.03	2.22	**Winter/Spring-No Ventilation**	86	3.51	0.61	1.24	2.90	5.67
Summer/Early Fall	148	0.84	0.33	0.63	0.93	1.20	**Summer/Early Fall-SRV Installed**	85	0.50	0.38	0.50	0.61	0.71
							January 2020-Baseline mode	12	0.37	0.18	0.21	0.40	0.99
							January 2020-Optimized Mode	19	0.46	0.18	0.25	0.47	1.11

Source: University of California, Davis

Table D-5: $PM_{2.5}$ Indoor/Outdoor Ratios for the East House Calculated as Daily Means for Nonsource Period (Midnight to 5am), with Values Averaged by Retrofit Status and Season

Pre-Retrofit							Post-Retrofit						
	N	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**		**N**	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**
Winter/Spring	81	6.27	0.82	2.35	5.13	12.54	**Winter/Spring-NightBreeze Heating**	53	3.33	0.40	0.72	1.45	6.71
Summer/Early Fall	131	1.61	0.46	0.69	1.07	2.06	**Summer/Early Fall-NightBreeze Cooling**	68	0.42	0.32	0.44	0.50	0.59

Source: University of California, Davis

Table D-6: $PM_{2.5}$ Indoor Source Concentration for West House Calculated as Daily Means for Source Period (12pm-6pm), with Values Averaged by Retrofit Status and Season

Pre-Retrofit							Post-Retrofit						
	N	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**		**N**	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**
Winter/Spring	121	14.71	6.05	10.71	20.11	30.23	**Winter/Spring-No Ventilation**	95	20.60	7.33	12.56	24.17	38.46
Summer/Early Fall	152	11.47	4.29	9.04	16.92	22.34	**Summer/Early Fall-SRV Installed**	99	6.99	2.40	5.09	9.29	15.53

Source: University of California, Davis

Table D-7: $PM_{2.5}$ Indoor Source Concentration for East House Calculated as Daily Means for Source Period (12pm-6pm), with Values Averaged by Retrofit Status and Season

Pre-Retrofit							Post-Retrofit						
	N	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**		**N**	**Mean**	**25th Pctl**	**Median**	**75th Pctl**	**90th Pctl**
Winter/Spring	94	16.40	1.99	7.53	19.75	49.87	**Winter/Spring-NightBreeze Heating**	72	7.75	0.43	2.83	8.95	26.19
Summer/Early Fall	135	-3.66	-9.40	-1.23	0.93	6.31	**Summer/Early Fall-NightBreeze Cooling**	81	3.35	0.58	1.58	4.72	7.00

Source: University of California, Davis

Formaldehyde

Table D-8: Formaldehyde Level (ppb) Measured in West Home

	Mean	25th Pctl	Median	75th Pctl	90th Pctl	95th Pctl	Max
Pre-retrofit Winter/Spring (April 2018)	18.15	14	18.5	23	25	26	31
Post-retrofit- Winter/ spring-No Ventilation (March 2019)	21.20	20	23	25	27	27	29
Post Retrofit- SRV installed (Jan 2020)	12.13	9	11	14	17	19	25

Source: University of California, Davis

Table D-9: Formaldehyde Level (ppb) Measured in East Home

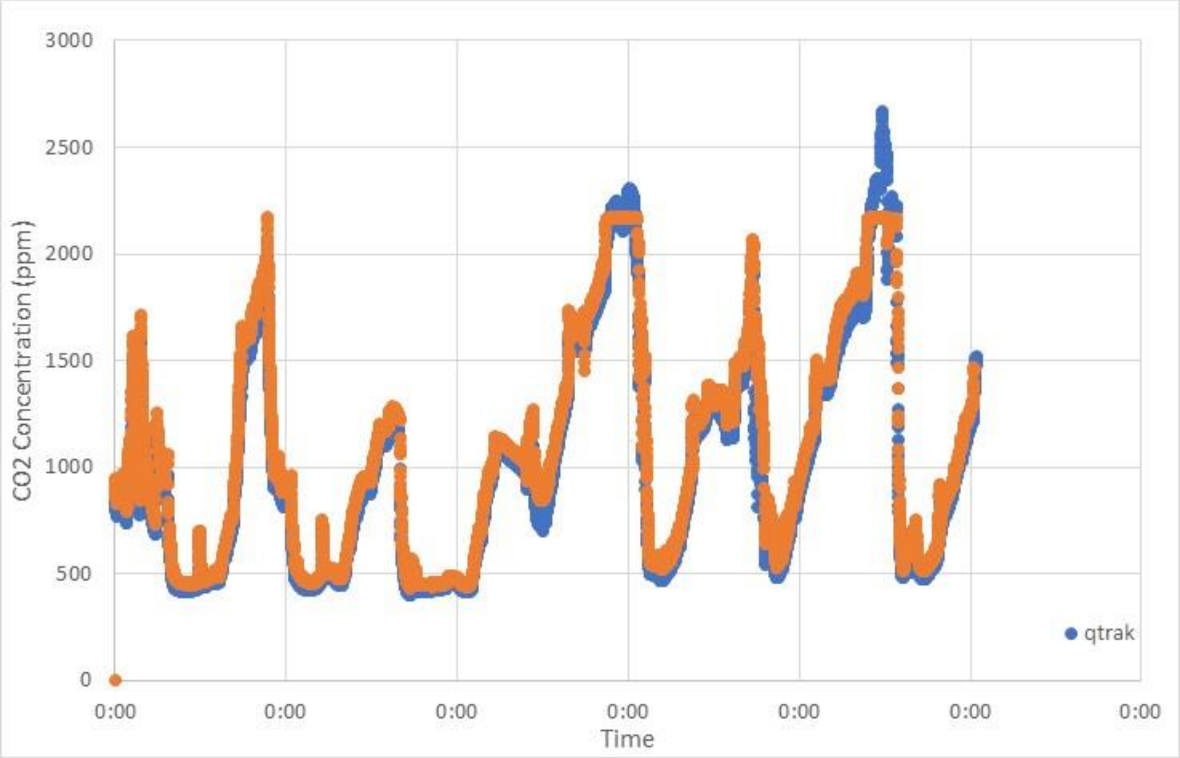
	Mean	25th Pctl	Median	75th Pctl	90th Pctl	95th Pctl	Max
Pre-retrofit Winter Spring (April 2018)	17.51	14	17	21	23	25	30
Post-retrofit- Winter/spring- NightBreeze heating (March 2019)	13.31	12	14	15	16	17.05	39
Post-retrofit Summer NightBreeze cooling (July 2019)	11.33	9	9	13	15.8	18	42

Source: University of California, Davis

Quality Assurance/Quality Control

The Vaisala CO_2 monitors in the home were compared with TSI Q-trak monitors as a QA/QC activity. Three comparisons periods were completed in the West home, with two resulting in comparable data, as the Q-trak was accidently unplugged inside the West house by the residents during the July sampling period. Four comparison periods were completed in the East home. Overall, there was good agreement between the two monitors. The Vaisala monitors read slightly higher than the Q-trak, with the Vaisala monitors reading 5 percent higher than the Q-trak on average. Therefore, the Vaisala concentrations were multiplied by 95 percent. One problem with the Vaisala is that in the West house, the highest concentration the monitor records is approximately 2200 ppm and in the East House is approximately 2300 ppm. An example of this can be seen in the figure below. Time periods where the concentrations were higher than this were excluded from the comparison. Each co-location period was also plotted against each other and an R^2 value was calculated, and the data was fit with a trend line, with results listed in the table below. The R^2 values were all above 0.97 with the exception of the April 2019 values in the west home, which had an R^2 value of 0.92. These high R^2 values indicate high quality data.

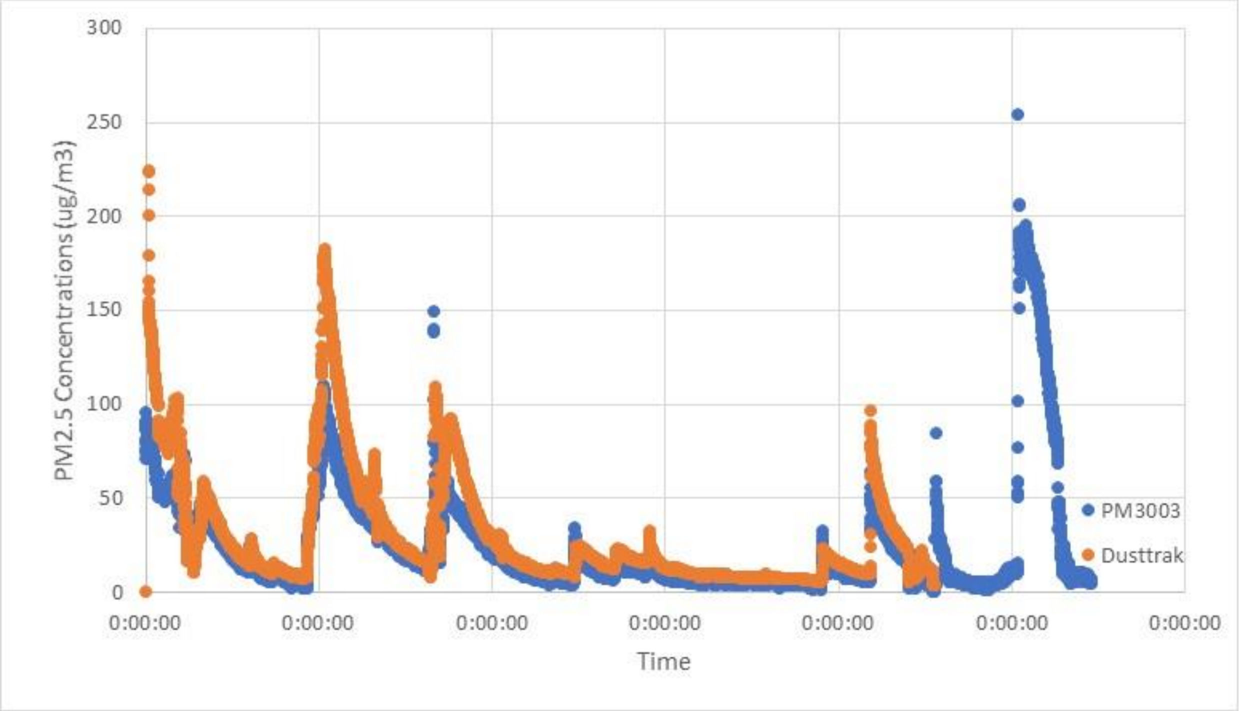
Figure D-1: Comparison of Carbon Dioxide Concentrations with Vaisala and Q-trak, as Measured in East House in April 2019 Over 5 Days



Source: University of California, Davis

The PMS3003 monitors inside and outside the homes were compared with TSI Dusttrak monitors for one week on five separate occasions for indoor monitoring and on three occasions for outdoor monitoring. The Dusttrack was accidently unplugged inside the West house by the residents during the July sampling period. The general trend of the data is very similar between the two monitors, see the figure below comparing the concentration over time. For each co-location period, the two instruments were plotted against each other and an R^2 value was calculated, and the data was fit with a trend line, with results listed below. The R^2 values were all above 0.84, with the exception of the May 2018 values in the east home and outdoors, which had an R^2 values of 0.73 and 0.53, respectively. The low R2 for the one outdoor comparison is due to the fact that outdoor levels were very low during that sampling period and thus there was little variability during the sampling problem. Therefore, small changes in the outdoor concentrations resulted in a low correlation coefficient. Both the PMS3003 and the Dusttrak are known to report values that are likely higher than would be measured with a gravimetric method. However, since the primary goal of this project is to compare pre- and post- values, this does not present a problem for the conclusions in this report. Values in this report, however, may be overestimates of exposure, particularly on days with several high-concentration events.

Figure D-2: Comparison of PM$_{2.5}$ Concentrations with PM3003 and Dusttrak, as Measured in East House in April 2018 Over 5 Days



Source: University of California, Davis

Table D-10: Vaisala Comparison to Q-trak for Carbon Dioxide Concentration Comparisons in West Home

Sampling Period	West (SRV)			Vaisala					Qtrak					Ratio of Means
	Y	R^2	N	mean	25%	median	75%	95%	mean	25%	median	75%	95%	
August 2018 pre-retrofit	0.9834x -44.399	0.98	2260	1625	1491.18	1615.62	1757.83	1921.51	1553.26	1421	1544.00	1689.00	1842.05	0.96
April 2019 sealed, no mechanical ventilation	0.967x-5.5184	0.92	2630	1737	1659.10	1757.34	1923.52	2090.85	1674.05	1577	1715.50	1853.75	2016.00	0.96
July 2019 post retrofit with SRV installed	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Source: University of California, Davis

Table D-11: Vaisala Comparison to Q-trak for Carbon Dioxide Concentration Comparisons in East Home

Sampling Period	East (NightBreeze)			Vaisala					Qtrak					Ratio of Means
	Y	R^2	N	mean	25%	median	75%	95%	mean	25%	median	75%	95%	
August 2018 pre-retrofit	0.9777x-42.072	0.99	8017	1570	1341.76	1586.58	1813.19	2050.16	1492.6	1277	1496.00	1732.00	1977.20	0.95
April 2019 Night-Breeze heating mode	0.9307x-31.132	0.97	3566	1525	1298.09	1473.14	1844.05	2020.93	1388.12	1170	1347.00	1686.00	1860.00	0.91
April 2019 Night-Breeze cooling mode	0.9415x-12.498	0.99	9342	985	562.20	932.11	1267.41	1819.02	915.26	511	865.00	1186.00	1710.00	0.93
July 2019 Night-Breeze cooling mode	1.0152x-30.144	0.99	7954	678	458.38	598.62	862.134	1135.92	658.20	436	574.00	837.00	1133.70	0.97

Source: University of California, Davis

Table D-12: PM3003 Comparison to Dusttrak for PM2.5 Concentration Comparisons in West Home

Sampling Period	West (SRV)			Vaisala					Qtrak					Ratio of Means
	Y	R^2	N	mean	25%	median	75%	95%	mean	25%	median	75%	95%	
April 2018 pre- retrofit	1.8037x+ 0.8362	0.93	10141	8.93	2	4	11	37	17.02	5	8	18	67	1.91
May 2018 pre-retrofit	1.347x+0.4242	0.88	2149	14.2	3	6	16	48	19.61	3	9	23	69	1.38
August 2018 pre-retrofit	1.33x+1.6817	0.89	9106	23.8	18	23	29	42	33.40	25	31	38	60	1.40
March 2019 sealed, no mechanical ventilation	1.7466x+ 1.7708	0.88	9028	7.35	1	4	9	30	14.62	3	9	19	55	1.99
July 2019 post retrofit with SRV installed	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Source: University of California, Davis

Table D-13: PM3003 Comparison to Dusttrak for PM2.5 Concentration Comparisons in East Home

Sampling Period	East (NightBreeze)			Vaisala					Qtrak					Ratio of Means
	Y	R^2	N	mean	25%	median	75%	95%	mean	25 %	median	75%	95%	
April 2018 pre- retrofit	1.5397x-2.1051	0.93	9063	20.60	6	13	30	59	29.92	10	17	36	95	1.45
May 2018 pre-retrofit	1.5463x+3.0599	0.73	2149	19.20	13	16	22	36	32.79	22	28	36	65	1.71
August 2018 pre-retrofit	1.4213x+4.8762	0.91	6098	11.30	7	11	14	21	20.97	15	20	25	35	1.85
March 2019 Night-Breeze heating mode	1.9277x+2.7483	0.86	9021	4.25	0	2	3	16	10.94	4	6	8	28	2.57
July 2019 Night-Breeze cooling mode	1.8392x-0.1293	0.84	8420	3.46	1.5	2.7	4	12	6.24	3	4	6	23	1.80

Source: University of California, Davis

Table D-14: PM3003 Comparison to Dusttrak for PM2.5 Concentration Comparisons Outdoors

Sampling Period	Outside			Vaisala					Qtrak					Ratio of Means
	Y	R^2	N	mean	25%	median	75%	95%	mean	25%	median	75%	95%	
May 2018	0.4224x-1.7009	0.54	2149	5.53	4	5	7	10	0.63	0	0	0	4	8.72
August 2018	1.5347+0.8556	0.83	9082	31.1	22	31	40	51	48.52	33	45	60	87	0.64
March 2019	1.1974x+3.7669	0.94	6104	15.1	10	15	20	26	21.89	15	23	29	35	0.69

Source: University of California, Davis

APPENDIX E:
Occupant Surveys

The following tables contain the occupant responses to the research team's surveys conducted throughout the project. The information is organized by home. Responses in 2018 seasons are pre-retrofit while the responses for 2019 seasons are post-retrofit.

West House

Table E-1: Typical Home Occupancy by Season

Summer 2018	Fall 2018	Winter 2018/2019	Spring 2019	Summer 2019	Fall 2019
Occupied by multiple residents day, evening, and night M-Su.	Occupied by multiple residents day, evening, and night M-Su.	Occupied by multiple residents day, evening, and night M-Su.	Occupied by multiple residents day, evening, and night M-Su.	Occupied by multiple residents day, evening, and night M-Su.	Occupied by multiple residents day, evening, and night M-Su.

Source: University of California, Davis

Table E-2: Home Cooling

	Summer 2018	Fall 2018	Spring 2019	Summer 2019	Fall 2019
Daytime					
Setpoint (°F)	75	70-75	73	65	65
Respondent's assessment*	Comfortable	Comfortable	Comfortable	Warm	Comfortable
Spouse's assessment*	Warm	Comfortable	Comfortable	Warm	Comfortable
Open windows/doors	Yes, Bathroom window is always open to remove humidity since there is no exhaust fan	Yes, Bathroom window is left open because there's no vent	Yes, Bathroom window is left open because there's no vent	No, too hot	No
Nighttime					
Setpoint (°F)	Off	Off	74-75	65	Off
Respondent's assessment*	n/a	n/a	Comfortable	Warm	n/a
Spouse's assessment*	n/a	n/a	Comfortable	Warm	n/a
Open windows/doors	No, For safety	No	No, for safety	No, too hot	No
Use of fans	No	No	No	Yes	No

***Options were: Warm, Comfortable, Cold**

Source: University of California, Davis

Table E-3. Subjective Assessments of Cooling

	Summer 2018	Fall 2018	Spring 2019	Summer 2019	Fall 2019
How well does the A/C work on the hottest days [of the season]? *Well, Okay, Not well*	Okay	Well	Don’t know yet	Not well	Not well
How satisfied are you with your home’s A/C? *Very satisfied, Satisfied, Dissatisfied, Very dissatisfied*	Satisfied	Very satisfied	Don’t know yet	Very dissatisfied	Very dissatisfied
How much noise does the A/C make? *A lot, A little, Almost none*	A little	N/A	N/A	A lot	A lot
What do you like about the A/C in your home?	Always works well	N/A	N/A	Thermostats are well lit	Thermostats are well lit
What do you not like about the A/C in your home?	“In winter the gas bill is a bit high, higher than summer”	N/A	N/A	Noise, slowness, doesn’t chill the air	Noise, slowness, doesn’t chill the air
Do you use the A/C LESS than you would ideally like to? *Yes, No, and why*	No	No	No	No	No
Do you use the A/C MORE than you would ideally like to? *Yes, No, and why*	No	No	No	Yes	Yes

Source: University of California, Davis

Table E-4: Home Heating

	Winter 2018/19	Fall 2019
Daytime		
Setpoint (°F)	74	n/a
Respondent's assessment*	Comfortable	
Spouse's assessment*	Comfortable	
Nighttime		
Setpoint (°F)	75-76	72-73
Respondent's assessment*	Comfortable	Comfortable
Spouse's assessment*	Comfortable	Comfortable
Used space heaters?	no	no

***Options were: Warm, Comfortable, Cold**

Source: University of California, Davis

East House

Table E-5: Typical Home Occupancy by Season

Summer 2018	Fall 2018	Winter 2018/2019	Spring 2019	Summer 2019	Fall 2019
Unoccupied M-F during business hours. Occupied evenings, nights, and weekends.	Unoccupied M-F during business hours. Occupied evenings, nights, and weekends.	Unoccupied M-F during business hours. Occupied evenings, nights, and weekends.	Unoccupied M-F during business hours. Occupied evenings, nights, and weekends.	Unoccupied M-F during business hours. Occupied evenings, nights, and weekends.	Unoccupied M-F during business hours. Occupied evenings, nights, and weekends.

Source: University of California, Davis

Table E-6: Home Cooling

	Summer 2018	**Fall 2018**	**Spring 2019**	**Summer 2019**	**Fall 2019**
Daytime					
Setpoint (°F)	73	73	Off	73	73
Respondent's assessment*	Comfortable	Comfortable	n/a	Comfortable	Comfortable
Spouse's assessment*	Comfortable	Comfortable	n/a	Comfortable	Comfortable
Open windows/doors	No, was not cool enough to leave them open.	Yes, For fresh air	Yes, once a week for fresh air	No, air quality and security	Yes, when home
Nighttime					
Setpoint (°F)	75	Off	Off	73	Off
Respondent's assessment*	Comfortable	n/a	n/a	Comfortable	n/a
Spouse's assessment*	Comfortable	n/a	n/a	Comfortable	n/a
Open windows/doors	Yes, Bedroom window	No, for safety	No, for safety	No, air quality and security	No, air quality and security
Use of fans	No	No	No	No	No

***Options were: Warm, Comfortable, Cold**

Source: University of California, Davis

Table E-7: Subjective Assessments of Cooling

	Summer 2018	Fall 2018	Spring 2019	Summer 2019	Fall 2019
How well does the A/C work on the hottest days [of the season]? *Well, Okay, Not well*	Well	Well	Don't know yet	Okay	Okay
How satisfied are you with your home's A/C? *Very satisfied, Satisfied, Dissatisfied, Very dissatisfied*	Very satisfied	Very satisfied	Don't know yet	Satisfied	Satisfied
How much noise does the A/C make? *A lot, A little, Almost none*	Almost none	n/a	n/a	A little	n/a
What do you like about the A/C in your home?	It starts right away, keeps temperatures cool without resetting it.	n/a	n/a	Vents open when cold outside, not loud, easy to control	n/a
What do you not like about the A/C in your home?	Nothing	n/a	n/a	Didn't get cold enough	n/a
Do you use the A/C LESS than you would ideally like to? *Yes, No, and why*	No	No	No	No	No
Do you use the A/C MORE than you would ideally like to? *Yes, No, and why*	No	No	No	No	No

Source: University of California, Davis

Table E-8: Home Heating

	Winter 2018/19	Fall 2019
Daytime		
Setpoint (°F)	72	n/a
Respondent’s assessment*	Comfortable	n/a
Spouse’s assessment*	Comfortable	n/a
Nighttime		
Setpoint (°F)	Off	n/a
Respondent’s assessment*	Comfortable	n/a
Spouse’s assessment*	Comfortable	n/a
Used space heaters?	no	No

***Options were: Warm, Comfortable, Cold**

Source: University of California, Davis