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Energy Research and Development Division

FINAL PROJECT REPORT

Integrating Smart Ceiling Fans and Communicating Thermostats for Energy-Efficient Comfort

November 2022 | CEC-500-2022-015

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Contract Number: EPC-16-013

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ACKNOWLEDGEMENTS

The authors would like to thank the many people whose efforts led to the success of this project:

- UC Berkeley: Stefano Schiavon, Sonja Salo, Jovan Pantelic, Fred Bauman, Wenhua Chen, Yingdong He, Maohui Liu, Marta Delgado Lombardo, Carlos Duarte, Tom Parkinson, and Amy Mostacho.
- TRC: Mia Nakajima, Abhijeet Pande, Kristen Bellows
- Big Ass Fans: Jay Fizer, Christian Taber, Justin Risner, Pete Maley, Michael Smith, Jayme Webb, Michael Harp.

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 CEC 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 CEC 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.

Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort is the final report for the Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort project (Contract Number: EPC-16-013) conducted by the Center for the Built Environment, a representative of The Regents of the University of California. 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 research project identified and tested the integration of smart ceiling fans and “communicating” thermostats. These highly efficient ceiling fans use as much electricity as an LED light bulb and have onboard temperature and occupancy sensors for automatic operation, based on space conditions. The Center for the Built Environment (CBE) at UC Berkeley led the research team including TRC Companies (TRC), Association for Energy Affordability (AEA), and Big Ass Fans (BAF).

The research team conducted laboratory tests, installed 99 ceiling fans and 12 thermostats in four affordable multifamily housing sites in California’s Central Valley, interviewed stakeholders to develop a case study, developed an online design tool and design guide, outlined codes and standards outreach, and published several papers.

The project team raised indoor cooling temperature setpoints and used ceiling fans as the first stage of cooling; this sequencing of ceiling fans and air conditioning reduced energy consumption, especially during peak periods, while providing thermal comfort. The field demonstration resulted in 39 percent measured compressor energy savings during the April-October cooling season when compared with baseline conditions. Weather-normalized energy use varied from a 36 percent increase to 71 percent savings, with median savings of 15 percent across all of the 13 compressors that were measured. This variability reflects the diversity in buildings, mechanical systems, prior operation settings, space types, and occupants’ schedules, preferences, and motivations. All commercial spaces with regular occupancy schedules showed energy savings on an absolute basis before normalizing for warmer intervention temperatures, and 10 of 13 sites showed energy savings on a weather-normalized basis. The ceiling fans provided cooling for one site for months during hot weather when the cooling equipment failed. Occupants reported high satisfaction with the ceiling fans and improved thermal comfort. This technology can apply to both new and retrofit residential and commercial buildings.

Keywords: multifamily housing, HVAC, cooling, fans, air movement, thermal comfort, energy efficiency

Please use the following citation for this report:

Rafter, Paul, Dana Miller, Hui Zhang, Therese Peffer, Gail Brager, Lindsay Graham, Elaina Present, Ed Arens, David Douglas-Jaimes, Gwelen Paliaga, Andy Brooks, Sebastian Cohn, and Mitch Greene. 2022. *Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort.* California Energy Commission. Publication Number: CEC-500-2022-015.

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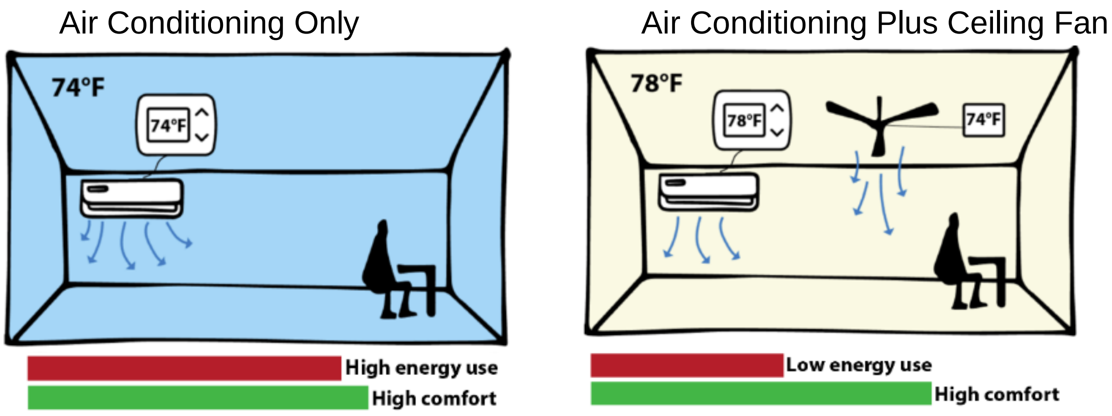
Background

California's electricity peak demand is driven by summertime air conditioning loads in both residential and commercial buildings. Air conditioning has become a necessity in many of the state's hottest climate zones. Extreme heat kills more Americans every year than any other weather-related disaster, and as climate change advances heat waves are increasing in intensity and frequency. Low-income populations are more vulnerable since these communities are often in areas that are disproportionately warmer than wealthier communities; housing tends to be less energy efficient, and residents pay a greater percentage of their income for energy. This research project studied low-income populations, though its energy-saving benefits apply to all Californians.

Ceiling fans cool occupants with a fraction of the electricity required by conventional air conditioners. Modern, efficient ceiling fans with electrically commutated direct current motors and improved blade design use only 2 watts to 30 watts of electricity when compared with 2,000 watts to 3,500 watts for a typical 1.5-ton to 3-ton air conditioning system. These fans can offset a 4°F to 8°F (2.2°C to 4.4°C) increase in indoor air temperature while maintaining or improving occupant comfort. Some "smart" ceiling fans have onboard temperature and occupancy sensors for automatic operation within a given space. These devices improve occupant comfort and perceived air quality while decreasing energy consumption, especially important during peak demand. In addition, ceiling fans provide a back-up cooling strategy during power outages since these low-power devices can be powered by very small batteries or by solar photovoltaic systems. This project supports three of California's energy efficiency goals: doubling energy efficiency savings by 2030, removing and reducing barriers to energy efficiency in low-income and disadvantaged communities, and reducing greenhouse gas emissions from the building sector.

Figure 1 illustrates this study's essential concept.

Figure 1: Using Ceiling Fans to Provide Cooling to Lower Energy Use



Left: Air conditioning provides cooling and comfort—at an energy and carbon cost. Right: Coordinating ceiling fans with air conditioning can provide comparable comfort with less energy.

Source: Dana Miller, UC Berkeley

On the left, traditional air conditioning provides cooling and comfort. On the right, a ceiling fan provides the cooling effect of moving air and creates comparable comfort at 78°F (26°C) when compared with still air at 74°F (23°C). Coordinating and sequencing ceiling fans with air conditioning provides greater comfort with less energy by initially cooling with air movement (the fan starts operating above 74°F) before adding air conditioning at a higher temperature of 78°F.

There are several barriers to rapid deployment of ceiling fans to reduce energy consumption. One is the coordination of ceiling fan controls with heating, ventilation, and air conditioning (HVAC) controls, including thermostats, to adjust air conditioning setpoints when ceiling fans are operating. Another is the relatively high cost of automated ceiling fans and a limited number of available models. Other barriers stem from general lack of knowledge of how these technologies benefit occupants by "cooling people, not spaces," and the erroneous perception that they consume large amounts of electricity. Other barriers include the installation of ceiling fans; designers often lack knowledge of the optimal size, number, spacing, and location of ceiling fans, especially in commercial spaces.

These barriers encompass multiple disciplines including thermal comfort, architecture, engineering, and psychology, in multiple sectors including manufacturers, housing developers, designers, facility managers, and end users. These broad, multi-faceted effects make it difficult to smooth the technology's path to market; it is therefore essential that field studies effectively demonstrate potential energy savings from integrated ceiling fans and thermostat systems to accelerate widespread adoption.

Project Purpose

The goal of the Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort project was to identify and test optimal configurations for the integration of two newly available technologies — smart ceiling fans and communicating thermostats — to reduce energy consumption while providing improved comfort. This integrated solution can potentially automate energy savings in ways customers not only accept, but actually seek, for it provides improved comfort and lower energy costs. The project examined the impact of such technology integrations and provides guidance to manufacturers, designers and engineers as they implement these new energy-saving technologies. Specific study objectives were to:

1) Demonstrate the energy savings and improved comfort potential of this integrated system in retrofit applications.
2) Identify and address market barriers to wider acceptance and adoption.
3) Provide guidance on how to implement this technology into energy efficiency retrofit programs and policies.
4) Develop standard rating methods, a design web tool, a design guide, and energy code language to facilitate widespread adoption.

Beginning in October 2020, the State of California now requires mandatory time-of-use electricity rates for the state's three large investor-owned utilities: Pacific Gas and Electric Company, Southern California Edison, and San Diego Gas and Electric. In Pacific Gas and Electric Company's service territory in Central and Northern California, residential customers have transitioned to time-of-use electricity rates of between $0.32 and $0.40 per kilowatt-hour (kWh) every day from 4 p.m. to 9 p.m. from June-September. These hours exactly coincide with the hottest temperatures of the day. (The Tier 1 rate for most residential homes in PG&E’s service territory in 2019 averaged $0.23 per kWh.) This research provides timely, workable solutions for lowering residential energy bills.

The audience for this research includes residential or small commercial ratepayers, designers of commercial and residential buildings, fan and thermostat manufacturers, and policy makers.

Project Approach

The Center for the Built Environment (CBE) at UC Berkeley led the research team, which also included TRC Companies, the Association for Energy Affordability, and Big Ass Fans to study the integration of smart programmable ceiling fans with advanced thermostats at affordable multifamily housing sites, shown in Figure 2.

Figure 2: Field Demonstration Sites

Source: Therese Peffer, UC Berkeley; David Douglass-Jaimes, TRC

The project team conducted six tasks in addition to the project’s general project tasks, including:

- Laboratory testing to analyze fan air flows with different furniture and configurations.
- Multifamily common space and dwelling unit field demonstrations.
- Technology readiness to identify market factors, barriers, and case studies.
- Evaluation and Project Benefits.
- Knowledge and technology transfer activities.

The main barriers encountered were in the project’s field studies. The smart ceiling fan and smart thermostat did not directly integrate as expected. Ideally, ceiling fans communicate directly with thermostats to adjust air conditioning setpoints or prompt occupants to increase setpoints to save electricity. Some end users inadvertently changed operation of their HVAC blower fans or other controls, while others found the newly installed thermostats challenging. The team produced educational materials about the thermostat settings and blower fan operation.

Project Results

The research team successfully conducted laboratory and field tests, interviewed stakeholders to develop a case study, developed an online design tool and guide, and outlined codes and standards outreach, which together met the goals and objectives of the project.

Field Studies

Overall, the field demonstration returned compressor energy savings of 39 percent during the April-October cooling season when compared with baseline conditions. Ceiling fans used an average of only 8.0 watts when operating. Total ceiling fan energy consumption during the April-October cooling season was less than 3 percent of compressor energy use. When additionally normalized for weather, compared with the baseline period, energy use per zone varied from an increase of 36 percent to savings of 71 percent, with median savings of 15 percent across all of the 13 compressors that were measured. This variability reflects building diversity, mechanical systems, prior operation settings, space types, and occupants' schedules and preferences. All commercial spaces with regular occupancy schedules had measured energy savings, and 10 of 13 sites showed energy savings on a weather-normalized basis. Energy savings frequently coincided with peak electricity demand, which had additional emissions and grid benefits.

The low-energy ceiling fans provided an additional resilience benefit when air conditioning at one site unexpectedly failed during hot weather. The ceiling fans improved comfort while the site continued to operate, and the project team helped the facilities manager identify the problem and solution. While not the focus of this study, the ability of efficient ceiling fans to provide cooling for an order of magnitude less power than traditional air conditioners suggests they could additionally provide supplemental cooling during equipment failure, or feasibly rely upon battery or solar-powered sources during power outages.

Occupant interviews and surveys revealed that all occupants reported high satisfaction with the ceiling fans. The fans increased the range of thermal comfort and acceptability for all participants, who reported that the fans provided both adequate cooling and improved indoor air quality. Occupants were pleased with the ability to cool the space quickly and effectively. Even on sites where the measured energy data did not show savings, occupants still used the fans regularly. These automated ceiling fans had temperature and occupancy sensors that allowed them to operate automatically. This automated speed feature was widely accepted by occupants. One onsite office worker reported that the ceiling fans helped by his "not having to worry about being too hot or too cold in the office."

The project team outlined several lessons learned, especially regarding behavior change. At some sites occupants did not pay for their energy costs, which likely impacted air conditioning setpoints and subsequent energy savings. The research team actively encouraged occupants to set desired thermostat setpoints and change their fan-use behaviors over a 15-month period. Development of custom fan firmware was required to fully implement automated fan operation. Although the results of the field demonstrations showed substantial energy savings, there is a need for further development to spur widespread adoption. The technologies could be simplified, and their usability improved, especially for the thermostat. Many occupants felt that the Ecobee thermostats had a steep learning curve and were challenging to use at first. The lack of multiple language support in the thermostats was also an issue for many occupants. At least one occupant inadvertently scheduled the blower fan to operate continuously, which substantially increased overall energy consumption. Additionally, the networked fans and thermostats reportedly caused Wi-Fi interference for a few residents, potentially from router congestion.

Case Studies

The research team at the Center for the Built Environment conducted interviews with architects, engineers, and facilities managers from California and from around the country to create a case study of commercial spaces with existing ceiling fans. Researchers found that just 25 percent of the 20 projects discussed had any type of automation in their ceiling fan controls. Occupants also often chose to turn the ceiling fans on even when airspeeds were too low to create a cooling effect. One building used upward air flow to provide more even distribution of air flow throughout the space.

Laboratory Studies

The laboratory studies performed during this project yielded new insights, including a new method for designers to estimate airspeeds under a set of fan and room conditions, airflows around furniture from ceiling fans, and design of the distribution ductwork. These findings have been incorporated into project reports along with an online design tool and a design guide, both publicly available and developed in this project. The aim of these resources is to make it easier to incorporate air movement into designs.

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

The team shared project results through multiple channels. Outreach included six papers published and 18 presentations at various venues to developers, manufacturers, policy makers, and end users. Through the students hired, future thought leaders were trained. The project also developed an online design tool, which can be used by designers, architects, and engineers to provide recommendations for their clients.

Ceiling fans are already relatively common in residences; the U.S. Energy Information Administration estimates that roughly 80 percent of single-family homes and over 40 percent of multifamily units have at least one ceiling fan. The majority of these, however, are probably older, less efficient models with few if any onboard sensors and controls for automation. As an established market for ceiling fans, the residential sector is an ideal near-term market for integrating smart ceiling fans and communicating thermostats. Large-diameter ceiling fans are increasing in popularity in industrial and warehouse applications, however, both as supplements and alternatives to mechanical cooling. The development of resources and information on the thermal comfort and energy-saving benefits of ceiling fans could spur longer-term growth in a range nonresidential building types including offices, schools, hospitality, and other commercial buildings.

Though the widespread existence of ceiling fans in residences suggests a nearly saturated market, a single ceiling fan is not enough to provide consistent thermal comfort. Multiple ceiling fans, strategically placed throughout a home, can provide both thermal comfort and energy savings. On the nonresidential side, with the exception of specialized applications such as warehouses and industries, ceiling fan market penetration is nearly nonexistent, which presents a major opportunity for as-yet-unrealized energy savings.

There have so far been limited resources to broadly communicate the benefits of ceiling fan models to building owners or clients. This research significantly bridged that barrier. The team additionally conducted codes and standards outreach activities, including:

- Development of a new American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard, ASHRAE 216, entitled "Methods of Test for Determining Application Data of Overhead Circulator Fans."
- A proposed Addendum C to ASHRAE Standard 55, which defines thermal environmental control classification levels for some compliance options.
- A description of barriers and opportunities for ceiling fans in the state's building energy efficiency standards.
- A discussion of building code considerations and opportunities for additional clarification of code requirements for ceiling fans.

The development of these new industry standards provides metrics and performance data that reliably integrate alternative thermal comfort strategies, including ceiling fans and higher thermostat setpoints.

Benefits to California

Automated ceiling fans and communicating thermostats together provide greater energy security and reliability: energy and cost savings, peak energy reductions, emission reductions, and cooling. Though ceiling fans are often considered purely residential appliances, and often categorized as purely lighting products, ceiling fans provide thermal comfort benefits in both nonresidential and residential applications.

The project team estimates statewide energy, cost, and CO_2 emission reductions of 30 percent from both the ceiling fans and thermostats. The team additionally estimates that a 15 percent market penetration of California buildings over the next 15 years will yield annual reductions of 736 GWh of electricity, $125M, and 537M pounds of CO_2 emissions. This estimate includes multifamily, single family, schools, offices, and retail spaces. For occupied commercial sites with high cooling potential, this technology represents a cost-effective retrofit option (less than a 7-year payback), even at current market prices and utility rates. Identifying buildings and spaces with favorable characteristics would also increase the technology's reach and maximize future energy savings. The cost of the equipment and installation is still greater than annual utility-bill cooling costs, so this technology would not be a cost-effective option if considering energy savings alone. The team developed best practices that will lead to broader market penetration and ultimately reduce the costs of adoption and operation.

CHAPTER 1: Introduction

Background

California's peak electricity demand is driven by summer air conditioning loads in residential and commercial buildings. Air conditioning has become a necessity; extreme heat events kill more Americans every year than any other weather-related phenomenon (U.S. Department of Homeland Security 2020), and as climate change advances, heat waves are increasing in both intensity and frequency (Center for Climate and Energy Solutions (C2ES) 2017). Cooling workplaces and homes through air conditioning has saved lives during heat waves, and has provided thermal comfort that improves satisfaction and productivity, especially in the last few decades—but at tremendous cost. The U.S. uses more electricity for cooling than the entire African continent consumes for all uses. (Cox 2012). More and more residences in the U.S. have air conditioning. In 2020 88 percent of American residences had air conditioning (U.S. Energy Information Administration (EIA) 2020). This growing energy use contributes to greenhouse gases[1] and ozone depletion. This air-conditioning use leads to physiological "addiction," which causes people to become less tolerant of temperatures outside a narrow range. In California, residential air conditioning exacerbates the already high cost of living, which contributes to California's high poverty rate, which is the highest in the U.S. Low-income households in California spend 67 percent of their income on housing, about 11 percent more than low-income households in the rest of the U.S. (Alamo, Uhler, and O'Malley 2015). Compared with average households, low-income households are less likely to have compact fluorescent bulbs and low-flow showerheads, but are 25 percent more likely to have energy-intensive space heaters and 50 percent more likely to rely on window air conditioning units (Berelson 2014). Furthermore, the cost of electricity from California's large investor-owned utilities (IOU) ranges from $0.18 to $0.23 per kilowatt hour kWh), compared with $0.13 for the national average (U.S. Energy Information Administration [EIA] 2019). In Pacific Gas and Electric Company's (PG&E) service territory in Central and Northern California, residential customers will soon move to time-of-use (TOU) rates where customers will have electric rates of between $0.32 and $0.40 per kilowatt-hour (kWh) from 4 p.m. to 9 p.m., June through September, which exactly coincide with the hottest temperatures of the day (Pacific Gas and Electric Company [PG&E]) 2019).

Air movement, like that from ceiling fans, provides cooling, but with a fraction of the energy required by heating, ventilation and air conditioning (HVAC) systems. Modern efficient ceiling fans with electrically commutated DC motors and improved blade design use only between 2 watts (W) and 30 W (compared with between 2,000 W and 3,500 W for a typical 1.5- to 3-ton air conditioning system). By producing 1.5 to 2 miles-per-hour (mph) (0.7 to 0.9 meters per second) air movement near building occupants, these fans can offset a 4°F to 8°F (2.2°C to 4.4°C) increase in indoor air temperature. Some of these modern, highly efficient ceiling fans

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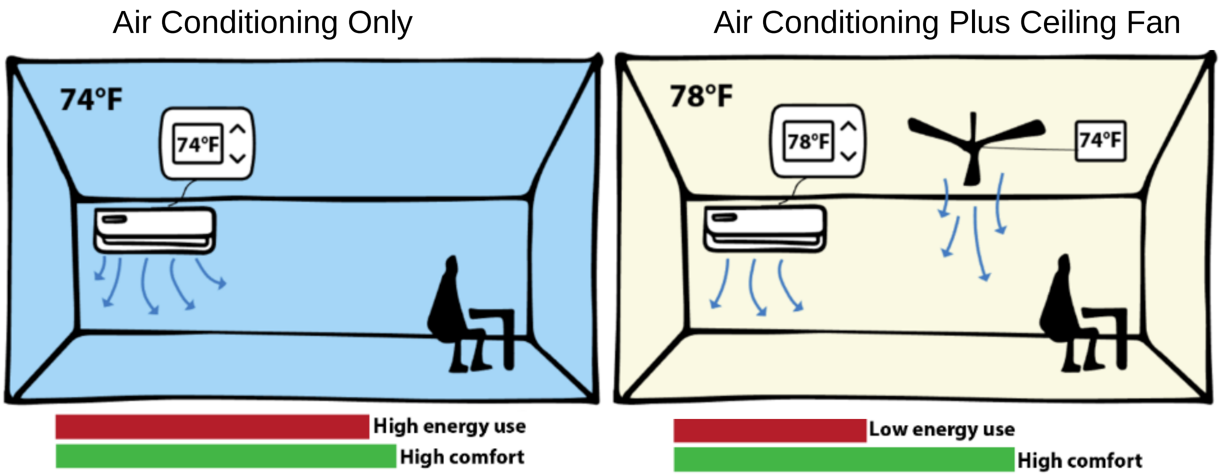
[1] Project Drawdown's most effective solution for reducing greenhouse gas emissions is the management and destruction of refrigerants already in circulation in air conditioners and refrigerators. (Project Drawdown 2019).

also have onboard temperature and occupancy sensors allowing them to operate automatically based on conditions in the space, improving both usability and occupant satisfaction. These devices improve occupant comfort and air quality while decreasing energy consumption, especially during California’s peak electricity demand periods. In addition, ceiling fans provide a back-up cooling strategy during power outages since these low-power devices can be battery-powered.

Allowing higher indoor temperatures reduces a building's total HVAC energy by an average of 5 percent per ºF. These savings are even greater in climate zones where natural ventilation or evaporative cooling systems are used instead of compressor-based cooling, or where there are more airside economizer hours (such as California).

Figure 1: Using Ceiling Fans to Provide Cooling



Air Conditioning Only

Air Conditioning Plus Ceiling Fan

Left: Air conditioning provides cooling and comfort—at an energy and carbon cost. Right: Coordinating and sequencing ceiling fans with air conditioning can provide comparable comfort with less energy by initially cooling with air movement (fan starts operating above 74°F) before adding air conditioning at a higher temperature (78 °F). The immediate cooling effect of moving air (‘wind chill effect’) creates comparable comfort with gentle air movement at 78 °F or still air at 74 °F.

Source: Dana Miller, UC Berkeley

Project Goals and Objectives

The goal of the project was to identify optimal configurations for the integration of two technologies: smart ceiling fans and communicating thermostats. This integrated solution can potentially automate energy savings and provide improved comfort and lower energy costs. The project examined the impact of these technology integrations, and provides guidance to manufacturers, designers and engineers as they adopt these new energy-saving technologies.

This project conducted primary research to increase understanding and insight into energy-use patterns and customer acceptance of the integrated installation of smart ceiling fans and smart thermostats. The objectives of this project were to: (1) demonstrate energy savings and improved comfort in integrated smart ceiling fan and smart thermostat systems; (2) identify and address market barriers to broad adoption; (3) provide guidance on how to incorporate this technology into energy efficiency retrofit programs and policies; and (4) develop standard rating methods, a design guide, and energy code language to ease more widespread implementation.

To achieve these goals, the interdisciplinary team studied the integration of smart Haiku® ceiling fans from Big Ass Fans with SenseME™ control and the Ecobee smart thermostat through laboratory testing and demonstration pilots at affordable multifamily housing sites. The project team also conducted interviews with designers and engineers to develop a case study, a design guide, and an online design tool.

The research team installed 99 smart ceiling fans and 12 smart thermostats in 4 multifamily sites in California’s Central Valley. The team installed monitoring equipment at the sites (Summer 2017), installed fans and thermostats (Summer 2018), and conducted several laboratory tests to determine the impact of various parameters (e.g., multiple fans, ceiling height, fan diameter). The team additionally surveyed the office workers and residents who occupied both common rooms and dwelling units and monitored the effects of high indoor temperatures and ceiling-fan use to reduce energy consumption while maintaining comfort.

CHAPTER 2: Project Approach

This project consisted of four technical tasks: laboratory testing, multifamily common area site demonstrations, multifamily dwelling unit site demonstrations, and technology readiness, described in a case study here and further in Chapter 4.

Lab Studies

Lab Study #1: Scale Configuration Optimization

Lab Study #1 described laboratory testing that determined the velocity and temperature profiles for various fan configurations. The objective of the first lab study was to measure and compare air-speed profiles with obstacles placed in different locations in the air-flow path of a ceiling fan. This study was performed at UC Berkeley in CBE's climate-controlled environment chamber[2] with one ceiling fan, one table, and a partition. The objective of the lab test was to explore measurements with one and two fans to determine air-speed changes in an occupied zone as a function of fan-blade to floor height and the interaction of flows generated by two ceiling-mounted fans (as a function of fan speed).

Lab Study #2: Multi-Fan and ASHRAE 216 Design Tool

Lab Study #2 examined airflows and helped develop the design tool and guidance for sizing and spacing fans. The goal of the design tool was to specify and locate a fan (or fans) to create a desirable air distribution within a given space. This work was based on laboratory testing of variations in ceiling-fan-driven air movements in terms of room size, fan mounting height, and other factors. The research team measured ceiling fan air speeds in 78 full-scale laboratory tests using different fan models and manufacturers. Factors included room size, fan diameter, type, speed, up/down direction, blade height, and mount distance (i.e. blade to ceiling height).

Lab Study #3: Comfort Performance

The Lab Study #3 reviewed ceiling fans and other personal comfort systems for thermal comfort. This included consulting the *Corrective Power Index* (CP) for quantifying the effects of personal comfort systems (such as ceiling fans) in providing comfort and additionally reducing energy use. The CP index can be used to evaluate both the equivalent change in ambient temperatures caused by fans as well as the changes in subjective responses, such as thermal sensation and comfort.

Field Studies

The goals of the field studies were to: (1) assess the installation and operation of ceiling fans and thermostats in common rooms and dwelling units at multifamily sites; (2) assess the

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[2] http://www.cbe.berkeley.edu/aboutus/facilities.htm

operation and power consumption of this joint technology over two cooling periods, compared with only air conditioning; (3) assess general impressions of users (e.g., office, common room occupants, and residential occupants); and (4) assess indoor air quality and thermal comfort during interventions of raised temperature setpoints. The original schedule was to run the field study through summer 2018, but delays in obtaining the sites and installing monitoring equipment pushed the study period through 2019. The overall schedule of the field demonstrations follows.

- July 2017: Installation of monitoring equipment
- July 2017 (through June/July 2018): Pre-installation monitoring period
- June/July 2018: Installation of ceiling fans and thermostats
- June/July 2018 (through October 2019): Post-installation monitoring period
- December 2019: Removal of monitoring equipment

Site Recruitment

Site recruitment established a set of criteria for participating sites:

- Must have electrical service provided by one of the state's three investor-owned utilities (IOU): Southern California Edison (SCE), Pacific Gas and Electric Company (PG&E), or San Diego Gas and Electric (SDG&E)
- Sites must be in an area with a CalEnviroScreen score of at least 75 percent[3].
- Must have no additional planned retrofits or renovations between now and December 2018
- Must have existing air conditioning controlled by thermostats

The criteria for shared common spaces in the demonstration study included: multiple types and sizes of spaces (e.g., offices, dining rooms, lobbies) greater than 1,000 square feet, regularly used spaces, and lighting systems able to accommodate fans. Criteria for individual residential dwelling unit spaces in the demonstration study included: ability to accommodate living room, bedroom, and dining room ceiling fans; are currently occupied; and have lighting systems that can accommodate fans. TRC and AEA solicited sites through owners of several affordable housing sites and existing contacts from utility incentive programs managed by TRC or AEA.

Site Description

Following the evaluation of the original committed sites and recruitment of additional sites, the research team proceeded with four sites for participation:

- Franco Center, Stockton, California (Climate Zone 12)
- Rolling Hills, Newman, California (Climate Zone 12)
- Parksdale Village (two separate sites), Madera, California (Climate Zone 13)

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[3] A map showing CalEnviroScreen scores for the entire state is available http://oehha.maps.arcgis.com/apps/Viewer/index.html?appid=112d915348834263ab8ecd5c6da67f68.

All buildings were within PG&E’s service territory. Figure 2 shows the locations of each site.

Figure 2: Field Demonstration Sites

The project sites included four common rooms in three towns in California’s warm Central Valley, and six individual dwelling units at one site.

Source: Therese Peffer, UC Berkeley; David Douglass-Jaimes, TRC

The Franco Center Apartments serve senior citizens and are owned and operated by WNC & Associates. One onsite manager and one janitorial staffer live on the property full time. Franco Center staff manage and occupy the main office, located on the first floor.

Study locations included the community rooms, offices, and kitchen prep area located on the first floor, a total floor area of 6,070 square feet (sq. ft.). Offices are used during standard business hours (9:00 a.m. to 5:00 p.m., Monday-Friday); the community areas are lightly used during the day, with heavier use at mealtimes and during events.

The building was built in 1967 and renovated in 2007 and is solid concrete masonry with no additional insulation. The first-floor retail, office, and common areas are served by six rooftop variable refrigerant flow compressors that provide conditioned refrigerant to eight 3-phase fan coil units (FCU).

Rolling Hills is owned and operated by Self Help Enterprises. One onsite manager and one janitorial staff live on the property full time. Rolling Hills staff manage and occupy the main office, located in the community center. The site consists of the community center and office, and 13 tenant buildings containing 52 units. The central community building is approximately 2,750 sq. ft. Residents of Rolling Hills are a mix of couples and families.

The focus of the study was the central community building, which includes an open community space, a kitchen, a computer room, and an office. The office is used during standard business hours and the community area and kitchen are very lightly used during the day.

The buildings were constructed in 2004 and are built of stucco over wood framing. The community building is serviced by two outdoor condensing units for air conditioning and two furnaces in the attic for heating. Both the condensing units and furnaces are connected to air handlers, also in the attic. The first air conditioning unit and furnace service the office and computer room, while the second unit services the community room and kitchen. Air conditioners provide 30-60 MBtu/hr (British thermal units/hour) of cooling, while the furnaces supply up to 88 MBtu/hr. Each of the two zones has a separate programmable thermostat.

The Parksdale Village properties are owned and operated by Self Help Enterprises. An on-site manager and janitorial staffer live on each property full time. Parksdale Village staff manage and occupy the main office of each property, which is located in the community center of each property.

Parksdale Village consists of two neighboring identical developments (Parksdale #1 and Parksdale #2) of townhome residential units and central common buildings. Parksdale #2 was the location for all six residential demonstrations. Each is a complex consisting of the community center, office, and 12 tenant buildings containing 48 units (4 units each, arranged side by side). Each unit has 2, 3, or 4 bedrooms, is 1-2 stories, and accessible from the ground floor. The central community building is approximately 3,190 sq. ft. Residents of Parksdale Village are a mix of couples and families.

Study locations are the two central community buildings and six units of Parksdale Village #2. The community buildings include an open community space, a kitchen, a computer room, and two offices. The main office of each building is used during standard business hours on weekdays, while the second office is rarely used. The community area and kitchen are very lightly used during the day, though the computer room is frequently used.

Residential units have either all spaces on the first floor, or, in 2-story units, the kitchen, living room, laundry room, and bathroom are on the first floor, with bedrooms and a bathroom on the second floor.

The buildings were constructed in 2009 and are built of stucco over wood framing.

The community building is serviced by two outdoor condensing units for air conditioning and two furnaces installed in the closet outside the building. Both the condensing units and furnaces are connected to air handlers attached to the furnaces. The first air conditioning unit and furnace serve the offices and computer room, while the second serves the community room and kitchen. Air conditioners provide 42-60 MBtu/hr (3.5 to 5-ton) of cooling each, while the furnaces supply up to 80 MBtu/hr. Each of the two zones has a separate programmable thermostat.

Residential units have outdoor compressors for air conditioning and a furnace located in a closet in the rear of the unit. Air conditioners provide 18–24 MBtu/hr (1.5 to 2-ton) of cooling per hour, while furnaces provide 48 MBtu/hr of heating.

Figure 3: Field Demonstration Space Types

4 community rooms

4 computer rooms

5 offices

6 residential units

The four sites included different space types: community rooms, computer rooms, offices, and dwelling units.

Source: AEA and UC Berkeley

Monitoring Installation

The research team installed monitoring equipment at each site to monitor energy use and indoor environmental quality (IEQ) conditions for all common area spaces and each residential unit included in the study. Pre-installation monitoring consisted of one year of data collection before the fans and smart thermostats were installed. These data included:

- **Air Conditioning Energy Use:**
    - Power metering at each air conditioning compressor serving common areas or residential units was included in the demonstration study.
    - Amperage metering at each of HVAC system fans (e.g., a fan coil unit)
    - Collected data was transmitted to the research team in real time via Wi-Fi.
- **Indoor Environmental Quality Measurements:**
    - Temperature, relative humidity, and light levels were collected in all common areas and in each residential unit, using Hamilton sensors.[4]
    - Collected data were available to the team in real time, at 20-second intervals.
- **Ceiling Fan Measurements and Settings:**
    - Temperature, cooling setpoints, occupancy, and other fan settings and measurements were collected for all ceiling fans.
    - Collected data were available to the team in real time, at 5-minute intervals.

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[4] www.HamiltonIOT.com

- **Thermostat Settings:**
    - The research team observed and recorded thermostat settings in common spaces and residential units during visits to the site. This included asking occupants about their thermostat use. The team collected data from the installed thermostats at 5-minute intervals.
- **Monitored Data Communication:**
    - The research team installed cellular data Wi-Fi hotspots to provide real-time energy monitoring and IEQ measurement data.

AEA and BAF performed installation of the monitoring equipment at all four sites over two weeks in July 2017. Installations typically took one or two days per site.

Details of the field study appear in Appendix D.

Figure 4: Parksdale #2 Typical Dwelling Unit Monitoring Equipment Installation

Source: AEA

Demonstration Preparation

Equipment Preparation

While testing the ceiling fan and thermostat in the test chamber at CBE, researchers encountered several challenges. The Haiku Home smart phone app for the ceiling fan allowed integration with smart thermostats from Nest and Ecobee. The team chose Ecobee thermostats for the demonstration sites since they could download thermostat data for the entire field study through the Ecobee application programming interface (API). The Haiku product was designed primarily for use with a single fan per residential room, with one individual using the smart phone app to control the fan. However, the goal of the study was to test applications of the Haiku technology in combination with smart thermostats in multi-room, multi-user, and nonresidential applications. The Haiku product functionality and user interface were not optimized for these applications. This initial testing resulted in two primary concerns about the technology functionality at the demonstration sites:

- The Haiku product's automatic "smarter cooling" functionality did not operate in the transition phase (or "deadband") between heating and cooling modes on the thermostat, posing problems when heating and cooling are required on the same day (e.g., heating mode during cool early morning hours and cooling mode during daytime hours). The fan's smarter cooling mode, which automatically increases air movement in a space to match a user's comfort setting, would not activate until the thermostat switched to cooling mode. This could create a comfort gap if thermostats are set to higher temperatures with the expectation that the fan will provide additional cooling before the AC is triggered.

- The current fan and smart phone interface allow access to fans from any device on the same Wi-Fi network, and smart phone control was only possible when connected to the same network as the fan. This posed challenges for user permissions in common areas, or in shared spaces like offices.

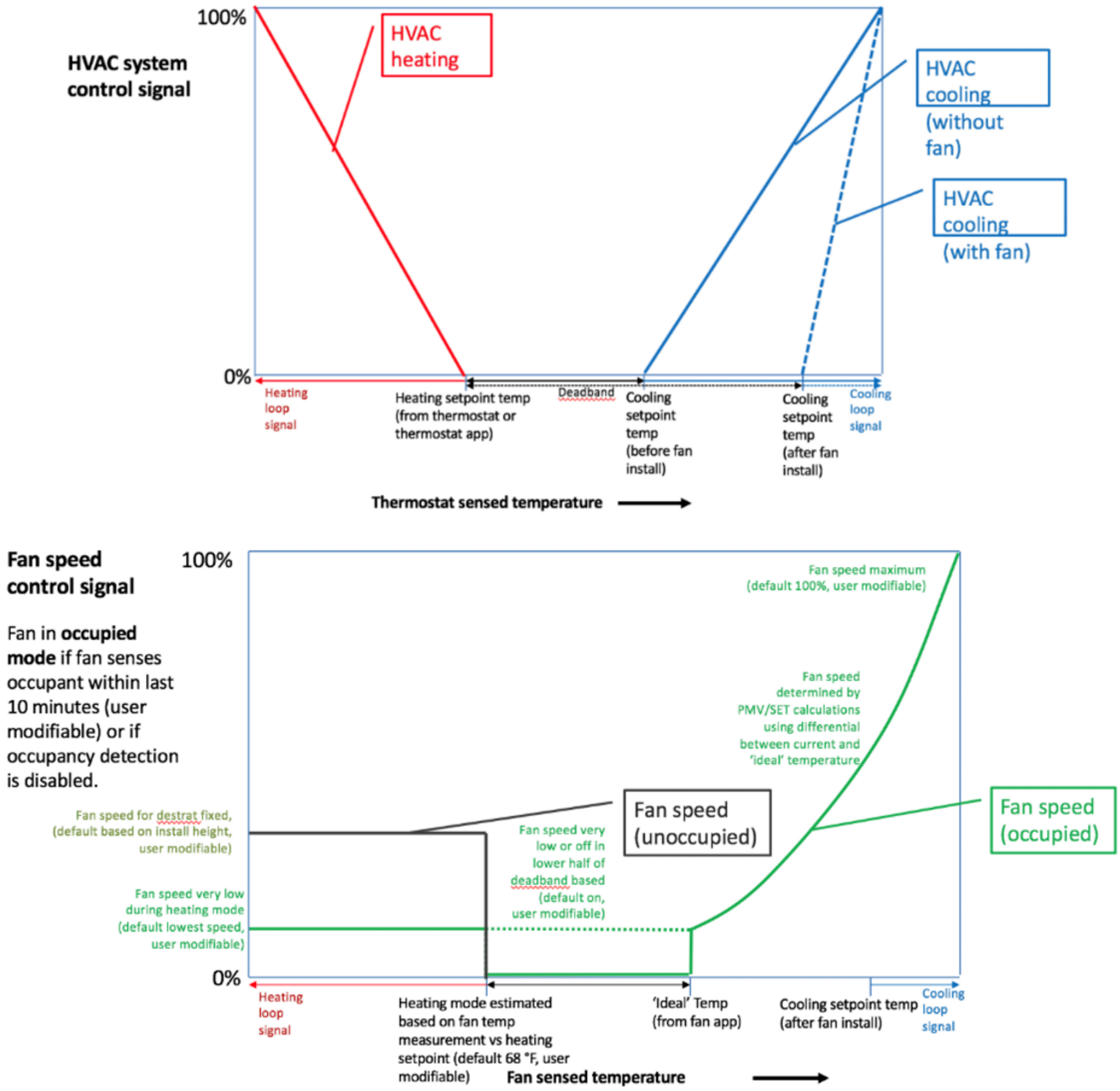
The research team worked with BAF to develop a custom version of the fan firmware to better align with project goals. These changes included improvements to the control protocols and smart phone (Haiku Home) control interface for the Haiku fan.

Following the initial testing, CBE and TRC developed the following priorities for updates to the Haiku controlinterface:

- Address the switchover between "smarter cooling" and "smarter heating" modes so that ceiling fans will continue to operate to provide comfort cooling as needed in the thermostat "deadband" between heating and cooling modes, allowing for higher cooling setpoints. This could potentially be resolved by separating the operation and control of "smarter cooling" and "smarter heating" modes from the thermostat settings.
- Limit user access to fans in common areas or other shared spaces. Because anyone with the Haiku Home app connected to the same Wi-Fi network as the fans could potentially control the fans in that space, it may be necessary to establish user profiles that could limit controls in public spaces to a facility manager, or limit access to a specific user's space in settings like an office suite with a single shared Wi-Fi network.
- Allow multiple fans in different rooms to be connected to a single thermostat, especially in separate rooms within a single dwelling unit. This could also be resolved by separating the function of the "smarter cooling" and "smarter heating" modes from the thermostat settings.
- Provide easier access to Ecobee thermostat control within the Haiku Home app, including proactive suggestions to adjust thermostat setpoints to increase energy savings.
- Implement learning functionality where fan cooling setpoints gradually change based on user interactions.
- Improve the user interface for setting the smart cooling "ideal temperature," and clarify how the setting works.

CBE and TRC collaborated with BAF to develop solutions for these strategies to provide fully functional products for the demonstration sites.

Figure 5: Control Sketch for Air Conditioning and Fan Operation



Top: When staged with ceiling fan operation to increase the setpoint, air conditioners can use less energy from less overall runtime. Bottom: Fan operation is based on both temperature and occupancy. A ceiling fan will run if a space is occupied and above a setpoint temperature; fan speed gradually increases at higher air temperatures up to a defined limit.

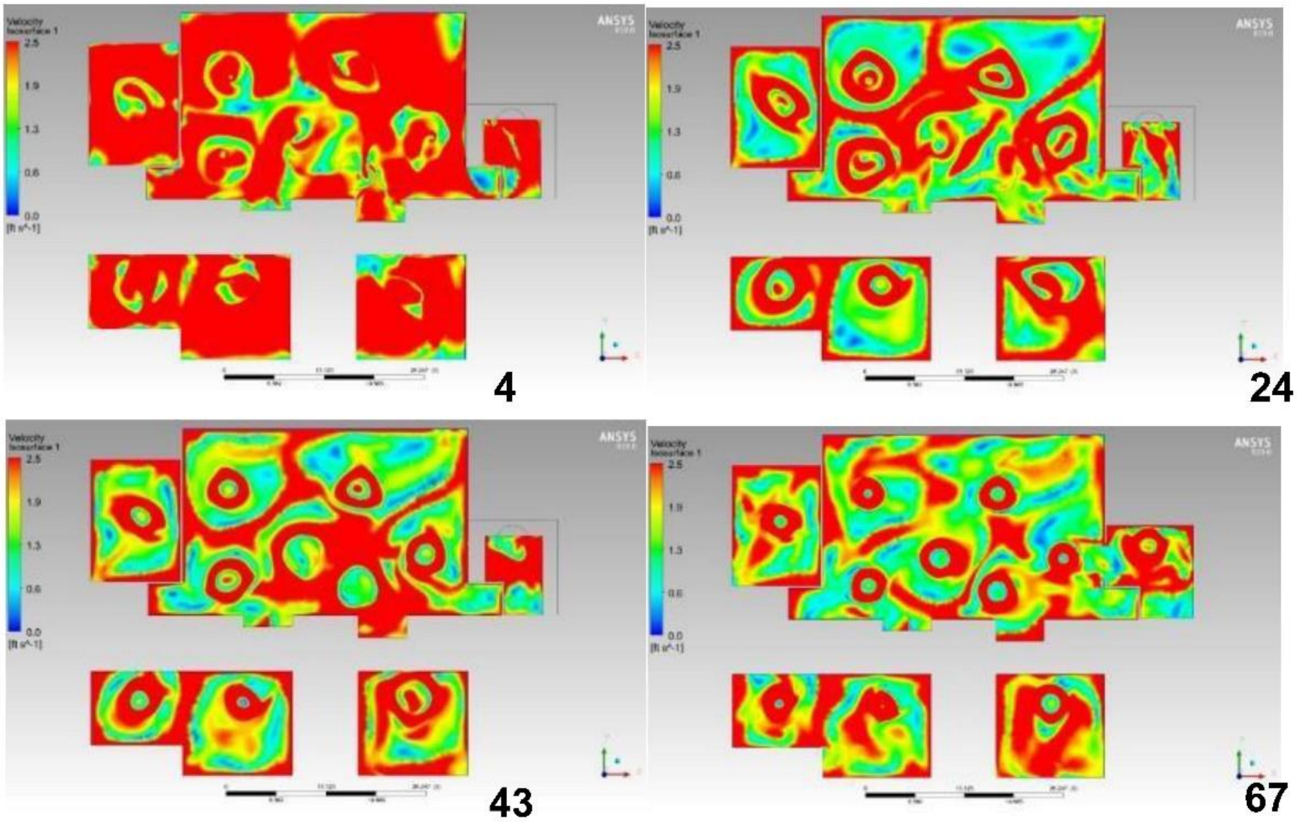
Source: CBE

The project team incorporated a learning functionality that modifies the fan's "ideal" temperature based on user feedback. If a user increases the fan speed when the fan is operating automatically, the ideal temperature setpoint decreases slightly so that in the future the fan will operate at higher speed at this temperature. The same applies in reverse if a user decreases the fan speed. In this manner, the fan's automated speed features will gradually adjust to a user's preferences without any direct interaction with the fan settings. This essentially happens in the background whenever a user changes the fan speed.

Site Preparation

Since the goal of the site demonstrations was to test the potential of ceiling fans to maintain comfort at higher thermostat setpoints, the fan layout was critical. BAF therefore provided computational fluid dynamic (CFD) simulations to test and develop proposed fan layouts for each site. The research team developed the overall goal of achieving an average of up to 150 feet per minute (fpm) or 2.5 feet per second (fps) of air flow in each demonstration space. This velocity was based on previous studies that found that speeds above 150 fpm start to move papers on desks; this was considered the upper limit air velocity since it maximized cooling without becoming disruptive. (This air flow target assumes the highest fan speed setting, so occupants could always use the fans at lower speeds to achieve lower air velocities.) Using this target, BAF ran CFD simulations that measured air flow at four different levels to determine the effectiveness of various fan layouts. The four heights were 4″, 24″, 43″ and 67″ above the floor. Figure 6 shows an example of the CFD analysis for an initial fan layout plan at the Rolling Hills community building.

Figure 6: Example Rolling Hills CFD Analysis



CFD analysis visualizations showing air speeds at vertical heights of 4”, 24”, 43”, and 67” above the floor.

Source: BAF

Based on the CFD analysis and existing conditions (e.g., light fixtures, fire sprinklers) at each site, BAF proposed initial layouts for all the spaces at all four sites.

Prior to finalizing the designs for each of the sites, CBE, TRC, and AEA conducted site visits at each of the demonstration sites with the BAF installation team to familiarize themselves with the spaces in the study and confirm the final layouts and details for the fan installations.

Fan and Thermostat Installations

Based on the CFD analysis and the site visits just described, the research team developed the final fan layout designs. In addition to the fan installations, full installation included both installing and configuring thermostats at the Rolling Hills and Parksdale sites and lighting reconfigurations in areas where fans and existing lighting conflicted.

Network and Connection Issues

After physical installation of the fans the research team ran into multiple challenges with connecting the fans and thermostats to internet networks and connecting the fans to the BAF Haiku app. The initial intent was to connect all the new devices to whichever local network occupants used at the site, but this posed several challenges. At some sites the research team was not able to access the same network that onsite staff used because of privacy protections with tenant records. Ceiling fans were additionally connected to a password-protected network to function properly, which also limited connection options at the Franco Center site where the public wireless network does not require a password for access.

Separately, the installation team ran into challenges connecting the fans to the Haiku app at several sites, requiring multiple return visits from AEA and coordination with BAF to resolve connection problems. These two connection issues were largely resolved in community spaces with the addition of separate wireless routers and network connections to get all the fans up and running. However, post-installation, some of the occupants of the demonstration residential units experienced problems connecting their personal devices to their existing wireless networks, which were shared with the new fans and thermostats. Residential units at the Parksdale #2 site used an internet modem/router provided by the property for internet access. The project team found that these systems allowed a maximum of 15 individual IPs to be registered at any given time. Since each fan and thermostat counted as a separate IP, existing smart phones, computers, TVs, and other internet-connected devices frequently exceeded the maximum number of allowed IP addresses. To remedy this AEA installed separate mobile internet hot spots at each unit dedicated for the fans, removing them from the residents' networks.

Supplemental Desk Fans and Lighting

In order to ensure personal comfort and supplement ceiling fans in areas where air circulation was less than optimal, the research team provided the option of small desk fans for all office occupants at each site, as well as for each computer lab station at each site, though few occupants actually used these devices.

The light kit for the ceiling fan at the Franco site was insufficient to meet lighting needs in the small office and computer lab spaces. To address this issue, the research team provided supplemental desk lighting for each computer station in the computer lab, and both a desk light and a floor light for the small office to supplement light from the ceiling fans.

Final Installation Conditions

In total, 99 ceiling fans and 12 thermostats were installed across the four demonstration sites in June-July 2018, as follows:

- Franco Center: 35 ceiling fans, 6 existing thermostats (VRF system)
- Rolling Hills Community Building: 13 ceiling fans and 2 thermostats

- Parksdale #1 Community Building: 7 ceiling fans and 2 thermostats
- Parksdale #2 Community Building: 8 ceiling fans and 2 thermostats
- Parksdale #2 Three 2-bedroom units: 5 ceiling fans each (15 total), 3 thermostats
- Parksdale #2 Three 3-bedroom units: 7 ceiling fans each (21 total), 3 thermostats

The details of all installations appear in Appendix D, Final Field Report. Figure 7 and Figure 8 show an example of final installation layouts for the ceiling fans, thermostats, and other equipment in both a common room and a residence.

Figure 7: Franco Center Installation Layout

FAN SCHEDULE		
TAG	QTY.	DESCRIPTION
BAF01	26	60" HAIKU, 20" EXT. TUBE
BAF02	6	52" HAIKU, 20" EXT. TUBE
BAF03	2	52" HAIKU, LOW-PROFILE MOUNT, LED KIT

GENERAL NOTES

1. VERIFY EXTENSION TUBE LENGTH AND MOUNTING BRACKET WITH MANUFACTURER PRIOR TO ORDERING
2. BOTTOM OF FANS SHALL BE AT LEAST 10' AFF (EXCLUDING HAIKU)
3. FANS SHALL BE AT LEAST 2' AWAY, IN ALL DIRECTIONS FROM POSSIBLE OBSTRUCTIONS
4. FANS SHALL NOT BE MOUNTED WITHIN TWO TIMES THE FAN DIAMETER OF EXHAUST OR RETURN AIR INTAKES, AND SHALL NOT BE IN DIRECT LINE OF DISCHARGE OF HVAC EQUIPMENT
5. EXTENSION TUBES 4' OR LONGER SHALL BE INSTALLED WITH GUY WIRES PER THE MANUFACTURER'S INSTALLATION REQUIREMENTS (EXCLUDING HAIKU)
6. FANS SHALL BE AT THE SAME LEVEL OR HIGHER THAN RADIANT HEATERS AND OUTSIDE THE MINIMUM CLEARANCE TO COMBUSTIBLES
7. FANS SHALL BE AT LEAST TWO AND ONE-HALF TIMES THE DIAMETER OF THE LARGEST FAN AWAY FROM NEIGHBORING FANS

Fan Groups

Lounge	60" HAIKU, 20" EXT. TUBE
Activity Area	60" HAIKU, 20" EXT. TUBE
Storage Room	60" HAIKU, 20" EXT. TUBE
Dining Room	60" HAIKU, 20" EXT. TUBE
Food Prep	52" HAIKU, 20" EXT. TUBE
Reception	52" HAIKU, 20" EXT. TUBE
Individual Fans	52" HAIKU, LOW-PROFILE MOUNT, LED KIT 52" HAIKU, 20" EXT. TUBE

[redacted]

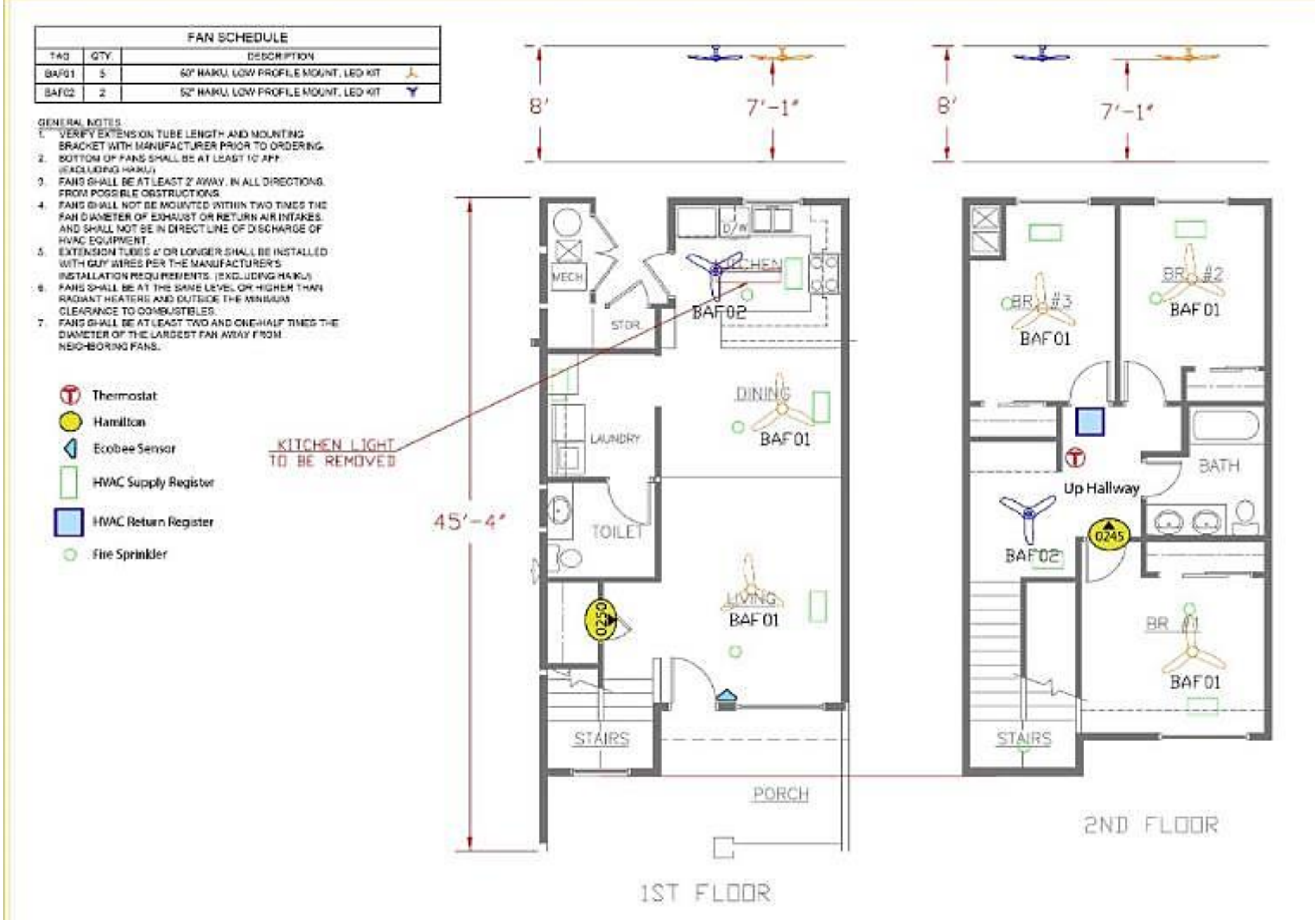
BAS SALES REP: MH
DATE: 6-19-2018
DRAWING BY: CP

FRANCO BUILDING
STOCKTON, CA

Layout of Franco Center demonstration site showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Sourcet: Mia Nakajima, TRC

Figure 8: Parksdale #2 Typical 3-Bedroom Unit Installation Layout



FAN SCHEDULE		
TAG	QTY.	DESCRIPTION
BAF01	5	60" HAIKU, LOW PROFILE MOUNT, LED KIT
BAF02	2	52" HAIKU, LOW PROFILE MOUNT, LED KIT

GENERAL NOTES:

1. VERIFY EXTENSION TUBE LENGTH AND MOUNTING BRACKET WITH MANUFACTURER PRIOR TO ORDERING.
2. BOTTOM OF FANS SHALL BE AT LEAST 10' AFF (EXCLUDING HAIKU)
3. FANS SHALL BE AT LEAST 2' AWAY, IN ALL DIRECTIONS, FROM POSSIBLE OBSTRUCTIONS.
4. FANS SHALL NOT BE MOUNTED WITHIN TWO TIMES THE FAN DIAMETER OF EXHAUST OR RETURN AIR INTAKES, AND SHALL NOT BE IN DIRECT LINE OF DISCHARGE OF HVAC EQUIPMENT.
5. EXTENSION TUBES 4' OR LONGER SHALL BE INSTALLED WITH GUY WIRES PER THE MANUFACTURER'S INSTALLATION REQUIREMENTS. (EXCLUDING HAIKU)
6. FANS SHALL BE AT THE SAME LEVEL OR HIGHER THAN RADIANT HEATERS AND OUTSIDE THE MINIMUM CLEARANCE TO COMBUSTIBLES.
7. FANS SHALL BE AT LEAST TWO AND ONE-HALF TIMES THE DIAMETER OF THE LARGEST FAN AWAY FROM NEIGHBORING FANS.

Layout of Parksdale 2 Typical 3-Bedroom Unit demonstration site (1286 sq. ft.) showing ceiling fan and thermostat locations, HVAC control zones, Hamilton temperature and humidity sensors, and lighting and HVAC vents.

Source: Mia Nakajima, TRC

Figure 9: Photo of Franco Center Community Room With Ceiling Fans Installed

Source: Paul Raftery, CBE, UC Berkeley

Site Interventions

During the first cooling season following the baseline period, June-September 2018, the project team monitored occupant interactions with the fans and thermostats and conducted two surveys at the Franco common room, both before and after the ceiling fans were installed.

Before the second cooling period began in late April 2019, AEA adjusted setpoints and schedules. With both worker and resident approval, thermostat and fan setpoints and scheduling were adjusted for consistency across sites at levels designed for comfort with moderate ceiling fan usage. Fans were set to an "ideal" temperature of 74°F (23°C) (temperature above which the fans turned on), except in bedrooms where the ideal temperature was raised to 78°F (26°C) to avoid overcooling residents while sleeping. Temperature setpoints for thermostats were:

- 80°F (26.7°C) during the day while occupants were present ("Home" setting on Ecobee thermostats).
- 78°F (26°C) during the night in residences ("Sleep" setting on Ecobee thermostats).
- 86°F (30°C) while occupants were not present ("Away" setting on Ecobee thermostats).

When the setpoints were adjusted, AEA and CBE conducted an educational campaign to ensure that all residents and workers were comfortable using the fans and thermostats. Education was provided at the initial installation, but follow-up surveys indicated that there was still some confusion over proper equipment use. In particular, scheduling the thermostats, temporary versus permanent temperature setpoints, and using the fans before reducing thermostat setpoints for cooling all needed to be re-emphasized. Education was provided in person, using an English-to-Spanish translator when needed, and informational flyers were left with each user.

Surveys

To determine occupant perceptions, the research team collected data using two primary methods: interviews and surveys. Interviews were conducted on two occasions with both residents and office workers. Surveys were distributed during Summer 2018 and early Fall 2018 with office workers and at both various community events and at a final community event in Summer 2019.

All participants were given two surveys: the "Personal Characteristics Survey" and the "Right Now Survey." The Personal Characteristics Survey queried occupants about their basic demographics and general perceptions of their energy use. The survey specifically asked occupants for their ages, genders, use of heating and cooling devices, and whether they easily became either hot or cold. The Right Now Survey was a brief 10-item survey aimed at understanding occupants' perceptions of the space they occupied at the time they filled out the survey. The survey also posed questions concerning thermal comfort and perceptions of air movement and air quality.

Participants included office workers in the common rooms at two sites and residential occupants at one site. Both groups participated in both surveys and interviews with the exception of Franco, which participated only in the surveys.

Technology Readiness

Case Study Method

The project developed a case study. Its purpose was to evaluate the current landscape of similar technologies, current installations of those technologies, and both market opportunities and barriers to the technologies. This case study:

- Included interviews with owners and designers to determine design features, control approaches, and owners' perceptions of the technology.
- Included spot measurements using the CBE Building Performance Toolkit to determine typical air speeds when using automated control settings.
- Described challenges and successes of planning and executing retrofits.
- Discussed lessons learned.

Technology Readiness Report

The project developed a technology readiness report. This report:

- Identified current product availability and estimated market size.
- Estimated current market penetration.
- Evaluated market barriers to adoption.
- Estimated likely market penetration, with and without intervention, through building codes.

CHAPTER 3: Project Results

Laboratory Studies

This section describes the results from the three laboratory studies.

Laboratory 1 Results

The research team conducted tests in the CBE chamber at UC Berkeley and at the BAF test facility in Kentucky. See Appendix A for details.

The CBE chamber tests looked at six different configurations of furniture (rectangular tables and partitions) on air-velocity contours. For example, air flows spread further around a table.

The tests in the BAF facility measured the effects of ceiling height on air speed, and of air speed from two fans when compared with one. For the single fan test, the highest speeds were directly below the fan, at low height; the lowest speeds were fairly uniform outside the fan diameter. At 7 ft and 10 ft, air flow was undisturbed 0.9 m from the fan center (Point 4). For the 15 ft height case the velocity increased, suggesting that air flow had spread laterally. For the 2-fan test, the additional operating fan had a significant impact on the flow field. Two fans at similar speeds created an upward flow from the collision of two floor-bounded flows and had an inherent oscillatory nature. However, the speeds of both fans could be manipulated to intentionally adjust the location of the higher air-speed region.

Laboratory 2 Results

The research team measured ceiling-fan air speeds in 78 full-scale laboratory tests. The factors were the room size, fan diameter, type, speed, up/down direction, blade height, and mount distance (blade-to-ceiling height). See Appendix B for details.

The team demonstrated the influence of these factors, showing that the most significant are speed, diameter, and direction. The area-weighted average air speed increased proportionally with fan air speed and diameter. Fans blowing upward yielded lower but far-more-uniform air speeds than fans blowing downward. Fans blowing upward also used more power to achieve the same area weighted average air speed. For the same diameter and rated airflow, fan type had little effect on air-speed distribution outside the fan blades. The team developed dimensionless models and demonstrated their appropriateness over a wide range of fan and room characteristics. Dimensionless linear models predicted the lowest, area-weighted average, and highest air speeds in a room with a median (and ninetieth percentile) absolute error of 0.03 (0.08), 0.05 (0.13), and 0.12 (0.26) meters per second (m/s) respectively over all 56 downward tests that represented typical applications. These models allowed the team to answer the question, "What air speed distribution can I expect for a given fan and room?"

In addition to the lab studies and case study measurements, the project team conducted a field validation of the upward-blowing ceiling fans, found in Appendix F.

Laboratory 3 Results

The research team proposed a Corrective Power (CP) index to quantify the extent to which a fan can deliver a warm ambient temperature toward neutral (Zhang, Arens, and Zhai 2015). (See Appendix C for more details.) The project reviewed over 40 studies with personal comfort systems (PCS), including ceiling fans. Published human subject and manikin studies show cooling and heating effects represented as a corrective power (CP) value, defined as the difference between two ambient temperatures at which the same thermal sensation is achieved—one with no PCS (the reference condition), and one with a PCS in use. CP is expressed in degrees Kelvin (K), the standard way of expressing temperature differences on the Celsius scale. If subjects said they felt as comfortable at a particular combination of warm air temperature and air movements at a lower air temperature without air movement, then the temperature difference is the CP. In this case it it would have a negative value. Cooling CP ranges from -1 K to -6 K, and heating CP from 2 K to 10 K. As an offset to normal ambient room temperature, the CP allows building engineers and operators to modify temperature setpoints and control sequences when PCS is included in their designs.

Field Studies Results

The detailed description and analysis of this field study are contained in Appendix D; a journal paper (Miller et al, 2021)[5] also provides details.

Automated Ceiling Fan Operation

Coordinating and sequencing ceiling fans and air conditioning can be achieved with multiple operation strategies and commercially available products. The strategy demonstrated in this field study used highly efficient ceiling fans with onboard temperature and occupancy sensors. These fans were configured to operate automatically so that when occupancy was detected they automatically began moving air above a configurable setpoint temperature, and gradually increased speed as ambient air temperatures increased. Importantly, occupants could always manually adjust and override fan operation by using provided remote controls for each fan. Figure 10 shows an example of a ceiling fan turning on when occupancy was detected and modulating speed based on the indoor air temperature.

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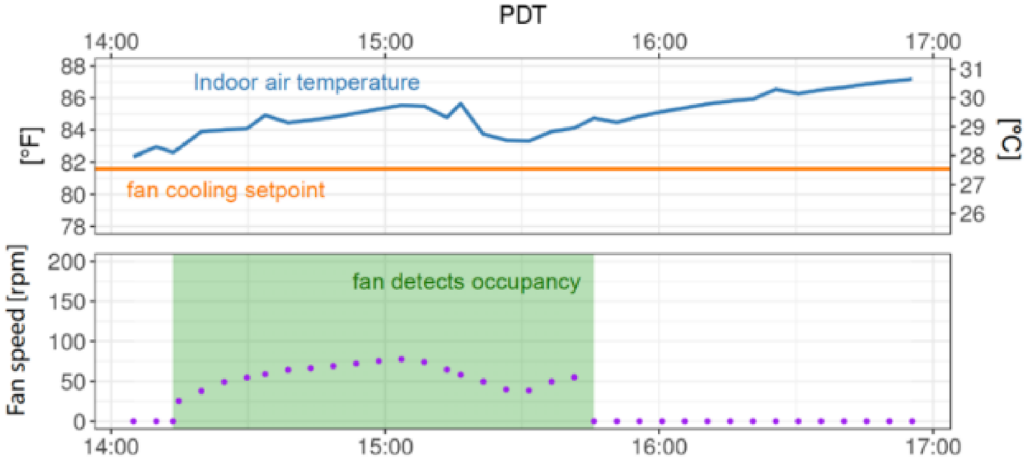
[5] Miller et al, 2021 available at https://www.sciencedirect.com/science/article/pii/S0378778821006034

Figure 10: Automated Ceiling Fan Operation Based on Temperature and Occupancy



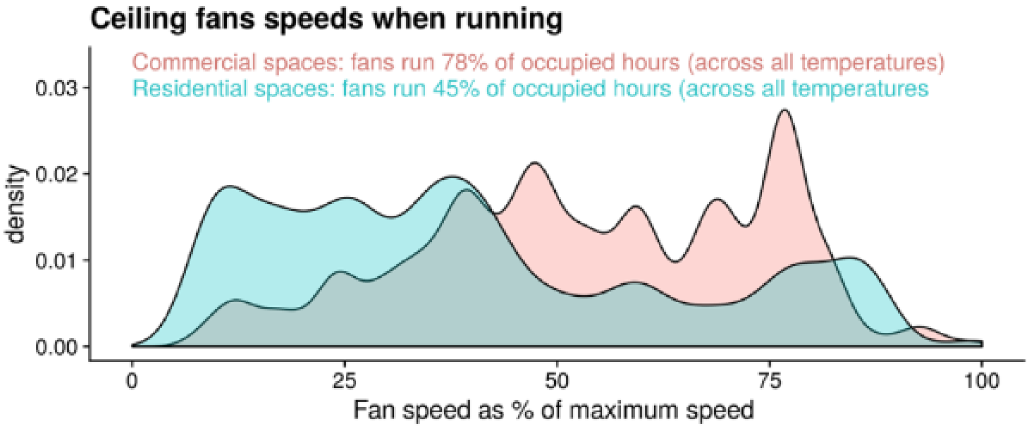
Top: Indoor air temperature and fan operation setpoint. Bottom: Ceiling fan speed adjusting based on occupancy and temperature.

Source: Dana Miller, UC Berkeley

Ceiling Fan Power Consumption and Runtime Analysis

Figures 11 and 12 summarize how all 99 ceiling fans operated over the field study during the April to October cooling period. Overall, the ceiling fans were frequently used at all sites, typically at low speeds, as shown in Figure 13, and used very little electricity, shown in Figure 14. The low power consumption of these efficient ceiling fans during operation (mean power consumption was 8 W) is comparable to that of an LED light bulb.

Figure 11: Ceiling Fan Speeds During Operation



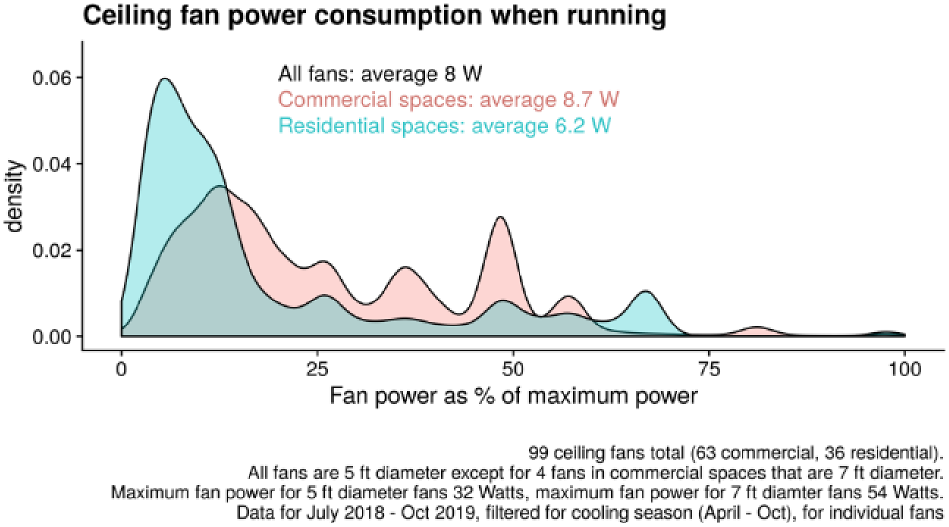
99 ceiling fans total (63 commercial, 36 residential). Overall mean fan speed 49 % of maximum
Data for July 2018 - Oct 2019, filtered for cooling season (April - Oct), for individual fans
Fan speed data shown for all hours of fan runtime, regardless of occupancy status
All fans are 5 ft diameter except for 4 fans in commercial spaces that are 7 ft diameter.
Max. fan speed for 5 ft diameter fans 200 revolutions per minute, max. fan speed for 7 ft diameter fans is 137 rpm

Ceiling fan speed during operation, as a percentage of maximum speed. For the majority of runtime in both residential and commercial buildings, fans run at 75 percent or less of the maximum speed.

Source: Dana Miller

Across all hours during the April to October cooling season, at all temperatures, the ceiling fans usually operated below 75 percent of maximum speed, and in residences usually operated below 50 percent of maximum speed, shown in Figure 11. In commercial spaces across all temperatures, the fans operated the majority of occupied hours (78 percent), ranging from a minimum of 29 percent to a maximum of 96 percent of occupied hours for fans in different locations. Runtime variations came from variations in indoor temperatures (occupants are less likely to desire air movement at cooler temperatures) and variation in occupant preferences (preferring fans to run more or less of the time). In residential spaces across all temperatures, the fans operated about half (45 percent) of occupied hours, ranging from a minimum of 2 percent to a maximum of 83 percent of occupied hours for fans in different locations, with similar variation due to indoor air temperatures, occupancy frequency, and occupant preferences.

Figure 12: Ceiling Fan Power During Operation


Ceiling fan power consumption when running

99 ceiling fans total (63 commercial, 36 residential).
All fans are 5 ft diameter except for 4 fans in commercial spaces that are 7 ft diameter.
Maximum fan power for 5 ft diameter fans 32 Watts, maximum fan power for 7 ft diamter fans 54 Watts.
Data for July 2018 - Oct 2019, filtered for cooling season (April - Oct), for individual fans

Ceiling fan power during operation, as a percentage of maximum speed. Since power consumption scales with the cube of fan speed, the mean fan speed of 49 percent equates to a mean fan power consumption of 24 percent of maximum fan power.

Source: Dana Miller

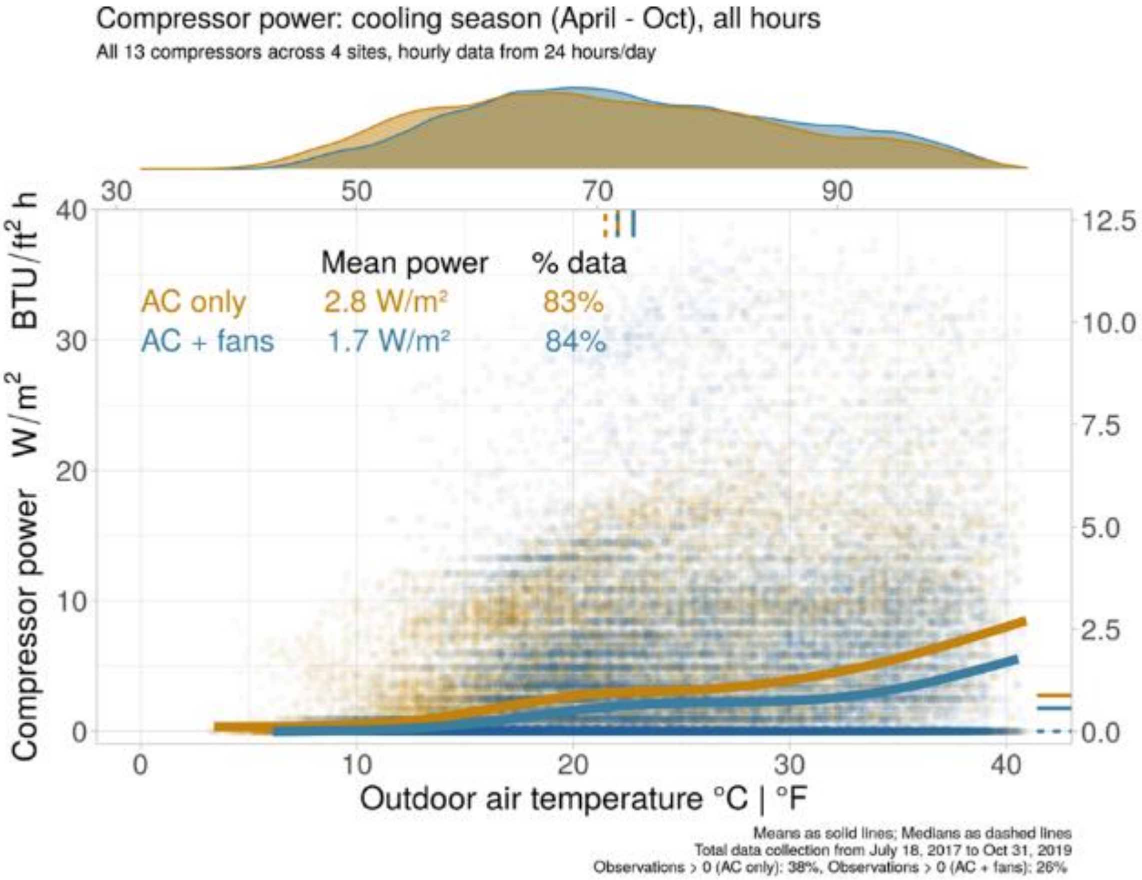
Energy Analysis

The research team collected air conditioner compressor and system fan energy consumption at each site from July 18, 2017 to October 31, 2019. The team also acquired measured weather data for the same period from the NOAA weather station nearest each installation site. Data acquisition difficulties caused numerous periods of missing data for some of the sites, and in one residential unit the team was unable to measure compressor energy consumption at all.

Overall, the intervention of adjusting air conditioning setpoints to cool first with ceiling fans and then with both ceiling fans and air conditioning and educating occupants about potential energy and comfort benefits yielded substantial compressor energy savings. Overall, the field demonstration resulted in 39 percent measured compressor energy savings during the April–October cooling season when compared with baseline conditions, across all sites. Over all months of the year, mean measured compressor power per floor area during the intervention period was 30 percent lower than the baseline period. The floor area served by each individual compressor varied more than six-fold, and the size and energy consumption of a compressor correlated with the floor area. The research team therefore reported normalized energy savings by floor area to avoid sites with larger floor area unduly weighting the percentage savings estimate in either direction. Without normalizing by floor area, the total project percentage savings during the cooling season were 48 percent in larger floor areas, which had substantially higher percentage savings than smaller floor area sites.

Figure 13 shows hourly average compressor power use across all sites, normalized by floor area served, compared with outdoor dry-bulb air temperatures.

Figure 13: Hourly Mean Air Conditioning Compressor Power



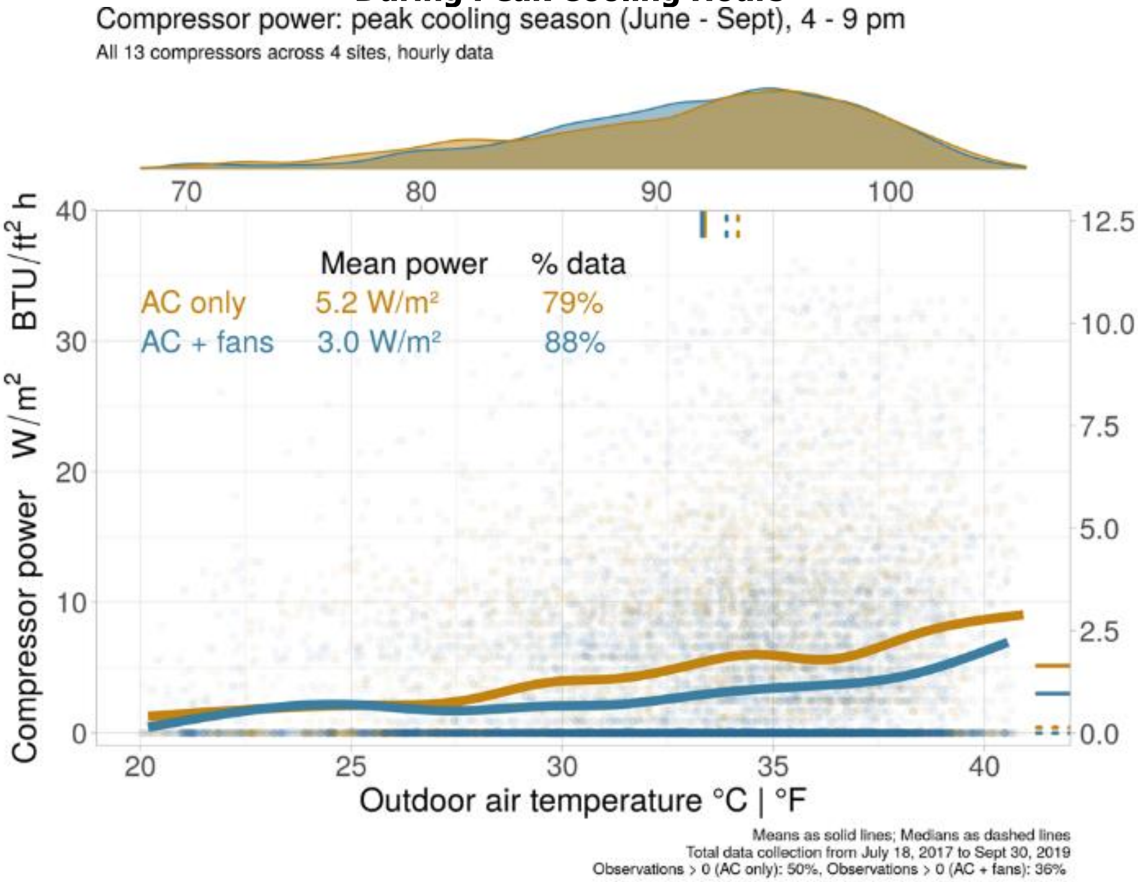
Hourly average compressor power use during baseline and intervention periods across all field study sites, normalized per floor area served, with respect to outside drybulb temperature for all 13 compressors measured in the project. Overall compressor energy savings shown are 39 percent.

Source: Dana Miller, UC Berkeley

Average hourly outdoor air temperatures across all sites were warmer during the intervention period than during the baseline period by 1.7°F (0.95°C), as shown at the top of Figure 14. The research team normalized energy savings values using both breakpoint regression and random forest models. The team fit individual models for each compressor during the baseline period, then used them to predict power consumption during the intervention period. The team reported normalized energy savings as the difference between the predicted and observed intervention periods. The team reported overall weather normalized savings as the mean of savings estimated for each compressor from each model.

Figure 14 shows air conditioning compressor energy consumption during hours of peak residential and commercial time-of-use charges (4 p.m. through 9 p.m.) in PG&E’s service territory during the warmest months of June through September. Energy savings during this period averaged 42 percent, normalized by floor area.

Figure 14: Hourly Mean Air Conditioning Compressor Power During Peak Cooling Hours



Hourly average compressor power use during peak time-of-use rate period during baseline and intervention periods across all field study sites, normalized per floor area served, with respect to outside drybulb temperature for all 13 compressors measured in the project. Overall energy savings shown is 42 percent. Note x axis differs from above plot.

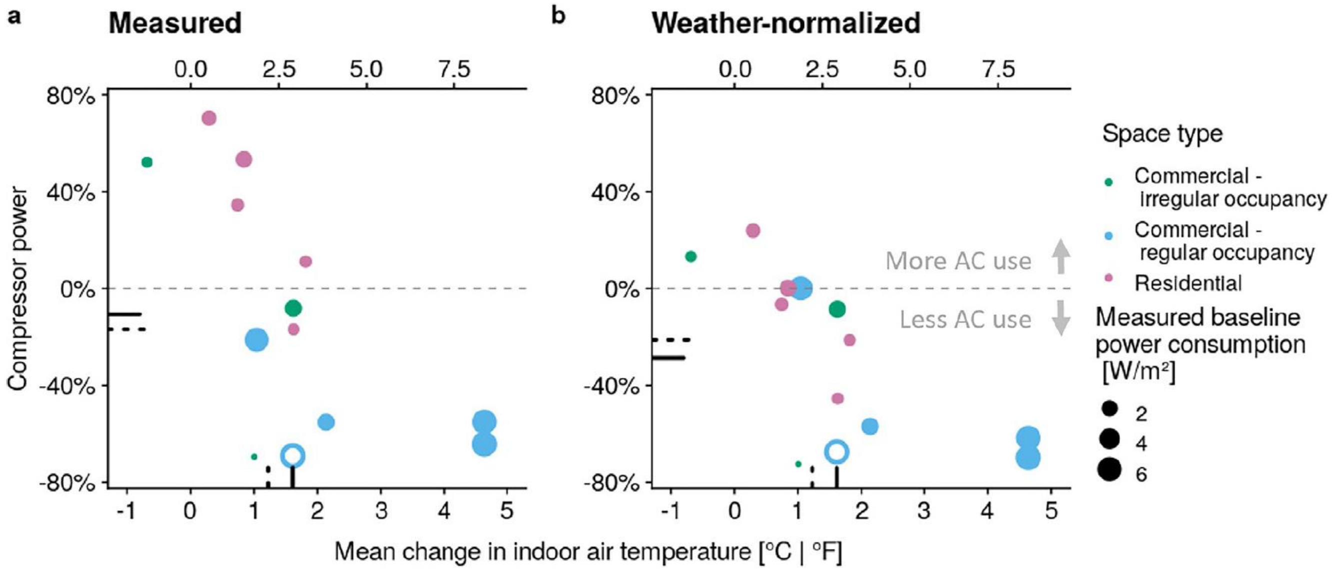
Source: Dana Miller, UC Berkeley

Zones in commercial buildings were also classified as either regularly or irregularly occupied; zones with infrequent occupancy had lower savings potential when compared with zones with lengthy and frequent cooling demand. These spaces also had irregular usage patterns that likely contributed to variability in savings between baseline and intervention periods.

When additionally normalized for weather due to warmer outdoor conditions during the intervention, energy use per zone varied from an increase of 36 percent to savings of 71 percent across all 13 compressors, with median per-compressor weather-normalized savings of 15 percent. This variability reflects the diversity of buildings, mechanical systems, prior operation settings, and space types, as well as occupants’ schedules and preferences. All commercial spaces with regular occupancy schedules had measured energy savings on an absolute basis before normalizing for warmer intervention temperatures, and 10 of 13 sites showed energy savings on a weather-normalized basis. In zones where indoor air temperatures did not increase (occupants did not raise air conditioning setpoints), energy savings were not realized. The zones with the largest increase in air conditioning temperature setpoints and the largest increase in indoor air temperatures realized the largest energy savings. Three sites did not realize energy savings on a weather-normalized basis. Two of these sites were residences that opted not to increase air conditioner setpoint temperatures after initially trying setpoint temperatures of 78°F (26°C). Setpoints were typically below 75°F (24°C), and one was an infrequently occupied commercial space where air conditioning was not operated regularly.

Figure 15 compares the compressor power savings, normalized by weather, versus increased indoor temperature compared with the baseline period. Larger increases in indoor air temperature, driven by increased thermostat setpoints, correlated with greater savings. Sequencing ceiling fans and air conditioning can only save energy if air conditioning is adjusted to run less often and less intensely, so occupants who did not raise setpoints did not realize energy savings.

Figure 15: Weather-Normalized Power Savings Versus Increase in Indoor Temperatures



Comparison of compressor energy savings against the mean hourly increase in indoor temperatures in each HVAC zone after ceiling fans began to operate and occupants were encouraged to increase air conditioner setpoints. Larger energy savings are correlated with larger increases in indoor air temperatures. Median savings per compressor, normalized for weather and floor area, are 15 percent, and ranged from an increase of 36 percent (in an infrequently used space), to savings of 71 percent (in a large zone with low initial setpoints).

Source: CBE

Table 1 summarizes the energy and cost savings across all sites for 13 compressors, separated by building type and occupancy. The table includes measured energy savings for the whole year, for the cooling season, and for peak periods in the cooling season as defined by the

PG&E TOU rate (4 p.m. through 9 p.m., June-September). The table includes weather-normalized energy savings and changes in mean hourly indoor air temperatures between the baseline period and the intervention periods. The site with the largest floor area, a regular occupancy schedule, and the largest increase in indoor air temperatures (Compressors C1 and C2) saw the greatest cost savings: an estimated $6,300 for a single cooling season. The residential sites showed less energy savings in general and fewer cost savings with a simplified fixed tariff of $0.1945 per kWh. The three residential sites that did achieve energy savings all had greater savings during peak period. Higher rates, for example, during peak periods, would increase the cost savings correspondingly. Note also that all of the residences studied were well insulated, of relatively new construction (2009), were relatively small (900–1,300 sq. ft.), and shared adjacent walls with other units. All of these factors substantially decreased cooling energy consumption when compared with more typical California homes. Sequencing ceiling fans and thermostats for cooling in older, leakier, larger homes would also see greater savings. Lastly, the table illustrates that this technology should first target buildings with high cooling energy consumption to maximize savings.

Table 1: Summary of Measured and Weather-Normalized Energy Savings and Estimated Cost Savings for All Zones

Measured compressor energy use and weather-normalized energy savings per zone

		Measured compressor power Cooling season (April – Oct)		Measured compressor energy savings			Weather-normalized energy savings	Mean zone temperature Cooling season (April – Oct)			Weather-normalized cost savings @ $0.2/kWh
	Zone area [m^2]	Baseline [W/m^2]	Intervention [W/m^2]	Whole year	Cooling season (April – Oct)	Peak cooling (June – Sept)	Cooling season (April – Oct)	Baseline [°C]	Intervention [°C]	△T [°C]	Cooling season (April – Oct)
Commercial – regular occupancy											
C1	564	6.8	2.4	57%	65%	72%	71%	20.5	25.7	5.2	$3,400
C2	564	6.4	2.8	48%	56%	66%	64%	20.5	25.7	5.2	$2,900
C4	91	2.5	1.1	43%	55%	62%	57%	26.0	28.9	2.9	$140
C5	107	2.7	0.8	61%	69%	74%	69%	NA	NA	NA	$200
C7	107	5.9	4.7	7%	21%	15%	9%	24.9	25.2	0.3	$58
Commercial – irregular occupancy											
C3	136	0.7	1.1	-95%	-54%	-39%	-36%	27.1	27.0	-0.1	-$35
C6	122	2.4	2.2	-5%	8%	2%	15%	25.4	26.9	1.4	$51
C8	122	0.2	0.1	68%	73%	64%	71%	25.0	24.9	-0.1	$18
Residential											
R1	83	0.9	1.0	-37%	-11%	9%	7%	25.4	26.6	1.1	$8
R2	83	2.2	3.4	-176%	-51%	-5%	-19%	25.2	25.5	0.4	-$35
R4	83	0.8	0.7	-10%	19%	55%	39%	26.6	27.1	0.5	$41

R5	119	1.2	1.5	-78%	-31%	20%	7%	25.9	26.4	0.5	$17
R6	119	1.5	2.5	-219%	-65%	-4%	-22%	24.6	23.9	-0.7	-$50

Source: Dana Miller, UC Berkeley

The following examples highlight findings at specific sites.

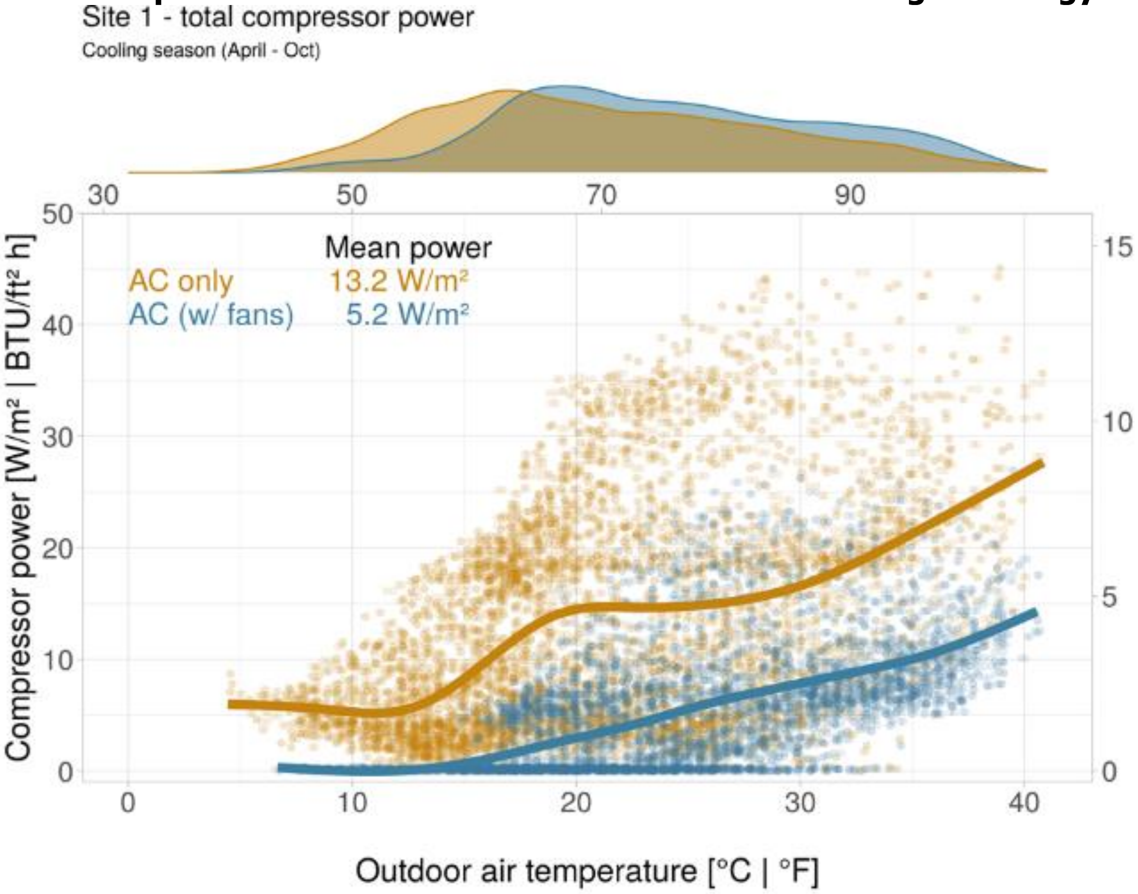
Examples of successful energy savings sequencing ceiling fans and air conditioning for cooling included:

(1): Commercial Site With Largest Sustained Cooling Setpoint Change and Energy Savings:

This site had a regular occupancy schedule, relatively low and stable air conditioning cooling setpoints, and substantial cooling energy consumption during the baseline period. It was the largest site in this study (6,070 sq. ft.) and had a high thermal mass building of concrete construction and a variable refrigerant flow (VRF) heat recovery system that provided both heating and cooling. The existing programmable thermostats were not replaced at this site as interoperability with thermostats (other than those provided by the VRF manufacturer) was not supported. This was therefore the only site where the team could assess the effect of installing the ceiling fans without the confounding effect of replacing the thermostat.

As shown in Figure 16, the absolute measured savings at this particular site were substantial (61 percent reduction in compressor power) even prior to normalizing for warmer weather during the intervention period. This particular site also encountered an extended HVAC failure during the study period due to a failure of the condensate pump system. During this period, the ceiling fans continued to operate, and the research team collected surveys and data. Despite indoor temperatures reaching temperatures higher than design recommendations, the majority of the occupants were still comfortable, demonstrating that the ceiling fans can provide a measure of resilience during mechanical system failures. Note that savings estimates due to the automated ceiling fans were comparable using data from either before or after the HVAC equipment repair, so the HVAC failure was *not* a driver of the large energy savings.

Figure 16: Compressor Power at Commercial Site With the Largest Energy Savings

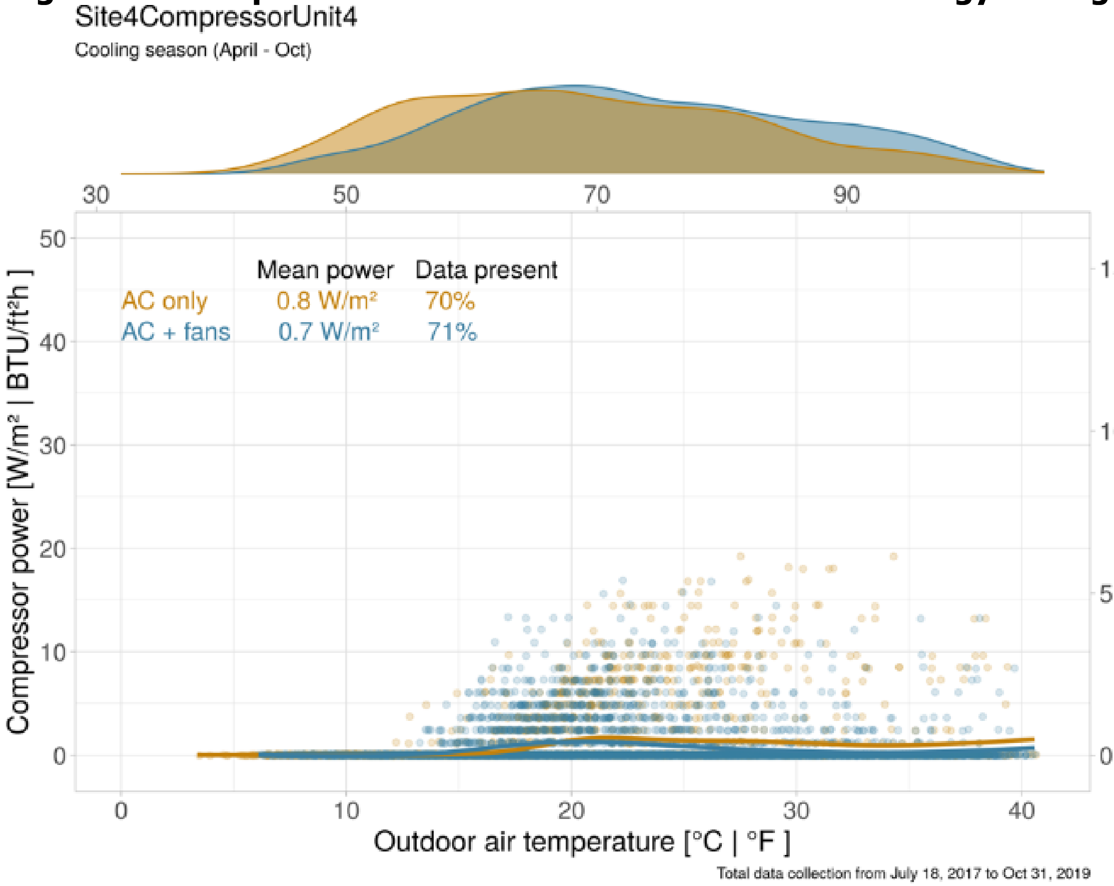


Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for the large zone at Site 1 with both offices and a community room. Raising cooling setpoint temperatures (from ~72 °F up to 78 °F) resulted in much lower air conditioning energy use, in addition to less hours of runtime.

Source: Dana Miller, UC Berkeley

(2): Residential Unit With Energy Savings: Figure 17 summarizes energy use in one of the one-story multifamily residential units. When the new programmable occupancy-sensing thermostat was installed as part of the retrofit, occupants were encouraged, and agreed to, set cooling setpoints to 78°F (26.5°C). While the air conditioning compressor ran for a comparable fraction of hours during the baseline and intervention periods (14 percent and 16 percent, respectively), the average cooling energy use during the intervention period was lower than the baseline period despite substantially warmer temperatures (seen in the distribution plot above the upper x axis). While the occupants’ schedules did not permit an interview for more detailed feedback, ceiling fan data showed that the fans operated frequently throughout Summer 2019. Thermostat data showed the thermostat was frequently off during Summer 2019 and occupants adjusted their air conditioning cooling setpoints to 80°F to 86°F (27°C to 30°C). This likely occurred because occupants did not need to run their air conditioning as often due to cooling provided by the ceiling fans.

Figure 17: Compressor Power at Residential Site With Energy Savings



Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for one multifamily residential unit. Despite higher temperatures during the intervention period, energy use was comparable or lower.

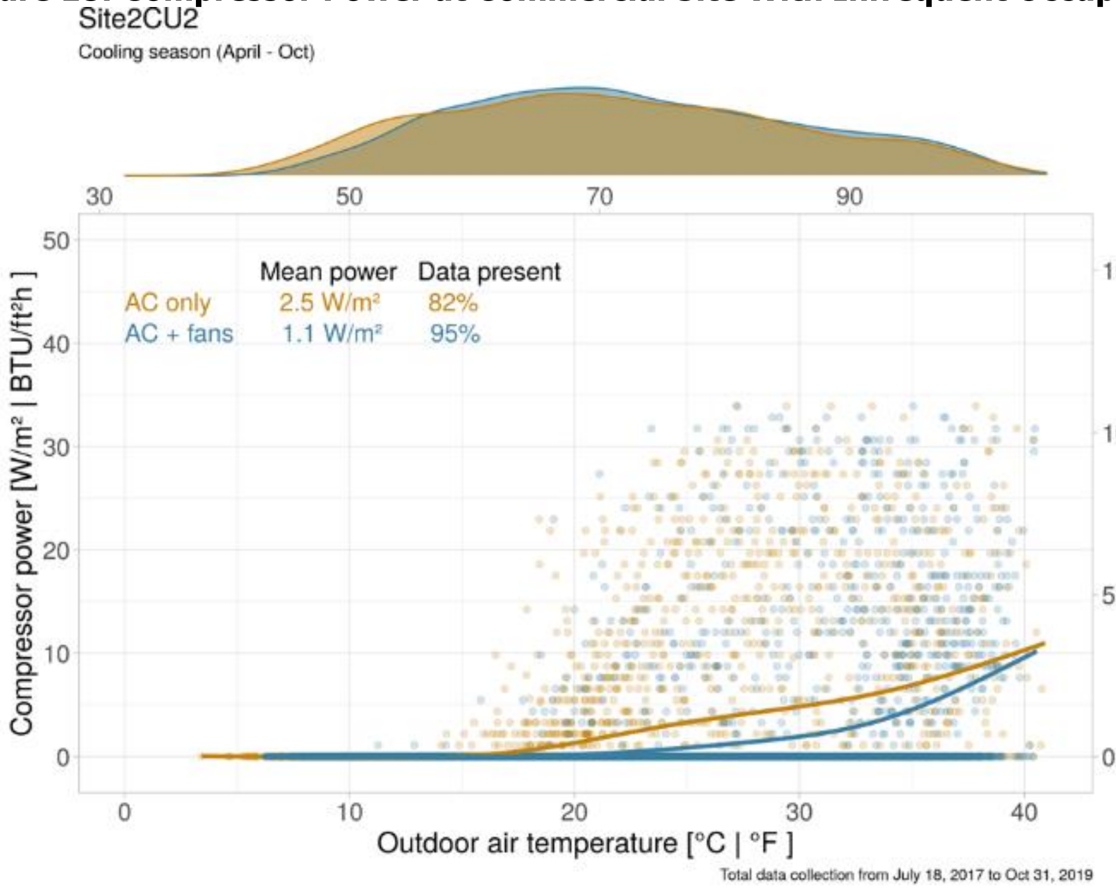
Source: Dana Miller, UC Berkeley

Examples of limitation of this retrofit approach include:

(3): Commercial Site With Infrequent Occupancy: Figure 18 summarizes energy use in the one-story community room at Site #2. While the average energy for air conditioning decreased in the intervention period after the fans and occupancy-sensing programmable thermostats were installed, the space was very infrequently occupied and mechanical cooling did not operate on a regular schedule. This is because, unlike the adjoining offices, the community room is primarily used for evening or weekend events booked by residents. The air conditioner compressors used less energy after the fans were installed (an average of 56 percent less compressor power), with positive feedback from the site manager. However, since the compressors operated for fewer hours than a more frequently occupied space, the total energy savings are less than would have been realized if the demand for cooling was more frequent.

Reduced potential for energy savings due to infrequent space usage was also an issue in the community room at Site #3, where despite measuring small energy savings in the intervention period, the compressor only ran for about 2 percent of total hours in both the baseline and intervention periods. This highlights an important consideration for future retrofits: potential savings from sequencing air movement and air conditioning are greatest at sites with more frequent or more intense air conditioning use. Note that in this project, sites were selected prior to any knowledge of air conditioning use.

Figure 18: Compressor Power at Commercial Site With Infrequent Occupancy

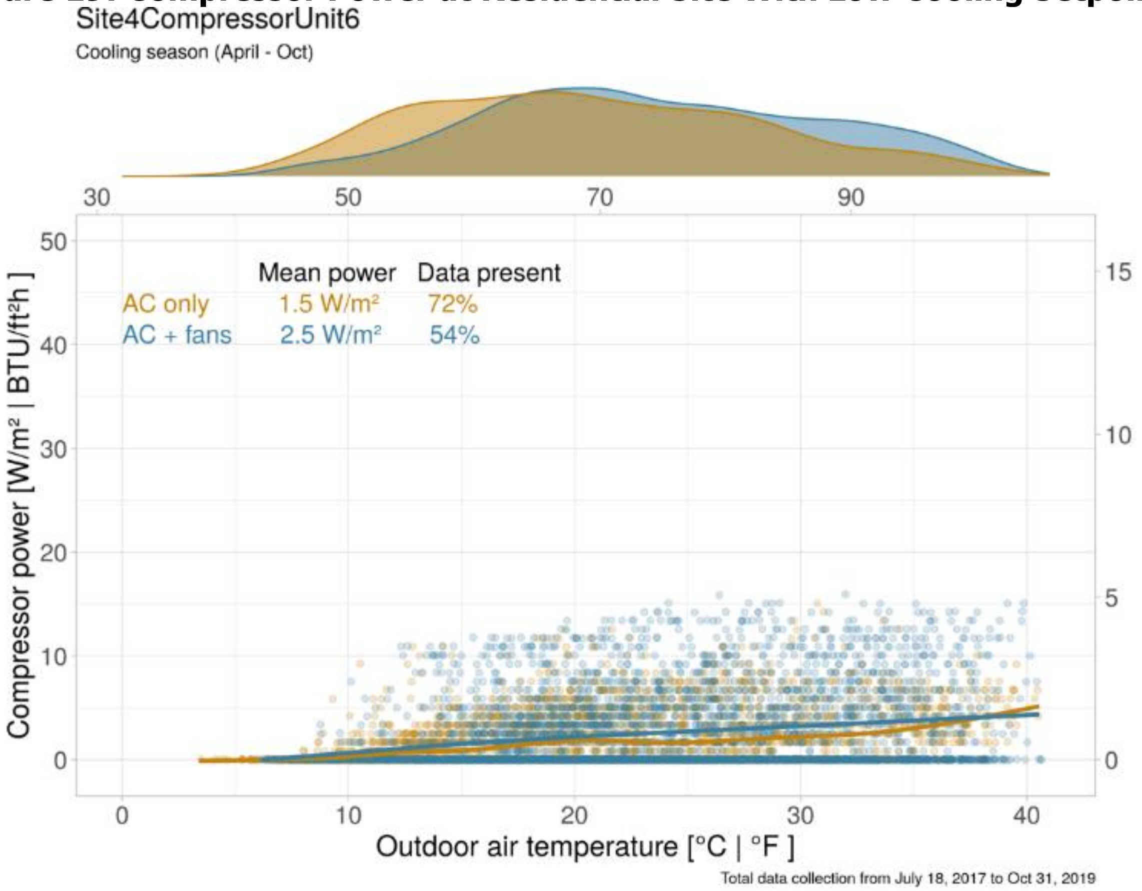


Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for a less-frequently used community room. Across comparable temperatures, the site used less air conditioning energy during the intervention period, but greater savings could have been realized if the space had required more frequent cooling.

Source: Dana Miller, UC Berkeley

(4): Residential Unit That Did Not Increase Air Conditioner Cooling Setpoints: **Figure 19** summarizes energy use in one of the two-story multifamily residential units. When the programmable occupancy-sensing thermostat was installed as part of the retrofit, occupants were encouraged to set their cooling setpoints to 78°F (25.6°C), though they typically selected lower air conditioning cooling setpoints of around 71°F (21.7°C). The air conditioning compressor ran for a comparable fraction of hours during the baseline and intervention periods (40 percent and 44 percent, respectively). However, the intervention period was warmer, with about twice as many 95°F (35°C) degree hours than during the intervention period. Without normalizing for the warmer weather, the team observed that compressor cooling energy use increased by 66 percent. In interviews, one occupant expressed that the fans improved their comfort in the space, particularly in one of the upstairs rooms, was excited to have the fans installed and would recommend them. Ceiling fan data also showed that one of the bedroom fans operated regularly during the summer. At the same time, occupants reported that cooling setpoints reflected their comfort preference, and that one adult occupant was home most of the day. Despite not saving energy, likely due to the lower cooling setpoints, occupants did report greater comfort.

Figure 19: Compressor Power at Residential Site With Low Cooling Setpoints



Compressor power use, normalized per floor area served, with respect to outside drybulb temperature for one multifamily residential unit that did not realize energy savings. The occupants preferred to maintain relatively low thermostat cooling setpoints (~71 °F) after fan installation.

Source: Dana Miller, UC Berkeley

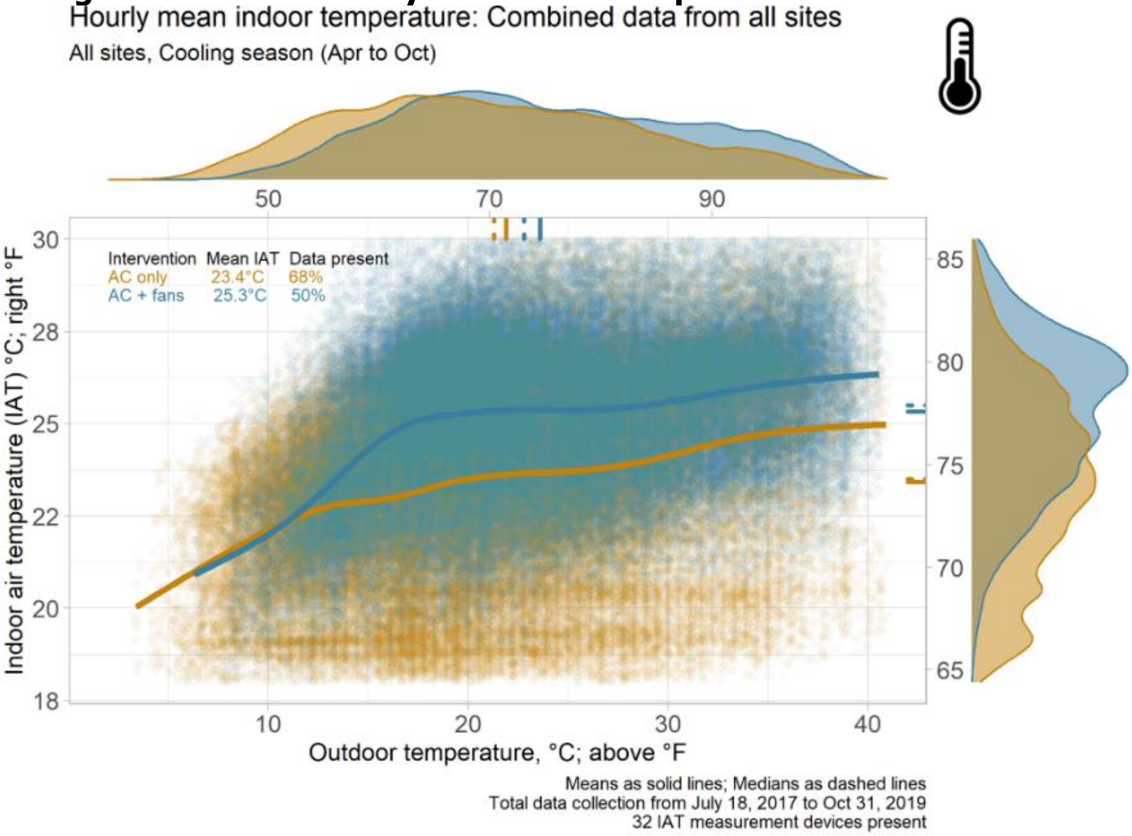
Indoor Environmental Quality Analysis

Indoor temperature sensors were installed at each site in Summer 2017, one year prior to the retrofit installation of the ceiling fans and new thermostats. Multiple temperature sensors were installed at some sites to capture potential variations across larger spaces such as a large zone or a 2-story residential unit. Due to data transmission issues, some sensors had periods of missing data. In the following plots, temperatures for each HVAC zone were based on the mean hourly temperature from all temperature sensors in each zone.

After the new ceiling fans and thermostats were installed, occupants at each site received educational materials and in-person visits to encourage them to increase their air conditioning cooling setpoints to account for the cooling effect of the fans. In commercial spaces, depending on prior cooling setpoints, cooling setpoints for the new thermostats were either directly increased to 78°F (25.6°C) at install, or gradually raised over a period of several weeks. Occupants were free to adjust the thermostat at all times and were provided with information on how to do so. In residential units, the default cooling setpoints were increased to 78°F during installation. Residents were similarly free to adjust thermostats and were provided with instructions on how to do so. Based on thermostat usage data, occupants in both commercial and residential spaces adjusted their thermostats, with changes ranging from permanently changing both the schedule or default setpoints to temporary overrides.

Consistent with reductions in air conditioning compressor use and observed increases in thermostat setpoints, mean measured indoor air temperatures, shown in Figure 20, were higher in the intervention period than in the baseline period across a similar range of outdoor temperatures. The mean hourly indoor air temperature across all sites increased approximately 2°C (3.4 °F).

Figure 20: Mean Hourly Indoor Air Temperatures Across all Sites



Mean hourly Indoor air temperature compared to outside drybulb temperature across all 32 temperature sensors across all hours (including unoccupied hours) and all zones across all field study sites.

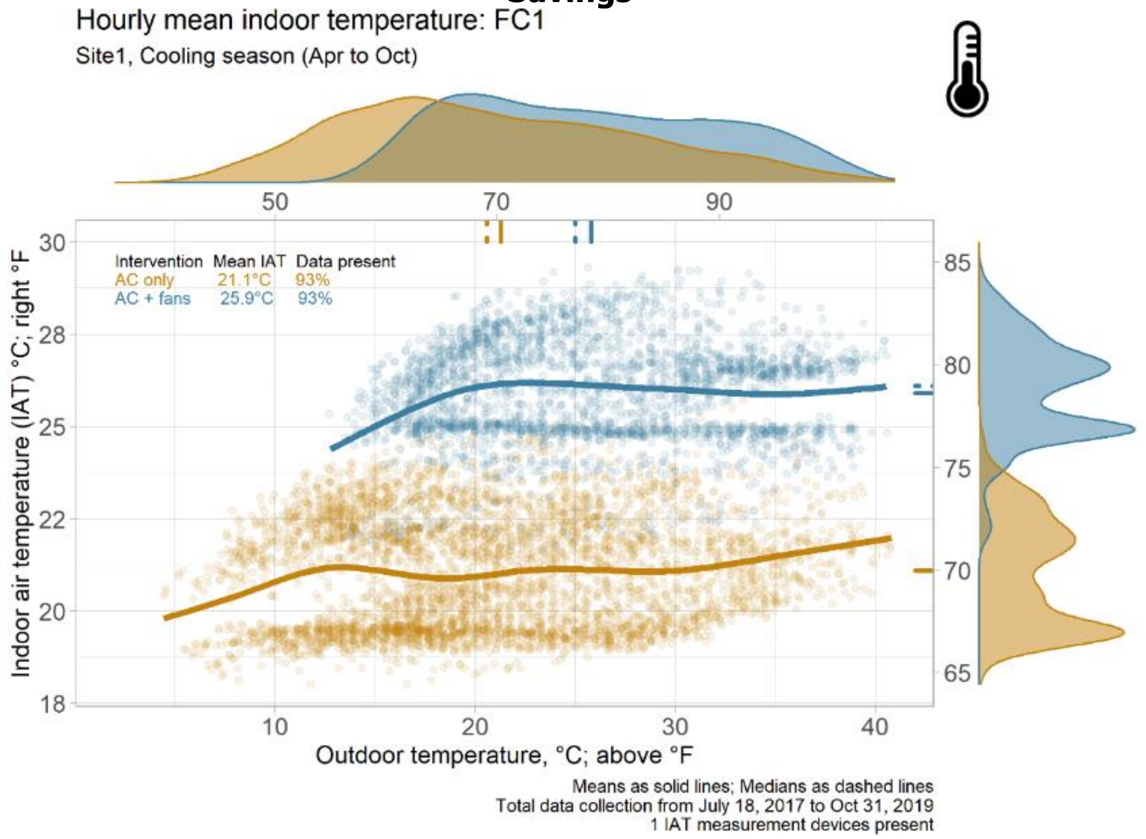
Source: Sonja Salo, UC Berkeley

Figures 21 to 24 show indoor air temperatures at the same four sites.

Examples of successful energy savings included:

(1): Commercial Site With Largest Sustained Cooling Setpoint Change and Energy Savings: As previously shown, this particular site had substantial savings: an overall 61 percent reduction in compressor power use. Figure 21 shows that the mean indoor temperatures also substantially increased, by approximately 4.5°C (9°F). This is partly due to the relatively low cooling setpoint (70°F - 72°F) prior to the intervention. The facilities manager, office staff, and occupants all had positive feedback about the fans, and point-in-time occupant surveys showed similar thermal comfort between the baseline and intervention periods.

Figure 21: Indoor Air Temperature at Commercial Site With the Largest Energy Savings

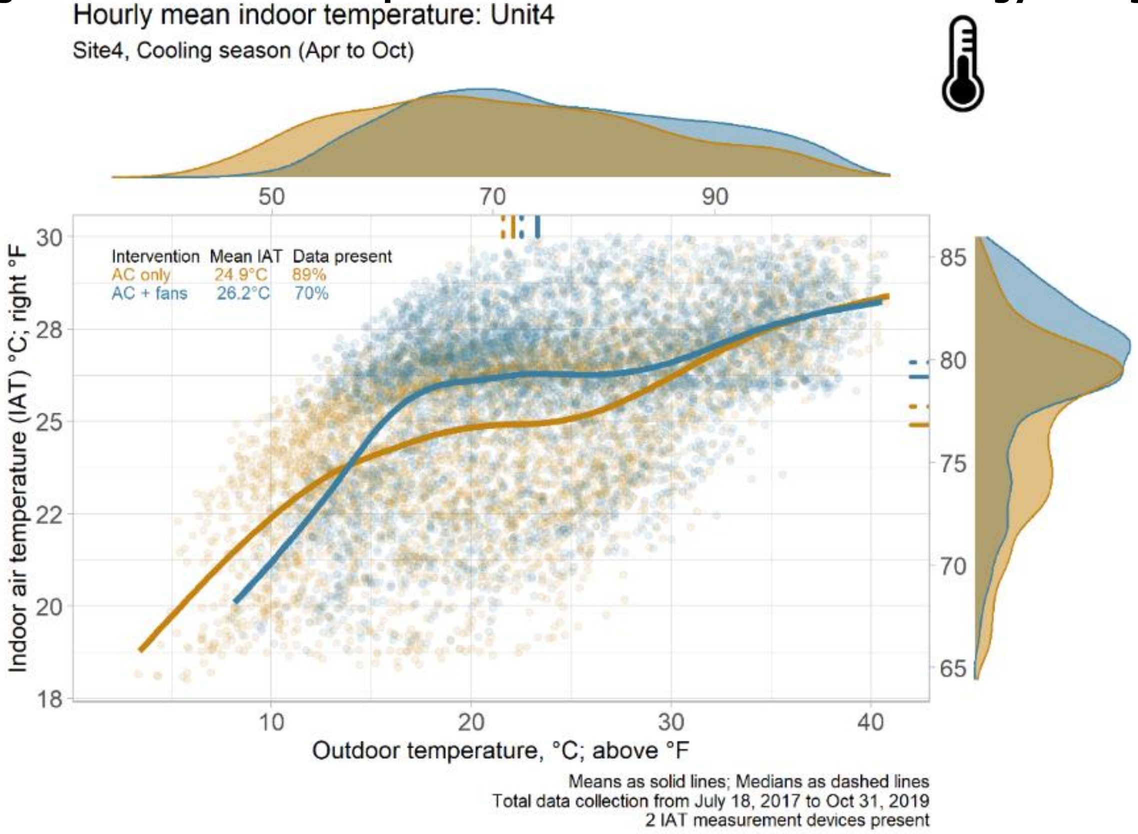


Indoor air temperature compared to outside dry bulb temperature for a large zone at Site 1 that increased cooling setpoints from 72 F to 78 F, resulting in higher indoor air temperatures, while maintaining occupant comfort.

Source: Sonja Salo, UC Berkeley

(2): Residential Unit With Energy Savings: Figure 22 summarizes indoor air temperatures in one of the one-story residential units at Site 4 that used less energy during the intervention period, despite higher outdoor temperatures. Mean and median indoor air temperatures were about 1°C (~ 2 °F) higher in the intervention period after fan installation and were noticeably higher between outdoor air temperatures of approximately 15°C and 30°C (60°F - 86°F). The data shown is for all hours, which may include periods when residents were not at home for extended periods of time.

Figure 22: Indoor Air Temperature at Residential Site With Energy Savings



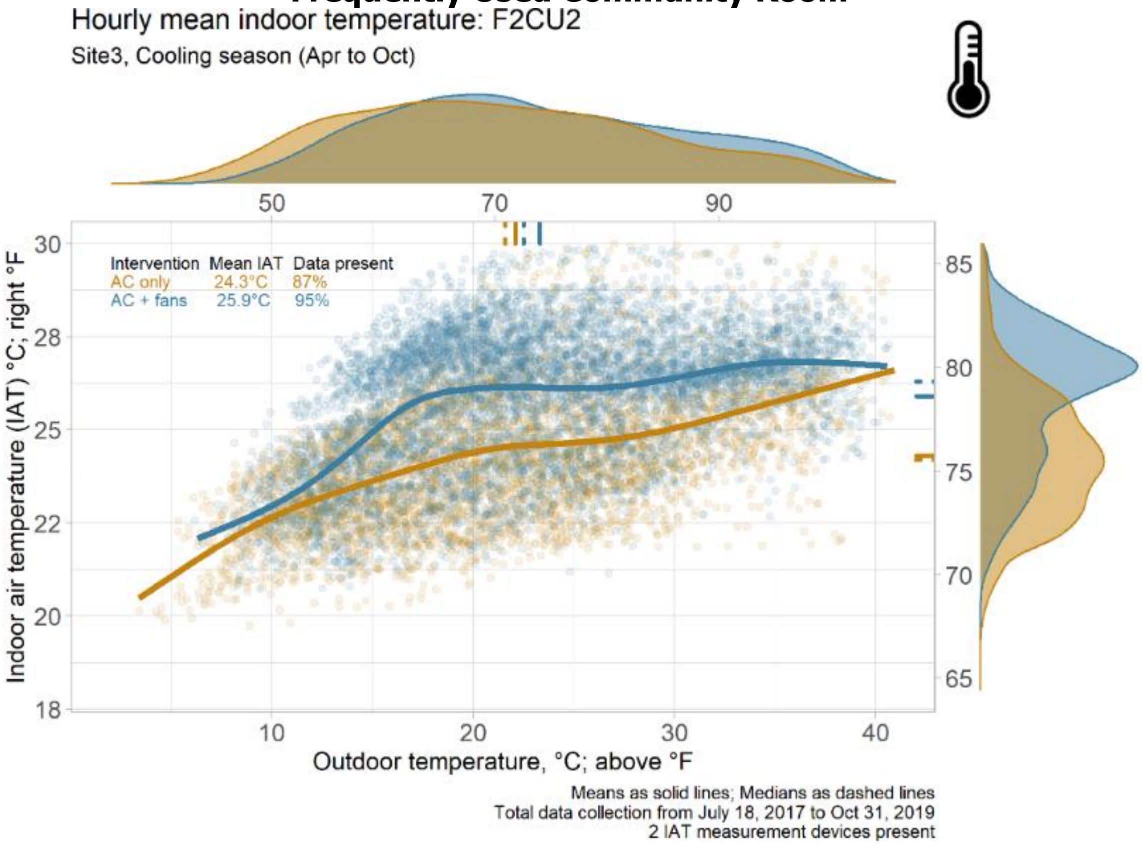
Indoor air temperature compared to outside drybulb temperature for a one-story multifamily residential unit that realized energy savings despite warmer temperatures during the intervention period. Mean and median indoor air temperatures are about 1 °C (~ 2 °F) higher in the intervention period after fan install.

Source: Sonja Salo, UC Berkeley

Examples of limitation of this retrofit approach include:

(3): Commercial Site With Infrequent Occupancy: This space was infrequently occupied so the HVAC system operated infrequently and total cooling energy savings were relatively low. Despite this, Figure 23 shows that the combined intervention of the new occupancy-sensing thermostat and ceiling fans led to higher indoor temperatures in the intervention period (consistent with the reduction in air conditioning use). This is likely due to the new thermostat schedule, setpoints, and occupancy sensing, including an unoccupied cooling setback setpoint of 82°F (27.8°C).

Figure 23: Indoor Temperature Compared With Outside Temperature for Less-Frequently Used Community Room



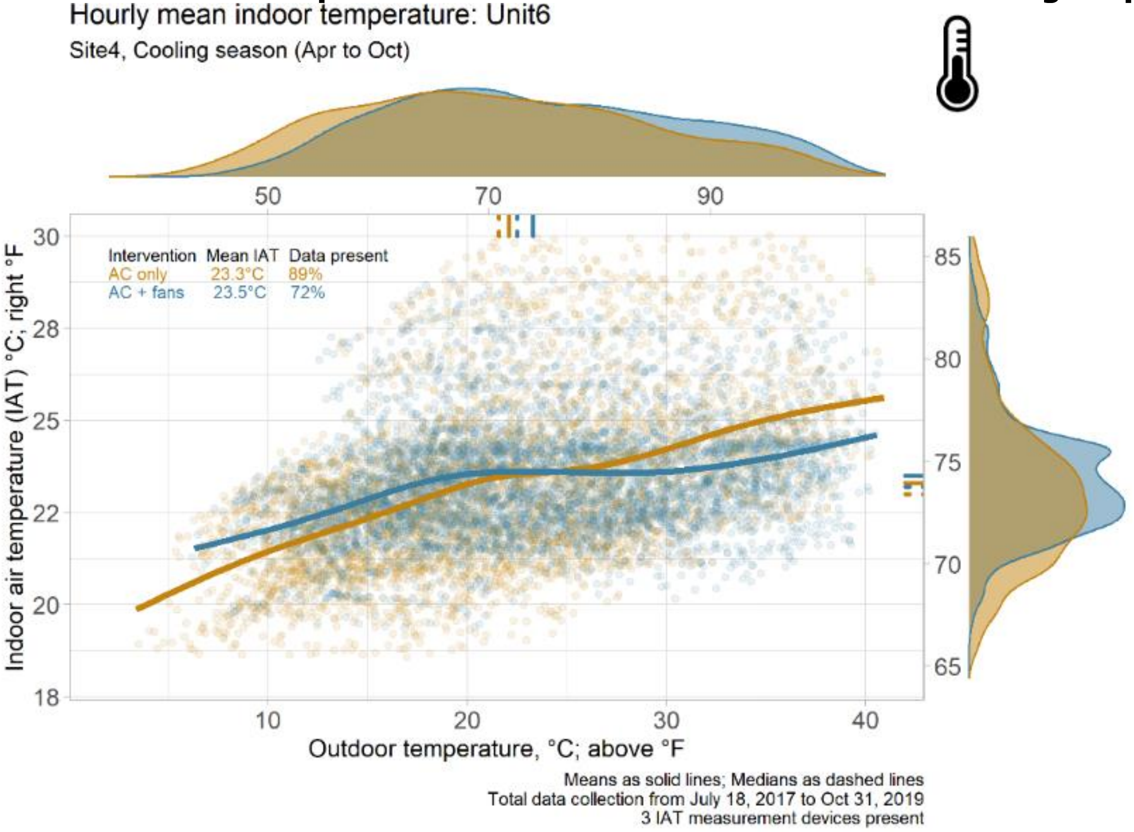
Indoor air temperature compared to outside drybulb temperature for a less-frequently used community room. Across comparable temperatures, the site with higher indoor temperatures during the intervention period used less air conditioning energy during the intervention period, but greater savings could have been realized if the space had required more frequent cooling.

Source: Sonja Salo, UC Berkeley

(4): Residential Unit That Did Not Adopt Increased Air Conditioner Cooling Setpoints: Occupants in this residential unit did not prefer to increase the air conditioning cooling setpoints after fan installation. Unsurprisingly, mean hourly indoor air temperatures were comparable in both the baseline and intervention periods, as shown in Figure 24. The occupants received written and verbal information about how increasing cooling setpoints could contribute to energy savings with comparable comfort but preferred their existing setpoints.

This highlights the conditional potential for energy savings using air movement: while ceiling fans staged with air conditioning can save substantial amounts of cooling energy, this intervention is only effective if the cooling effect from fans enables occupants to raise cooling setpoint temperatures. Personal needs and preferences, including differences in indoor activities, clothing levels, and health status, all contribute to cooling temperature preferences.

Figure 24: Indoor Air Temperatures at Residential Site with Low Cooling Setpoints



Indoor air temperature compared to outside drybulb temperature for a residential unit that maintained comparably low air conditioner cooling setpoints after the intervention, and therefore did not realize energy savings prior to weather normalization.

Source: Sonja Salo, UC Berkeley

Survey Results

Office Workers

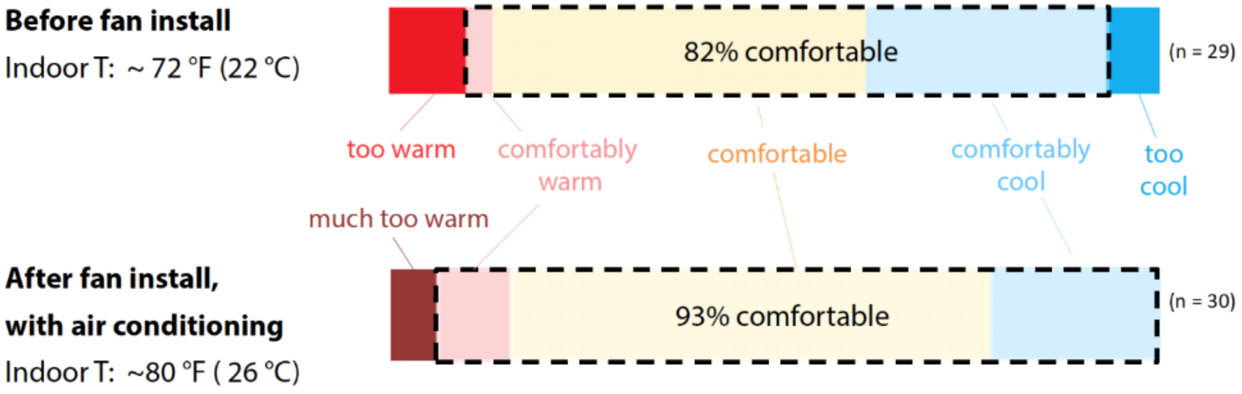
Because it was challenging to enlist office workers to complete surveys, little data are available, so the generalizability of this particular data source was limited. Findings from the Right Now survey suggest that individual differences across participants accounted for shifts in their preferences in thermal sensation, air movement acceptability, and thermal acceptability. These differences could be physiological, psychological, or situationally dependent. There was less variation in air quality acceptability; however, there were still likely individual differences in this perception, most likely due to situational circumstances in the space.

Common Room Users

The research team analyzed residential perceptions of the common room spaces at the Franco site at three time points: before installation of the fans, after fan installation when the air conditioning (AC) was not functioning at the end of Summer 2018, and with functional AC in mid-Summer 2019.

Overall, very little change was detected within the survey data from time point to time point. This lack of change in perspective was impressive given that the average temperature had shifted across each time point. While surveying at pre-install, the average indoor temperature was 72°F (22°C). During the second survey, (when the mechanical system failure occurred and only the fans were operating), the mean indoor temperature was warmer, 80°F (27°C). Finally, at the third survey point, both fans and the air conditioning operated as planned, and the average indoor temperature was 80°F (26.5°C). These results overall suggest that the presence of the fans increased the range of thermal comfort and acceptability.

Figure 25: Comfort Votes and Indoor Air Temperatures



The upper bar shows the votes of occupants before the fan install—note the number of 'too cool' votes. The bottom graph shows votes after ceiling fans were operating together with air conditioning (at a higher air conditioner cooling setpoint).

Source: Dana Miller, UC Berkeley

The surveys showed an increase in air movement acceptance after installation of the fans. The results highlight that, in addition to increasing one's range of thermal comfort, the fans also positively impacted air movement acceptability. Other possible influencers over variances across time points could include demographic differences (e.g., age, background) or circumstances within the physical environment at the time).

Interviews

The purpose of the interviews was to better understand occupants' experiences with the new equipment: ease of use, impacts on indoor environmental quality (caused by the equipment), perceived impact on energy costs, and perceived value. At the end of the second interview the team asked occupants for feedback and answered their questions. The team also solicited occupant feedback on how the study could have been improved.

Both occupant types were asked questions about their experiences with both the fans and the thermostat equipment. Overall, occupants felt the equipment was easy to use though they did remark that the Ecobee thermostats had a steep learning curve. However, each of those respondents also explained that they eventually felt comfortable with the Ecobee once they understood how to use them. They found the fans easy to use.

Manual Versus Automatic Control

By the end of the study, all participants reported on using the fan remotes on a regular basis and felt satisfied with them. None of the occupants reported using the mobile app, and many reported that they saw no purpose in the app. Initially one resident used the browser login for the thermostat but had stopped by the end of the study.

When the team pre-installation inquired whether occupants preferred fans to be automatic or manually operated, they were split on their preferences. After fan installation, all office workers reported preferring the automatic setting and most (80 percent) of residential occupants preferred the manual setting. Their desire for manual control appeared to stem from a general preference for greater control. Many residents also reported that the fans sometimes provided too much cooling, or that they did not always enjoy the air movement. In the exit interviews, office workers also expressed a desire for more control, but several voiced that they actually liked the fact that the fans did the work for them. One office worker said, "They've helped [me] by not having to worry about being too hot or too cold in the office. Because when you're too hot or too warm it's hard to concentrate. By having the fan, it helps me stay focused because I don't have to worry about the temperature."

Differences in preference for manual-versus-automatic control across participant types revealed a couple of possibilities. It appeared that there was an intrinsic motivation for some sense of control over the environment; however, there were individual differences across occupants in individual needs for control. Second, these results also suggest that the activity within the environment could also affect the level of need for control. Office spaces, unlike homes, tend to support a specific set of tasks (focus, productivity), whereas homes support a multitude of tasks (working, relaxing, childcare, socialization). Perhaps in spaces where activities vary more broadly, more occupant control (or the perception of control) is more important.

Indoor Environmental Quality

The team also asked participants about how the fans impacted their perception of IEQ. Overall, perceptions were quite positive from both occupant groups. All participants felt the fans provided adequate cooling, and importantly, none could recall an instance when the fans did not provide effective cooling. One resident reported using an additional portable fan during cooling season, but explained this was only in the bathroom (which did not have access to the ceiling fans). Additionally, most (100 percent of residents, 75 percent of office workers, one did not respond) reported at the first interview that the fans improved their overall air quality, and 100 percent reported this at the second interview. Though two residents reported random hot and cold spots throughout the space at the first interview, by the second all occupants reported that the fans had eliminated this issue. Finally, all residents reported that they felt the fans improved their overall IEQ, and 50 percent and 100 percent (at the first and second interviews, respectively) of all office workers reported that the fans improved their IEQ. (Two office workers did not comment on this at the first interview).

The researchers also asked occupants whether or not the fans influenced the functionality of other aspects of IEQ, specifically: Wi-Fi effectiveness, lighting, noise levels, ceiling clearance, and the safety of occupants. At the first interview, two residential occupants reported issues with Wi-Fi interference from the fans. The research team worked with those occupants to alleviate this situation and the problem was remedied after resetting the router. A related issue related to occupants' television sets.

Design Perceptions

Fans: Overall, both user groups expressed a lot of enjoyment with the fans. They were all pleased with their ability to cool the space quickly and effectively. Most users also enjoyed the design of the fans and the ability to adjust them easily and with the remote. Some occupants were troubled by the light on the fans. They believed they were too dim and were also confused by the blue sensor light. All occupants seemed satisfied with the air circulation that the fans provided, though many felt the fan speeds were too high at times.

Both groups felt both satisfied and dissatisfied with the automation of the fans. One interpretation of this may be that they were simply seeking more control. The fan automation seemed to be appreciated at times, but frustrating at others. Frustration seemed most palpable in the resident user group compared with office workers, who seemed more accepting and appreciative of the automatic nature of the equipment. This difference could be due to the different needs or expectations in a workspace as compared with a home.

Thermostats: Consistently, across user types, each reported that they felt the thermostat equipment was challenging to use, at first. However, by the second interview, all reported that they felt they had mastered the equipment. This finding suggests that over time the thermostats become understandable, but that there is likely a steep learning curve for users at installation.

Residents reported satisfaction with the lower energy costs from the installation of the fans and the thermostats. Both groups were also pleased with reduced use of AC. Many users, especially residents, also reported appreciation for the look and feel of the thermostat interface.

Suggested Design Improvements

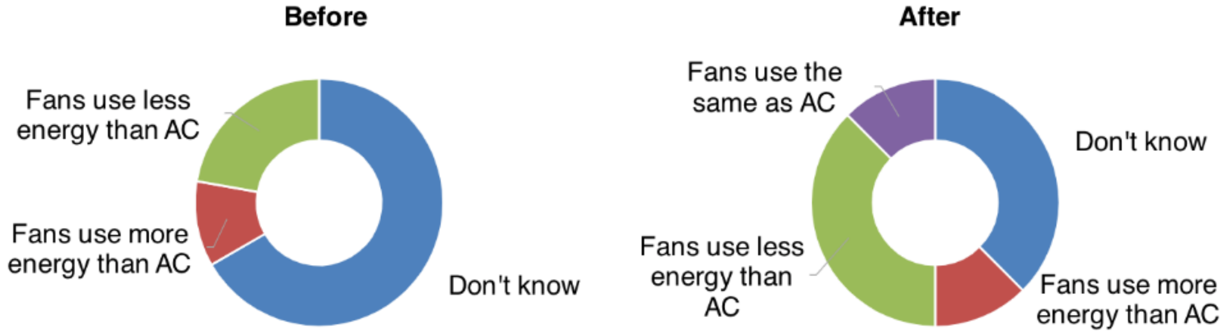
Overall, most occupants (regardless of type) did not have any suggestions for design improvements. One resident explained that perhaps having a slower start speed for the fans would be useful. Many occupants explained they felt the phone app was not useful and that they would never use it. And, in general, most occupants reported they would keep the design as is for both the fans and the thermostat equipment.

Occupants did not provide much direct feedback when asked explicitly about design improvements. For instance, in the case of the thermostats, it seems as though some effort should be directed to either providing more user education at installation or making the system more intuitive. Some users also mentioned that they would have preferred the thermostat interface to be available in Spanish (only English and French were available on the Ecobee). Over time, occupants learned how to use the thermostat, but almost unanimously stated that they were initially a challenge. As for the fans, one issue that came up a couple of times across occupant groups was their lights. Occupants wanted more control over the lights' brightness. Also, both occupant groups mentioned the fan speed was problematic at some times and expressed interest in having an even lower speed option.

Overall Value and Perceptions of Energy Use

During each interview the team asked participants their perceptions regarding whether fans use more or less energy than air conditioning. Results revealed that, overall, most occupants from both groups were unsure. One resident and one office worker believed they used less energy, and one office worker believed they used more. The data from the second interview is likely less reliable since occupants were asked for their recollections over the past year and a half.

Figure 26: Occupants' Perceptions of Fan Energy



Before fans were installed, more occupants didn't know the relative energy use of fans compared to air conditioning.

Source: Sonja Salo, UC Berkeley

Finally, occupants were asked whether they would recommend the fans to family and friends. At both time points, all occupants (except one employee who did not respond to this at the first interview) reported that they would recommend them. At the end of the exit interview most of the office workers expressed that they wished they had the fans in their own homes.

Close Out and Handover Challenges

The research team worked with BAF to specify, implement, and improve three successive versions of a new ceiling fan control algorithm (based on temperature, occupancy, and user interactions). As intended, occupant interaction did cause fan setpoints to gradually adjust over time. All occupants surveyed preferred the temperature-based fan operation with the firmware developed for this study (always with the option of manual override) over a commercially available version that did not support temperature-based controls.

Since all the equipment used in this study was chosen for its network integration and smart functionality, both fans and thermostats required a network connection. Removing equipment from the networks reduced the features available to users unless they reconnected to their own networks, which weren't guaranteed. Additionally, network control and usage was limited during the study so that the research team could control, update, and monitor equipment in real time. Residents and workers therefore had limited knowledge before the close-out of how to set up and use these additional features. While training and handouts were made available, most occupants were not interested.

Field Study Lessons Learned

Some space types, such as bedrooms, required special consideration. For example, occupants sleeping under blankets may have lower metabolic rates and desire higher fan setpoints that may not be detected by motion or infrared-based occupancy sensors. In addition, blinking LEDs that indicate fan speed are disruptive at night.

The end users in this study did not use the mobile phone apps or websites; furthermore, the learning curve for the thermostat was particularly steep. Both devices would benefit from further usability efforts. Most users did not change settings, which indicates that the default setting should be more robust and revert to a sensible default value after a reasonable amount of time (e.g., a few weeks). This would prevent occupants from accidentally locking themselves into a poor performance of which they are unaware.

Few of the interior spaces operated above 80°F (26.7°C) for substantial periods of time, even with air movement. This contradicts lab study findings that suggest much higher temperatures are feasible and comfortable with air movement.

Ongoing Maintenance and Site Challenges

Post-install visits were frequently required for a variety of concerns and data monitoring issues. All data were uploaded remotely to be visible in either real time or through daily downloads. This allowed the research team to see a problem immediately, but made it difficult at times to diagnose whether a lack of data was due to equipment or the network connection.

For convenience and price, the Wi-Fi hotspots selected were consumer models with minimal range and required a range-extending device for each one. For the residential units this equipment was installed in water heater closets outside of the units. During high summer temperatures these closets became hot enough to cause the range extenders to shut down; any equipment connected to them could not subsequently transmit data. While the range extenders did restart as the temperature cooled, the research team found that the equipment transmitting HVAC energy use would not reconnect automatically and had to be restarted. This problem was solved by replacing all range extenders with outdoor models built to withstand extreme temperatures.

Wi-Fi hotspots in exterior locations did not shut down in high temperatures, but regular temperature swings were thought to cause extreme battery expansion in many units, which in turn required battery replacement and sometimes caused loss of power and charging ability.

Ceiling fans could only be controlled and adjusted via smartphones connected to the same local area network as the fan, so required frequent visits. In order to correctly retrieve fan data from the BAF servers, all fans had to be registered to known users and firmware had to be tailored to this project. This required visits to register the fans and update the firmware. Fans in residential kitchens were found to have incorrect logic boards that did not allow them to be updated to correct firmware versions, so were replaced in December 2018. Two of the installed fans also developed motor problems and had to be replaced.

Many of the times when equipment either lost network connections or the network itself went down, the solution was to restart it, which was only possible manually. To avoid this problem, AEA installed "smart plugs" where possible; these could be controlled remotely and automatically turn equipment off and on.

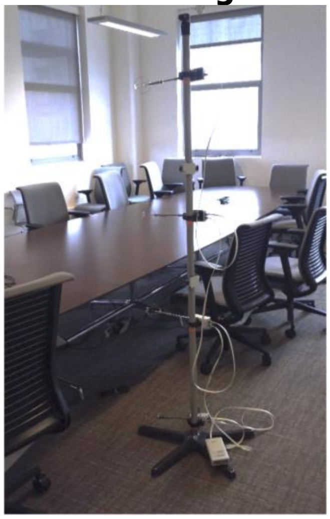
One location where Hamilton sensors were installed was at HVAC supply vents. This allowed determination of whether compressors were in heating or cooling mode since thermostat data were not available at this site. However, the project team found that changing temperature air streams caused condensation to form on the devices, which was sufficient in some cases to short it out. To eliminate this problem two methods were used: installing Hamiltons in plastic bags with an included desiccant, and installing separate temperature sensors wired directly into the Hobo U-30 data loggers.

Technology Readiness

Case Study Results

Ceiling fans are infrequently included in commercial spaces even with the benefits of increased occupant comfort and decreased energy use, either through raised setpoints in cooling or destratification[6] in heating. This case study provides practical insights into the case for ceiling fans in commercial spaces. The research team at CBE conducted 13 interviews with architects, engineers, and facilities managers from California and around the country. The team compiled data on common motivations and applications, control strategies, barriers to market adoption, best practices, and airspeeds. These professionals provided lessons learned from 20 operational projects, including ceiling fans that served a wide set of functions in commercial spaces. Understanding the challenges they faced and the lessons they learned from these projects can prioritize research and communication efforts. The researchers also took airspeed measurements at five of the projects to provide insight into real-world conditions in commercial buildings with ceiling fans. Ceiling fan operation results showed that the fans could operate at generally relatively low airspeeds, often under 0.2 m/s. The researchers also found that just 25 percent of the 20 projects had any type of automation in the ceiling fan controls. This study serves as a resource for both designers and the wider industry and can forge a commercial path for inclusion of ceiling fans in commercial buildings. The full report may be found in Appendix E (Present et al., 2019).

Figure 27: Measurements in Existing Buildings With Ceiling Fans



A tree of air flow sensors replaces a chair at a conference room.

Source: Elaina Present, UC Berkeley

Although interviewees revealed many challenges and barriers during the design process, occupant feedback about the fans was generally positive once installed. Occupants often chose to operate the ceiling fans even when airspeeds were too slow to create appreciable cooling. This aligns with findings from the interviews, that ceiling fans provide benefits not only for

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[6] Destratification refers to dispelling the natural thermal stratification of air where in heating environments, the hot air rises to the ceiling. Destratification would mix the room's air so make better use of the hot air.

comfort conditioning and energy use reductions, but also for individual control, non-thermal benefits (such as perceived and measurable air quality), or aesthetics.

Furthermore, even though the fan settings and resulting airspeeds were low, it is important to note that these zones already operated within ASHRAE 55 comfort conditions without fans. Higher airspeeds would have overcooled the occupants unless zone temperatures were increased. This revealed the opportunity to reduce HVAC energy consumption by increasing zone cooling setpoints and running ceiling fans faster.

Among the projects studied, there were few examples of automatic control, and interviewees did not agree about whether manual or automated controls were preferable; they described pros and cons for each one. A viable option would be occupancy- and temperature-responsive automated controls that can be configured and temporarily overridden by occupants (similar to current best practices in the lighting industry).

As with many strategies to improve building performance, best practices start with an integrated design process where different stakeholders communicate early in the process and coordinate decision making. This alone would help overcome many identified barriers. These barriers included perceived concerns about noise, maintenance, or papers blowing; ability to clearly explain the benefits of fans to building owners or other design team members; cost tradeoffs; and lack of design guidelines. It's also important that the process not end with design but be maintained through occupant education so that users fully understand the range of ceiling fan performance (i.e., cooling vs. destratification) so that benefits are fully realized.

This study found substantial uncertainty around designing with ceiling fans despite their significant benefits. Lack of design guidance and measured performance was a significant barrier to downsizing HVAC equipment upon ceiling fan inclusion. Designers would benefit from outside support from industry, government, or academia. The most significant support could be for design guidance backed by laboratory testing, CFD, and field studies, for commercial spaces with ceiling fans. This would make designers less reliant on manufacturers' guidance and improve communication regarding the abilities and design goals of ceiling fans. Another need is for expansion of available standardized product test specifications, which would allow designers to more directly compare ceiling fan products. This will require industry effort; ASHRAE has completed Standard 216, “Methods of Test for Determining Application Data of Overhead Circulator Fans,” which will meet most of this need. Industry could also better support ceiling fan products that easily communicate with building automation systems or, ideally, are BACNET-capable. In general, a more standardized design process would reduce several barriers to implementation.

CHAPTER 4: Technology/Knowledge Transfer Activities

This chapter documents project technology, knowledge or other market transfer activities, the online design tool, the design guide, codes and standards support, and additional outreach. The team shared project results through multiple channels. Outreach included seven published papers and 18 presentations to practitioners, developers, manufacturers, policy makers, and end users. Through the students hired, future thought leaders were trained. The project has also developed an online design tool, found at cbe.berkeley.edu/fan-tool and the design guide, found at https://cbe.berkeley.edu/wp-content/uploads/2020/04/CBE-Ceiling-Fan-Design-Guide-V0.pdf. The tool and design guide can be used by designers, architects, and engineers to provide ceiling fan spacing and other recommendations for optimal overall airflow. The team also conducted codes and standards outreach.

Outreach

Papers Published

Chen, Wenhua, Hui Zhang, Ed Arens, Maohui Luo, Zi Wang, Ling Jin, Junjie Liu, Fred Bauman, Paul Raftery. 2020. Ceiling-fan-integrated air conditioning: Airflow and temperature characteristics of a sidewall-supply jet interacting with a ceiling fan. Build Environ. 2020 Mar 15;171:106660. https://escholarship.org/uc/item/8cj7n6ps

Gao, Y, Hui Zhang, Ed Arens, Elaina Present, B. Ning, Y. Zhai, Jovan Pantelic, Maohui Luo, Paul Raftery, S. Liu. 2017. Ceiling fan air speeds around desks and office partitions. Build Environ. 2017;124. https://escholarship.org/uc/item/3pq2j9mh

He, Yingdong, Wenhua Chen, Zhe Wang, and Hui Zhang. 2019. “Review of Fan-Use Rates in Field Studies and Their Effects on Thermal Comfort, Energy Conservation, and Human Productivity.” Energy and Buildings. Elsevier Ltd https://escholarship.org/uc/item/7hx9338z

Present, Elaina, Paul Raftery, Gail Brager, Lindsay T. Graham. 2018. Ceiling fans in commercial buildings: In situ airspeeds & practitioner experience. Building and Environment. 147 (2019) pp. 241-257. https://escholarship.org/uc/item/84h3z7nx

Raftery, Paul, Jay Fizer, Wenhua Chen, Yingdong He, Hui Zhang, Edward Arens, Stefano Schiavon, and Gwelen Paliaga. 2019. “Ceiling Fans: Predicting Indoor Air Speeds Based on Full Scale Laboratory Measurements.” Building and Environment 155 (May). Elsevier Ltd: 210–23. doi:10.1016/j.buildenv.2019.03.040. https://escholarship.org/uc/item/4p479663

Parkinson, Tom, Paul Raftery, Elaina Present. 2020. "Spatial Uniformity of Thermal Comfort from Ceiling Fans Blowing Upwards." ASHRAE Transactions, Orlando Conference 2020 https://escholarship.org/uc/item/5fs9q6fq

Miller, Dana, Paul Raftery, Mia Nakajima, Sonja Saloa, Lindsay T. Graham, Therese Peffer, Marta Delgado, Hui Zhang, Gail Brager, David Douglass-Jaimes, Gwelen Paliaga, Sebastian Cohn, Mitch Greene, Andy Brooks. 2021. “Cooling energy savings and occupant feedback in a two year retrofit evaluation of 99 automated ceiling fans staged with air conditioning." Energy and Buildings. 251 (November) https://doi.org/10.1016/j.enbuild.2021.111319

Open-Source Software Released

- Design tool: cbe.berkeley.edu/fan-tool.

Students Hired

Elaina Present, Dana Miller, Marta Delgado Lombardo, Mia Nakajima

This project was the subject of two masters theses by Dana Miller and Elaina Present.

Presentations

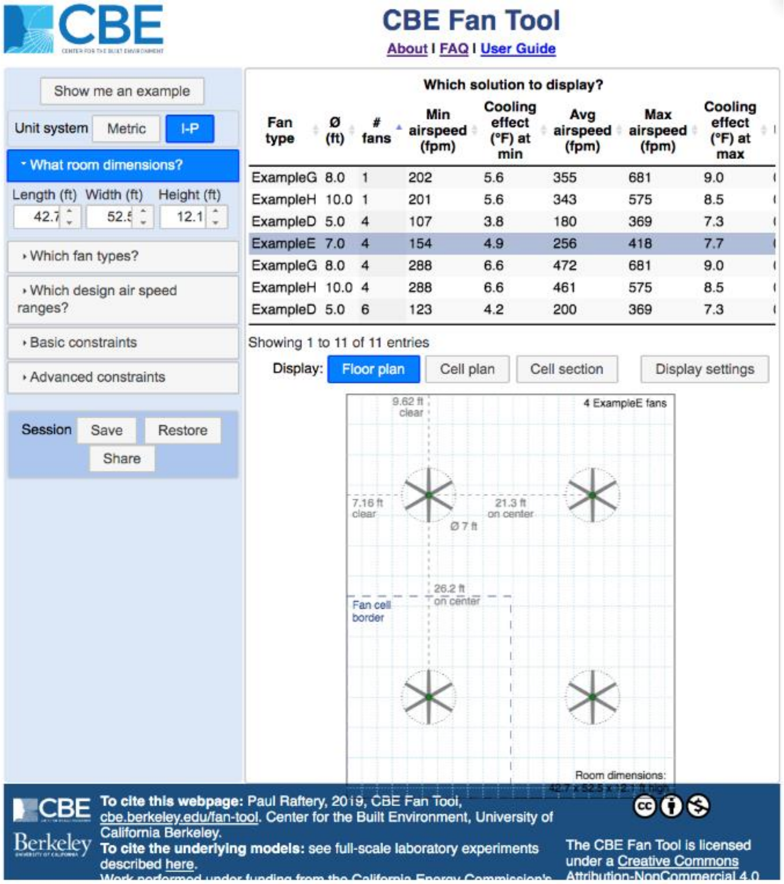
- **CBE Industry Advisory Board Meetings** from April 2017, October 2017, April 2018, October 2018, April 2019, October 2019
- **ACEEE Summer Study for Energy Efficiency in Buildings 2018**: Elaina Present, won a Linda Latham Scholarship and presented a poster: "Ceiling Fans in Commercial Buildings: Identifying Common Obstacles and Sharing Lessons Learned from Experience"
- **CEC EPIC Symposium, February 2019**, Paul Raftery gave a presentation entitled "Energy Efficient Comfort Cooling."
- **Lawrence Berkeley National Lab Rosenfeld Symposium on Grid Interactive and Energy Efficient Buildings, April 2019,** Dana Miller was selected from a student competition to give a presentation and present a poster on this project entitled "Air movement for energy efficient cooling: Perspectives from a field study coordinating ceiling fans and air conditioning."
- **2019 ASHRAE Summer Conference Seminar,** "Seminar 43: Advances in Ceiling Fans for Comfort Cooling," June 25, 2019. Research team members chaired the seminar (Gwelen Paliaga), and there were two presenters (Hui Zhang and Paul Raftery).
  - What Air Speeds Can I Expect for a Given Fan and Room? Predicting Indoor Air Speeds Based on Full Scale Laboratory Measurements, Paul Raftery
  - The Importance of Air Movement for Comfort When Occupants' Activity Levels Change, Hui Zhang
- **Cool Buildings Workshop, Lawrence Berkeley National Lab, July 2019,** Dana Miller gave a presentation entitled "Move air, then cool it–Integrating air movement for energy efficient comfort."
- **Science of Drawdown Conference, October 2019,** Penn State University, Dana Miller presented a lightning talk and poster that included this project, entitled "Move air, then cool it: low-carbon comfort with air movement."
- **2020 ASHRAE Winter Conference**, Orlando: six presentations on fan-related topics
  - **Indoor Environmental Quality With an Emphasis on Thermal Comfort**
    - Spatially Uniform Comfort from Ceiling Fans Blowing in the Upwards Direction (OR-20-C011) Thomas C. Parkinson, Paul Raftery, and Elaina Present

- **Best Practices for Ceiling Fan Comfort Cooling**. Research team members chaired the seminar (Gwelen Paliaga) and featured project presenters (Paul Raftery, Dana Miller, Sonja Salo, Christian Taber).
    - Publicly Available Ceiling Fan Design Guide and Tool. Paul Raftery.
    - Staging Ceiling Fans and Air Conditioning for Energy Savings and Comfort. Dana Miller.
    - Human Interactions With Ceiling Fans and Smart Thermostats: Learnings From Case Studies in Office Buildings (Sonja Salo).
    - Selecting Ceiling Fans Based on ASHRAE Standard 216 Performance Metrics. Christian Taber, Member, Big Ass Fans
    - Application and Design Consideration for Ceiling Fan and HVAC Integration Stet Sanborn, AIA, Smith Group, San Francisco, California

Online Design Tool

The online CBE Fan Design Tool allows designers to quickly select and lay out ceiling fans in a given room to meet their airspeed requirements and other constraints. The fan tool may be found at cbe.berkeley.edu/fan-tool. See Appendix H for details.

Figure 28: Screenshot of Online CBE Fan Design Tool



CBE Fan Tool

About I FAQ I User Guide

Unit system: I-P

What room dimensions?

Length (ft) 42.7 Width (ft) 52.5 Height (ft) 12.1

Which solution to display?

Fan type	Ø (ft)	# fans	Min airspeed (fpm)	Cooling effect (°F) at min	Avg airspeed (fpm)	Max airspeed (fpm)	Cooling effect (°F) at max
ExampleG	8.0	1	202	5.6	355	681	9.0
ExampleH	10.0	1	201	5.6	343	575	8.5
ExampleD	5.0	4	107	3.8	180	369	7.3
ExampleE	7.0	4	154	4.9	256	418	7.7
ExampleG	8.0	4	288	6.6	472	681	9.0
ExampleH	10.0	4	288	6.6	461	575	8.5
ExampleD	5.0	6	123	4.2	200	369	7.3

Showing 1 to 11 of 11 entries

Display: Floor plan

To cite this webpage: Paul Raftery, 2019, CBE Fan Tool, cbe.berkeley.edu/fan-tool. Center for the Built Environment, University of California Berkeley.

To cite the underlying models: see full-scale laboratory experiments described here.

Work performed under funding from the California Energy Commission's

The CBE Fan Tool is licensed under a Creative Commons Attribution-NonCommercial 4.0

The Fan Design Tool is an online tool (https://cbe.berkeley.edu/fan-tool) that can help designers figure out how many fans they need to provide cooling in space.

Source: Paul Raftery, UC Berkeley

The tool loads with a blank set of inputs for describing: the room dimensions (e.g., ceiling height), the candidate fan types being considered by the designer, airspeed related constraints (e.g., the range of desired minimum airspeeds in the room), basic constraints (e.g., limit the range of acceptable blade heights), and advanced settings (e.g. the acceptable minimum mount distance). Using the 'Add' button, users can add specific fan types that they are considering, and then select the newly added candidate(s) for consideration.

The 'Which Solution to Display?' table (top right) then shows the set of solutions that are considered viable given the selected inputs (e.g., size of room, selected candidate fan(s)) and constraints (e.g., range of acceptable minimum air speeds). A viable solution is defined as one in which the ceiling fan meets safety requirements, conforms with recommended guidance, and provides results that are within the constraints defined by the user.

The tool's intent is to provide a relatively even coverage of air speeds across an entire room. With a single fan, the best way to achieve that is to place the fan at the center of the space. With multiple fans, the best way to achieve that is to locate adjacent fans at equal center-to-center spacing, with half that spacing between the fan center and any wall that is immediately adjacent to a fan. Thus, these are the solutions that the tool identifies. However, ceiling fans can be installed anywhere that meets manufacturer, safety and code related requirements for that fan and application; fans certainly do not need to be centered in a room, or to be laid out in a perfectly uniform grid. Ceiling fans can be located so as to better co-ordinate with aesthetic, lighting and/or structural requirements, or located to best reach the intended target: people (e.g., above seated areas). However, due to the limitations of the measurement dataset on which the models underlying this tool were built, the further the actual fan layout differs from that identified by the tool, the less accurate the airspeed estimates will be.

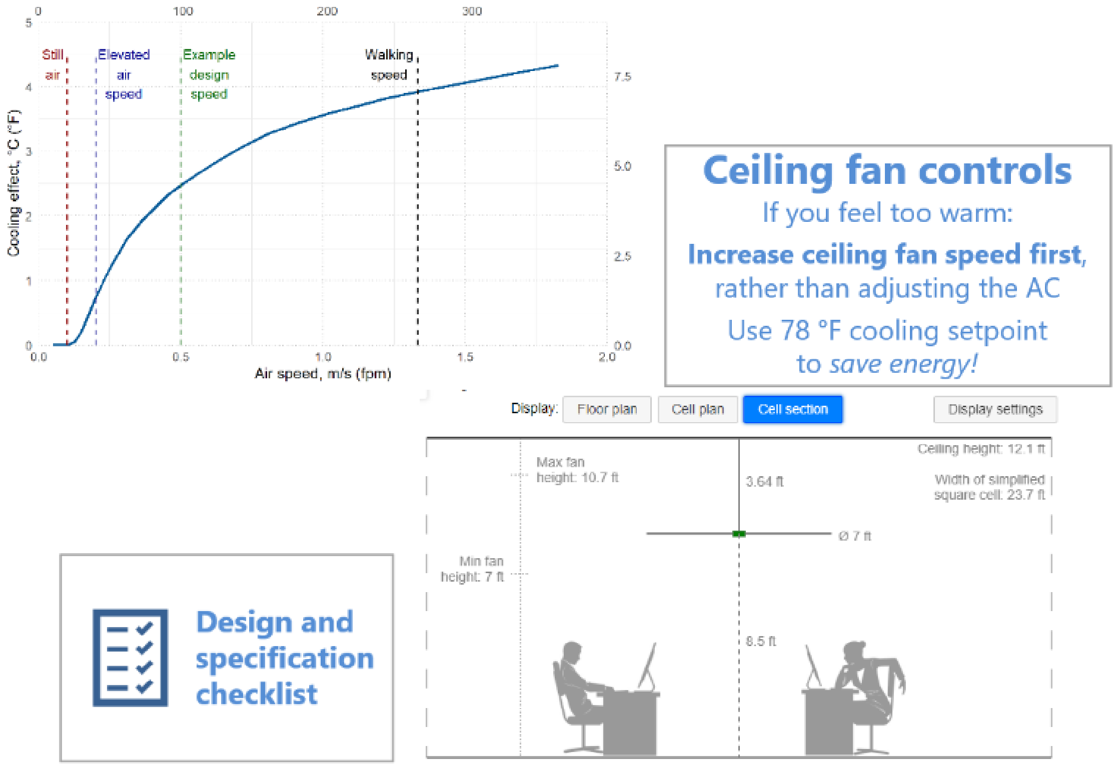
Design Guide

As part of this research project, the research team developed the CBE Ceiling Fan Design Guide, available at https://cbe.berkeley.edu/wp-content/uploads/2020/04/CBE-Ceiling-Fan-Design-Guide-V0.pdf. The guide enables architects, designers, and engineers to maximize the benefits of integrating ceiling fans into building systems. It introduces the advantages of using ceiling fans and how ceiling fans work and provides guidance and resources for designing spaces with ceiling fans, and for specifying ceiling fan products. Content and information in the design guide includes the following content:

- **Ceiling Fans and Thermal Comfort:** Details and resources to understand human thermoregulation and thermal comfort, and information on how ceiling fans can improve thermal comfort
- **About Ceiling Fans:** Details on various ceiling fan types and how ceiling fans work
- **Fan Selection, Sizing, and Layout:** Guidance on how to evaluate different ceiling fan performance metrics, and recommendations on how to determine fan sizing, layout, and location within a space
- **Controls:** Considerations and recommendations on how to implement ceiling fan controls, including guidance on user interface, automation, integration with other building systems, and airflow direction

- **Applications:** Recommendations for design and performance criteria, controls, and other considerations for various application types
- **Design, Specification, And Installation Checklist:** An additional reference to guide designers and specifiers through the process of designing, specifying, and installing ceiling fans on a building project
- **Additional Resources:** Details on other factors and considerations for designing with ceiling fans, including occupant interface and education, codes and standards, costs, modeling and simulation, project case studies, and further references and research

Figure 29: Highlights of the CBE Ceiling Fan Design Guide



Highlights of the design guide include thermal comfort benefits of ceiling fans, guidance for control and user interface strategies, a ceiling fan design and specification checklist, and an introduction to the CBE Ceiling Fan Design Tool

Source: CBE Ceiling Fan Design Guide

Codes and Standards Support

The research team has been supporting and researching a variety of issues related to building codes and standards. Appendix G summarizes those activities and findings.

Codes and standards support activities included:

- Development of a new ASHRAE Standard 216: "Methods of Test for Determining Application Data of Overhead Circulator Fans."
- Proposed Addendum C to ASHRAE Standard 55 defining thermal environmental control classification levels for certain compliance options.

- A description of barriers and opportunities for ceiling fans in California Building Energy Efficiency Standards.
- A discussion of building code considerations for ceiling fans, including a description of fire code requirements, and opportunities for additional clarification of code requirements related to ceiling fans.

Technology Readiness Report

The technology readiness report discusses both ceiling fans in general, and automated or smart ceiling fans more specifically (details in Appendix I).

CHAPTER 5: Conclusions/Recommendations

The research team conducted laboratory tests, conducted field tests with 99 ceiling fans and 12 thermostats in four affordable multifamily housing sites in California's Central Valley, interviewed stakeholders to develop a case study, developed an online design tool and design guide, outlined codes and standards outreach, and published several papers.

The project demonstrated networked thermostats working in conjunction with highly efficient ceiling fans with onboard temperature and occupancy sensors for automatic operation in order to reduce energy consumption. The project team raised indoor temperature cooling setpoints and used ceiling fans as the first stage of cooling; this sequencing of ceiling fans and air conditioning can reduce energy consumption, especially during peak periods, while providing thermal comfort. The mean hourly indoor air temperature across all sites increased approximately 2°C (3.4°F). Overall, the field demonstration resulted in 39 percent measured compressor energy savings during the April-October cooling season compared with baseline conditions, normalized for floor area. Energy savings during peak electrical demand periods (4 p.m. to 9 p.m., June-September) were 42 percent, suggesting that sequenced ceiling fans provide a feasible demand-response strategy.

Weather-normalized energy use varied from a 36 percent increase to 71 percent savings across all 13 compressors, with median savings of 15 percent. This variability reflects diversity in buildings, mechanical systems, prior operation settings, space types, and occupants' schedules, preferences, and motivations. All commercial spaces with regular occupancy schedules showed energy savings on an absolute basis before normalizing for warmer intervention temperatures, and 10 of 13 sites showed energy savings on a weather-normalized basis. Of the three sites that did not realize energy savings on a weather-normalized basis, two were residences that opted not to increase air conditioner setpoint temperatures, and one was an infrequently occupied commercial space where baseline energy consumption was relatively low and air conditioning did not regularly operate.

Overall, the ceiling fans were operated frequently at all sites, typically operated at low speeds, and consumed very little power. The mean power consumption of a ceiling fan when operating was 8 W; this is comparable to an LED light bulb.

The ceiling fans provided sole cooling for several months at one site during hot weather when the HVAC equipment failed. The project team helped the facilities manager identify the problem and implement a solution. Despite indoor temperatures reaching temperatures higher than design recommendations, the majority of the occupants were still comfortable, which demonstrated that the ceiling fans provided resilience during mechanical system failures.

All occupants reported high satisfaction with the ceiling fans. The fans increased the range of thermal comfort and acceptability across participants, and also had a positive impact on air movement acceptability. All participants reported that the fans provided adequate cooling and improved indoor environmental quality, and occupants were pleased with their ability to cool the space quickly and effectively. Even on sites where the measured energy data do not show savings, occupants still used and interacted regularly with the fans. One office worker reported, “The ceiling fans have helped [me] by not having to worry about being too hot or too cold in the office. Because when you’re too hot or too warm it’s hard to concentrate.”

The project team identified several lessons learned, especially regarding behavior change. At some sites occupants were not responsible for paying for their electricity, which affected air conditioning setpoints and savings. Some believed that moving air drafts were unhealthy, especially for a newborn child; this impacted ceiling fan use compared with air conditioning. One occupant inadvertently scheduled the blower fan to operate continuously, which increased overall energy consumption. Occupants felt that the Ecobee thermostats had a steep learning curve and were initially challenging to use. The lack of multiple language support in the thermostats was an issue for many of the occupants, particularly in the residences. The research team had extensive interactions with occupants and produced educational material to inform occupants about setpoints and blower fan operation. Future work should explore feedback and incentives that encourage optimal behavior change.

The smart ceiling fan and smart thermostat did not directly integrate as expected; custom fan firmware was required to fully implement automated fan operation as required.

The project demonstrated that savings from sequencing air movement and air conditioning are greatest at sites with frequent or intense air conditioning use. Although measured results from the field demonstrations showed substantial energy savings, there is a need for further development to spur more widespread adoption. The technologies could be further simplified, usability could be further improved, and additional effort should be devoted to user education and making the system more intuitive.

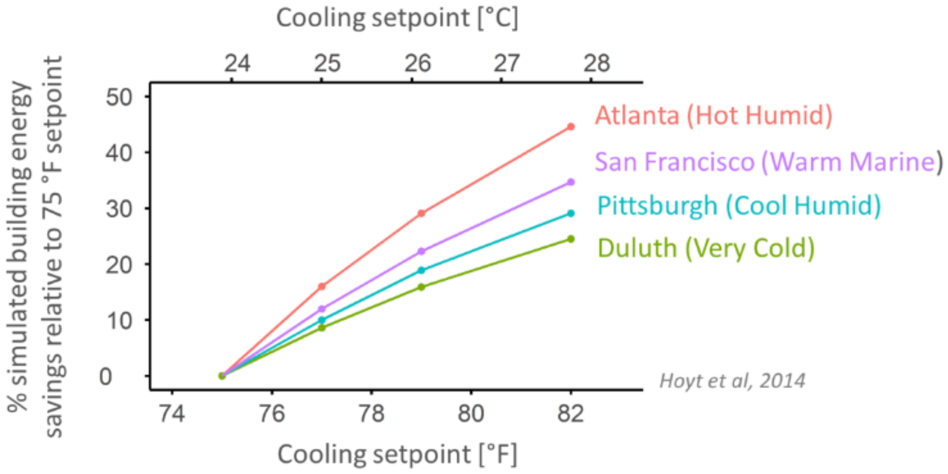
Laboratory studies performed during this project yielded new insights, including developing new methods for designers to estimate airspeeds achieved under a given set of fan and room conditions, airflows around furniture due to ceiling fans, and the design of distribution ductwork in coordination with ceiling fans. The online design tool, may be found at cbe.berkeley.edu/fan-tool, and the design guide appears at https://cbe.berkeley.edu/wp-content/uploads/2020/04/CBE-Ceiling-Fan-Design-Guide-V0.pdf. These can be used by designers, architects, and engineers to incorporate ceiling fans into design by providing ceiling fan spacing and other recommendations for optimal airflows across spaces.

CHAPTER 6: Benefits to Ratepayers

This project studied the use of ceiling fans with smart thermostats in low-income housing, thus reducing electricity consumption supporting three of California's mandated energy efficiency goals: doubling energy efficiency savings by 2030, removing and reducing barriers to energy efficiency in low-income and disadvantaged communities, and reducing greenhouse gas emissions from the building sector.

Regarding energy savings, simulations showed that raising cooling setpoints for air conditioning can save up to 35 percent in mild climates, such as in San Francisco (Figure 30). Integrating ceiling fans with temperature setpoints enables these savings without sacrificing thermal comfort.

Figure 30: Simulated Building Energy Savings Relative to Cooling Setpoints



Savings in the mild San Francisco area ranges from 10–35 percent depending on the temperature setpoint; ceiling fans can maintain comfort while raising setpoints.

Source: Dana Miller, Tyler Hoyt, UC Berkeley

Energy Savings: This project found an average of 39 percent compressor energy savings across sites in the hot Central Valley climate from setting higher HVAC temperatures and using ceiling fans.

Grid Reliability: Energy used for air conditioning compressors was reduced 42 percent during peak electricity demand periods, reducing emissions and providing grid benefits.

Safety: Ceiling fans provide a low-power source of cooling, especially as back-up in cases of HVAC failure (which occurred during this project). The fans included a small battery for operation during power outages.

Smart (automated or temperature-based sequenced) ceiling fans, together with communicating thermostats provide greater energy security and reliability for energy and cost savings, peak energy reduction, emission reductions, and a source of cooling (especially as a back-up) to IOU electric utility ratepayers. Energy savings stem from allowing an increase to the space cooling setpoint and by turning fans off when no occupancy is detected. Though ceiling fans are often considered purely residential appliances and categorized as lighting products, they also provide thermal comfort in virtually all nonresidential applications.

The project team estimated statewide energy, cost, and CO_2 emission reductions (assuming a combined cooling energy savings of 30 percent from both the ceiling fans and thermostats), as well as targets at sites with high cooling loads. The team estimates that a 15 percent market penetration of California buildings over the next 15 years will yield annual reductions of 736 GWh, $125M, and 537M pounds of CO_2 emissions. This estimate includes multifamily (24 GWh, $4M and 18M pounds), single family (228 GWh, $39M, 166M pounds), and schools, offices, and retail spaces (484 GWh, $82M, 353M pounds). While this demonstration focused on the multifamily sector, the technology is a scalable energy retrofit solution for a broad range of commercial and residential buildings throughout California. For commercial sites that are frequently occupied and have high cooling energy consumption, this technology can be a cost-effective retrofit (less than a 7-year payback), even at current market pricing and current utility rates. Targeting buildings and spaces with these characteristics will maximize energy savings potential. At other sites, including residences, the cost of equipment and installation currently exceeds annual utility bill cooling energy costs, and will not be a cost-effective solution through energy savings alone. This study developed and documented best practices, leading to increased market penetration that will reduce the costs of adoption and operation and increase payback. This will enable building owners to invest in the technology at lower risk. Additionally, installation costs will likely be substantially lower for new construction than for retrofit applications.

GLOSSARY

Term	Definition
Alliesthesia	The sensation of pleasant relief from a non-neutral (too-cold or too-hot) sensation to neutral
API	Application Programming Interface
CP (Corrective Power)	Corrective Power is the quantification of the thermal comfort effect provided by Personal Comfort Systems
EPIC (Electric Program Investment Charge)	The Electric Program Investment Charge, created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company.
FCU	Fan Coil Unit
HVAC	Heating Ventilation and Air-Conditioning system
IEQ	Indoor Environmental Quality
manikin	A full-size human-looking full body sensor used in thermal comfort testing.
Personal Comfort System	A device that provides heating or cooling to an individual independent of the central Heating and Cooling system
smart grid	Smart grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
Thermal comfort	Thermal comfort is defined as the condition of the mind that expresses satisfaction with the indoor environmental temperature.
VRF	Variable Refrigerant Flow

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