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Energy Research and Development Division

FINAL PROJECT REPORT

Improving Ventilation and Indoor Environmental Quality in California K-12 Schools

Gavin Newsom, Governor

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PREFACE

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

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The 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.

Improving Indoor Environmental Quality in California K-12 Schools is the final report for the Ventilation Solutions for Energy Efficient California Schools project (EPC-15-033) conducted by UC Davis Western Cooling Efficiency Center and Lawrence Berkeley National Laboratory. 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 916-327-1551.

ABSTRACT

This project developed and demonstrated approaches to synergistically improve ventilation and indoor environmental quality during replacements of packaged heating, ventilation, and air conditioning (HVAC) systems in California schools.

The research team 1) characterized HVAC systems, carbon dioxide concentration, and indoor thermal conditions in 104 classrooms that had replaced packaged HVAC systems serving a single classroom (single-zone) between 2013 and 2016; 2) evaluated HVAC system retrofits with regard to energy efficiency and indoor environmental quality performance at two field sites; and 3) completed building energy and indoor environmental quality modeling of HVAC equipment and filter selection for four climate and outdoor air conditions representative of California's regional variation and two different classroom vintages.

Inspections of 104 classrooms with HVAC equipment installed between 2013-2016 showed that only 15 percent of classrooms' estimated median daily ventilation rates met the 7.1 liters per second per person Title 24 code requirement, and 9 percent had carbon dioxide levels above 2,000 parts per million for significant portions of the school day, which implies a ventilation rate of less than half of that required. Where under-ventilation occurred, it tended to affect several observed classrooms within a given school and not occur as an isolated case. Periodic testing of ventilation systems and continuous real-time carbon dioxide monitoring could help to detect ventilation problems.

Field testing and modeling of HVAC technologies determined that variable speed motors for indoor blowers, two-speed compressors, economizers, demand control ventilation technology, and air filters with a minimum efficiency reporting value of 13 constitute an HVAC package suitable for all of California's climates. The combination of technologies can save between 28 and 57 percent of HVAC electricity use, depending on climate. Filters with a minimum efficiency reporting value of 13 can reduce indoor particulate matter exposures by 40 percent or more compared to filters with a value of 8.

Keywords: HVAC, indoor environmental quality (IEQ), K-12 schools, energy efficiency, occupant experience, demand control ventilation, economizers

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EXECUTIVE SUMMARY

Background

Previous research indicates that many California classrooms are underventilated relative to rates specified in California's *2016 Building Energy Efficiency Standards* (Title 24) and Guideline 62.1 published by the American Society for Heating, Refrigeration, and Air Conditioning Engineers. Previous research also shows that poor ventilation negatively affects student health, academic performance, and attendance. Heating, ventilation, and air conditioning (HVAC) systems are the most effective means of delivering the ventilation needed to remove indoor air pollutants such as volatile organic compounds (including formaldehyde) and carbon dioxide. Filtration of mechanical ventilation is also important to reduce exposure to outdoor particulate matter from sources such as vehicle emissions, dust, and smoke, especially when increasing outdoor ventilation rates.

Mechanical ventilation has consequences for HVAC system energy use. Both HVAC system energy use and indoor air quality are affected by filter type and condition, ventilation system design and efficiency, and volume of ventilation supplied. Analyzing ventilation and HVAC system technologies and strategies will help California identify approaches to reduce energy use while improving ventilation and indoor air quality in schools.

Project Purpose

The goal of this project was to develop and demonstrate approaches for improving ventilation and indoor environmental quality in California's K-12 schools using HVAC retrofits, with the ultimate target of advancing approaches and technologies needed to make California's schools carbon neutral while also protecting student health and learning.

Field data documented real-world performance of school HVAC systems and informed the final phase of the project: building energy modeling of these systems in varying environments that reflect California's range of climate zones and outdoor pollutant levels. Modeling results and the recommendations that stem from them are expected to be a valuable resource for school districts and state policymakers who seek to improve California schools' environmental quality.

Project Approach

A research team from the University of California, Davis Western Cooling Efficiency Center, which is part of the UC Davis Energy and Efficiency Institute, led the project. The team included the Western Cooling Efficiency Center and the Department of Public Health Sciences staff at UC Davis, as well as one subcontractor, Lawrence Berkeley National Laboratory. Equipment manufacturing partners supported the project through in-kind contributions of equipment, expertise, and connections to school districts. School districts voluntarily participated in the project by allowing use of the facilities as demonstration sites. Teachers voluntarily participated in the project by responding to surveys about their level of satisfaction with thermal comfort and indoor air quality.

An independent technical advisory committee provided input on the research design. Committee members represented state government (California Air Resources Board, California

Department of Public Health, and California Energy Commission), academia, and energy consulting firms.

The project consisted of three phases:

- Phase 1: Characterize HVAC systems, ventilation, and indoor environmental quality in 104 K-12 classrooms that had replaced their single classroom (single-zone) HVAC systems between 2013 and 2016. Schools reflected variations in district size, rural versus urban areas, and household incomes. The schools did not represent a random sample and were recruited from the professional network of the research team, as well as from a database of those Proposition 39 funding applications that stated the district was replacing HVAC equipment.
- Phase 2: Evaluate classroom HVAC retrofits for energy efficiency and indoor environmental quality performance over a one-year period at two schools — an elementary school in the Bakersfield region and a high school in the Sacramento region — chosen for the significant heating and cooling loads and distinct differences in outdoor air quality. Evaluations compared specific HVAC equipment options: a) baseline vs. high efficiency, b) ventilation types (namely, commercial room ventilator versus energy recovery ventilator versus economizer with demand control ventilation), and c) filtration levels with a minimum efficiency reporting value of 13 versus those with a value of 8.
- Phase 3: Conduct 96 simulation-based analyses of energy efficient HVAC systems for four climate and outdoor air conditions representative of California's regional variation (Sacramento, Bakersfield, Riverside, and Lake Tahoe) and two different classroom vintages, representative of 1998 and 2008 construction years, selected to show the effects of building code and for model validation using Bakersfield field data.

Project Results

Phase 1

Problems with HVAC installation and maintenance were prevalent in the classrooms visited in Phase 1. Classrooms were frequently non-compliant with ventilation standards, which resulted in high carbon dioxide levels. Facilities staff provided little oversight to the installation of equipment, making them largely unaware of the problems the study documented. Teacher satisfaction with classroom heating and cooling was relatively low. Strict thermostat policies aimed at saving energy and money appeared to yield discomfort and disruption among students and teachers.

Phase 2

Indoor environmental quality varied depending upon the ventilation type and occupancy. Commercial room ventilators tended to over-ventilate, producing lower carbon dioxide levels than classrooms with energy recovery ventilators, which had lower ventilation rates. The controller in the demand control ventilation system was slow to respond to occupancy changes. Classrooms at both schools with air filters with a higher minimum efficiency reporting value (13) had substantially lower concentrations of particulate matter less than 2.5 microns compared to classrooms with filters with a lower reporting value (8).

Increasing HVAC system efficiency alone reduced electricity use by 23 percent; however, energy recovery ventilation systems increased consumption due to electricity required to operate the additional fans and motors and by their inability to bring in extra outdoor air for cooling when outdoor conditions were favorable. The demand control ventilation with economizer systems performed well and reduced electricity consumption by 18 percent in Bakersfield for the all-electric systems and 8 percent in Sacramento for the gas/electric systems. Natural gas use was reduced by 7 percent in Sacramento.

The maximum 15-minute average power draw (peak demand) for systems in Sacramento did not differ significantly by system type. In Bakersfield, the energy recovery ventilator significantly reduced the winter electricity peak demand by preventing operation of the backup electric resistance heat.

The average standby power between 9 p.m. and 5 a.m. for each unit differed significantly between unit types, which was attributed to crankcase heaters that were standard in one model installed but were not in the others. Crankcase heaters are used keep compressors warm in cold climates but are generally not needed in small HVAC systems in California climates. Over the course of a school year, the additional standby power is estimated to equate to nearly two-thirds of the approximately 280 kilowatt-hours saved by the high efficiency units during operating hours.

As expected, filters with a minimum efficiency reporting value of 13 had elevated fan power consumption relative to those with a value of 8 due to their higher initial resistance and greater particle capture efficiency; however, this was estimated at a fairly low magnitude: 20 Watts of power consumption, or 32 kilowatt-hours annually.

Phase 3

Field testing and modeling of HVAC technologies determined that a combination of variable speed motors for indoor blowers, two-speed compressors, economizers, and demand control ventilation technology can save 28 percent to 57 percent of HVAC electricity use, depending on climate.

Conclusions/Recommendations

The research team offers numerous recommendations for improved code compliance, greater classroom comfort and energy savings, and informed future HVAC purchases, including the following:

- Enforcement and policy agencies can improve code compliance through training and certification requirements as well as requirements for periodic testing of ventilation systems and monitoring of indoor carbon dioxide levels.
- School districts can increase classroom comfort and improve indoor air quality by periodic testing of ventilation systems and monitoring of indoor carbon dioxide levels; installing and using energy management systems; and allowing teachers some control over their thermostats and informing them of the importance of continuous fan operation.

- School districts can oversee the purchase of motors, compressors, economizers, and filters for new HVAC equipment that have demonstrated energy efficiency, indoor air quality improvements, and cost savings.

Finally, the research team recommends further product development and research to:

1. Reduce standby power in HVAC systems, including ways to reduce electricity use by compressor crankcase heaters.
2. Standardize test methods to objectively compare and report the performance of demand control ventilation products and control algorithms.

Knowledge Transfer

The research team engaged in numerous activities to transfer the experimental results, knowledge gained, and lessons learned to the public and key decision makers. The team made presentations at seven conferences and two webinars and wrote and disseminated materials about the project through the Western Cooling Efficiency Center website, annual report, and monthly newsletters. The team's technical paper on the results of indoor environmental quality monitoring in Phase 1 has been published in *Building and Environment*, and another on occupant perception of carbon dioxide is partially drafted. A case study, webinar, and all reports resulting from this project will be publicly available on the Western Cooling Efficiency Center website.

The research team also convened numerous meetings with various school districts, the Division of the State Architect, and Commissioner McAllister of the CEC to explore the existing and potential policies regarding oversight of installation and commissioning.

Because the data revealed that the controller on the demand control ventilation units was too slow to respond to the normal occupancy changes that occur in school settings, Western Cooling Efficiency Center is working with the manufacturer to advocate for appropriate adjustments to factory settings when shipping equipment to schools.

Benefits to California

Assuming 10 percent of California schools adopt these efficient technologies over the next 10 years, which would reduce their HVAC energy use by 40 percent, the aggregate reduction in energy use would total 220 gigawatt-hours. This equates to roughly 63,000 metric tons of carbon dioxide. Improving ventilation in California classrooms is expected to reduce student illness-absence rates and increase in attendance, resulting in an additional $33 million in statewide attendance-linked funding per year. Thermal conditioning of this ventilation air is estimated to increase of energy costs statewide by $4 million annually if no upgrades are made to HVAC equipment. Improving air filtration in California schools is projected to yield $5 million in health benefits annually.

CHAPTER 1: Introduction

Millions of California children spend a large portion of their day indoors at school. Research indicates that many California K-12 classrooms are under-ventilated relative to rates specified in California Title 24 regulations and ASHRAE 62.1 (ARB & CDHS 2004; Mendell et al., 2013).

In a recent study, ventilation rates estimated from carbon dioxide (CO_2) measurements in 162 classrooms in three districts — in the South Coast, Bay Area, and Central Valley — all suggested median daily values below the 2016 Building Energy Efficiency Standard's requirement of 7.1 liters per second (L/s) per person (Mendell et al., 2013). Median ventilation rates were 40 percent lower in portable buildings than in permanent buildings, and 54 percent lower in air-conditioned buildings compared to naturally ventilated classrooms.

Several studies have found associations between reduced student performance and lower ventilation rates, or higher CO_2 concentrations (Bako Biro et al., 2012; Haverinen-Shaughnessy and Shaughnessy, 2015; Petersen et al., 2015; Wargocki et al., 2000). Lower ventilation rates have also been associated with an increase in student absence (Mendell et al., 2013). In addition, insufficient ventilation may result in poor indoor air quality in classrooms, including higher formaldehyde exposure, which is the largest estimated cancer risk in schools (Chan et al. 2015).

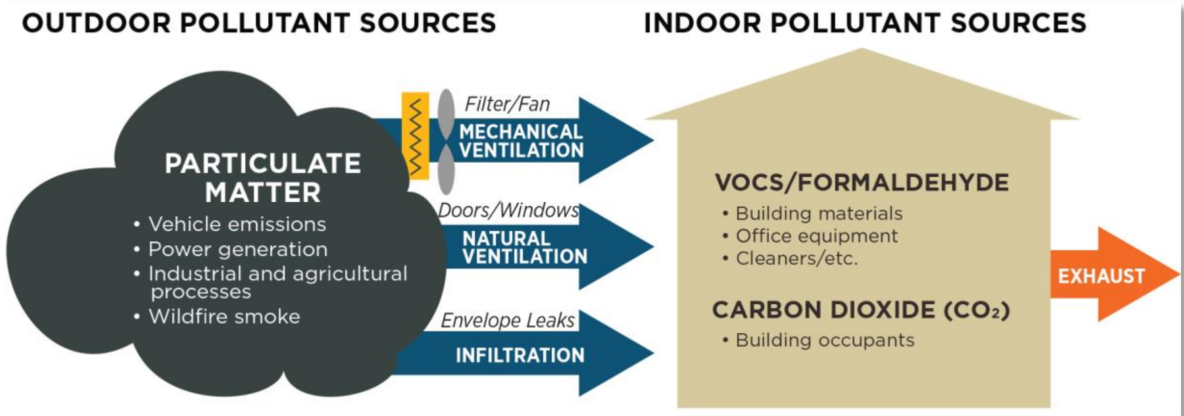
The causes of under-ventilation in classrooms include ventilation design or operational deficiencies (for example, providing outdoor air only when heating or cooling), failure or intentional disabling of outdoor air dampers, and limited operation of systems deemed too loud for a classroom environment (Jenkins et al. 2004).

Unfortunately, simply increasing air ventilation rates in classrooms alone can result in increased student exposure to outdoor air pollutants and increased energy use. Exposure to fine particulate matter less than 2.5 microns in diameter ($PM_{2.5}$), ultrafine particles, and diesel particulate matter are of particular concern because many schools are located near roadways. Exposure to $PM_{2.5}$ is one of the key chronic health risk concerns in schools (Chan et al. 2015). In addition, as California strives to achieve a 50 percent reduction in energy use in existing schools and future carbon neutral schools, there is a need to demonstrate ventilation approaches that are substantially more energy efficient.

Common Scenarios in Schools

Outdoor air enters indoor spaces through a combination of mechanical ventilation, natural ventilation, and infiltration (Figure 1). Infiltration is uncontrolled air movement through leaks in the building envelope; natural ventilation is air movement through doors and windows, and mechanical ventilation is filtered air supplied with a fan. Mechanical ventilation is the most reliable method to remove indoor air pollutants, particularly for densely occupied spaces and newer construction with tight building envelopes. Indoor air pollutants include volatile organic compounds (VOC), such as formaldehyde, and CO_2 exhaled by building occupants. Filtration of mechanical ventilation is important to reduce exposure to outdoor pollutants, such as particulate matter from vehicle emissions, dust, and smoke.

Figure 1: Outdoor and Indoor Pollutant Sources



Mechanical ventilation systems deliver filtered outdoor air to a space to reduce indoor pollutants.

Source: Western Cooling Efficiency Center, University of California at Davis

The amount of outdoor air that should be supplied to a classroom is driven by the number and age of occupants throughout the day. The average classroom size for elementary grades in California is 22 to 28 students per classroom, but some classrooms have as many as 33 students. In higher grades, classroom enrollment can be as high as 40 or 50 students in large districts, though 30 to 35 is more typical. Classroom occupancy in higher grades fluctuates from period to period as students rotate classrooms by subject, which also affects ventilation requirements.

The current baseline approach for providing code-compliant mechanical ventilation to classrooms served by single-zone packaged heating ventilation and air conditioning (HVAC) units is to draw outdoor air through a damper that is set to provide at least 7.1 L/s, or 15 cubic feet per minute (CFM), for each student and teacher during maximum classroom occupancy. The outdoor air is mixed with recirculating indoor air and moved through a filter and thermal conditioning coils before being supplied to the room. Classrooms served by multi-zone HVAC systems may have fixed or variable air volume distribution networks. In all of these systems, outdoor air is provided only when the HVAC air handler/supply fan is operating. Direct outdoor air systems exist in some larger schools, but they are uncommon. Standard HVAC systems in schools typically are operated on thermostat schedules set around occupied periods for a building (for multi-zone) or classroom (for single zone). The majority of classroom HVAC systems in California are either single-zone vertical packaged units installed on the classroom wall or single or multi-zone packaged units that are installed on the classroom roof.

Air filtration is an important component of HVAC system design in both rooftop units (RTUs) and vertical packaged units. Classrooms typically use panel filters, with a very low to moderate minimum efficiency reporting value (MERV) of 6 to 8, to protect the conditioning coils in their HVAC systems. MERV8 filters have limited efficiency in removing various fine particle measures including $PM_{2.5}$, ultrafine particles, and black carbon (estimated at 10 percent to 30 percent, depending on the specific filter and parameter).

Chapters 2 and 3 present details of the project approach and results, respectively. Chapter 4 summarizes project conclusions and recommendations. Chapter 5 describes ways the project team shared the project results and possibilities with various stakeholders, and Chapter 6 discusses the benefits this work can offer California ratepayers.

CHAPTER 2: Project Approach

The goal of this project was to develop and demonstrate approaches for improving ventilation and indoor environmental quality in California K-12 schools using HVAC and whole building energy efficiency retrofits, with the ultimate target of advancing approaches and technologies needed for carbon-neutral schools.

This project consisted of three phases:

- Phase 1: Characterize HVAC systems, ventilation, and indoor environmental quality (IEQ) in K-12 classrooms
- Phase 2: Evaluate classroom HVAC retrofits
- Phase 3: Conduct simulation-based analysis of energy efficient HVAC systems

Project goals and objectives were met by a research team led by the UC Davis Western Cooling Efficiency Center (WCEC), which is part of the UC Davis Energy and Efficiency Institute. The team included WCEC and the Department of Public Health Sciences staff at UC Davis, as well as one subcontractor, Lawrence Berkeley National Laboratory (LBNL).

Several equipment manufacturing partners were engaged to support the project. The partners included packaged HVAC equipment manufacturer, Bard, and its California distributor, Geary Pacific; controls manufacturer, Delta Controls; controls manufacturer, Pelican Wireless; and economizer controller manufacturer Honeywell.

An independent technical advisory committee was engaged to provide input on the research design. The technical advisory committee members were Qunfang (Zoe) Zhang of the California Air Resources Board, Mark Mendell of the California Department of Public Health, Elizabeth Shirakh and Mark Alatorre of the California Energy Commission, Josephine Lau of the University of Nebraska, and Auriane Koster of Pierce Energy Planning. The advisory committee met twice, on October 7, 2016, and March 9, 2017 and was also consulted for feedback via email over the course of the project.

Phase 1

During the 2016 – 2017 school year, the research team characterized HVAC systems, CO_2 concentrations, and indoor thermal conditions in 104 classrooms (from 11 schools across nine districts in California) that had replaced their single-zone HVAC systems in the past three years.

Schools were recruited from across California, reflecting variations in district size, rural versus urban areas, and household incomes. Schools were recruited from the professional network of the research team, as well as from a database of Proposition 39 funding applications where the application stated the district was replacing HVAC equipment. All schools recruited were public schools within California's investor-owned utility territory, had received at least five single-zone HVAC replacements serving classrooms within the last three years, and had no atypical outdoor air quality concerns. The classrooms themselves varied, too. Roughly two-thirds were permanent classrooms and one-third was portables. Collectively, the classrooms served all grades K-12, and had a mean student enrollment of 28.

This phase involved four data collection activities:

- Interviews with facilities staff regarding HVAC equipment selection and maintenance
- Characterization of classrooms and HVAC equipment
- Indoor environmental quality monitoring and
- Surveys of classroom teachers

HVAC Equipment Selection and Maintenance

School districts' facilities staff were interviewed to identify how new HVAC equipment was selected for retrofit projects; how ventilation rates were commissioned; what thermostat setpoint policies were adopted; how HVAC maintenance is conducted; and whether new equipment performance had been satisfactory. Telephone interviews were conducted with 11 facilities staff, covering all nine districts that participated in the study. Data analysis was geared toward deriving implications for increasing adoption of technologies that would improve energy efficiency and IEQ.

Classroom and HVAC Characterization

The research team conducted a site visit to document classroom characteristics and inspect the HVAC system for each classroom enrolled in the study. The data recorded were handwritten on paper forms, then entered in a Microsoft Excel database. In addition to recording information on paper forms, the surveyors took photographs of all items inspected for backup information. When needed, photographs of the systems and classrooms were used to fill in missing data. HVAC equipment capacity and efficiency data were obtained from the directory maintained by the Air-Conditioning, Heating, and Refrigeration Institute. Interviews of facilities staff were used to collect information not readily obtainable from the inspection, such as energy management system (EMS) settings.

Indoor Environmental Quality Monitoring

In each of the studied classrooms, the research team installed a wall-mounted CO_2 sensor (Vaisala, Finland) to measure CO_2 concentrations by infrared absorption. CO_2 concentrations, room air temperature, and relative humidity were logged at 3-minute time intervals using a HOBO U12 data logger (Onset, Massachusetts) as shown in Figure 2. The CO_2 sensor was installed at a location away from doors, windows, and supply air outlets. The CO_2 sensors, Vaisala CARBOCAP GMW86, used for the first two schools (1 and 2) had a range of 0 – 2,000 parts per million (ppm). After noticing that CO_2 concentrations routinely exceeded 2,000 ppm, CO_2 sensors with an extended range of 0 – 5,000 ppm (Vaisala CARBOCAP GMW94) were used in the remaining classrooms (schools 3 through 11) so that the full range of CO_2 concentrations could be monitored.

The research team also collected data to estimate duration of heating/cooling use and door use during the monitoring period. A HOBO U12 data logger was installed on the grill of the supply air outlets for monitoring supply air temperature and relative humidity. The door opening status was measured using a HOBO UX90 state data logger. The supply air temperature and relative humidity were measured at 2-minute time intervals and the door state data was collected at 1-minute intervals.

Figure 2: Sensors Deployed in Classrooms

Photo left: room CO_2, air temperature, and relative humidity sensor. Photo center: door open/close state sensor. Photo right: supply air temperature and relative humidity sensor.

Source: Western Cooling Efficiency Center, University of California at Davis

Teacher Surveys

Researchers also collected data from teachers in the monitored classrooms. An online survey was conducted, in which 86 teachers participated (a 77 percent response rate). The survey collected information on the classroom occupancy levels and hours and teachers' experience with temperature, air quality, and system controls. The survey protocol and procedures, as well as recruitment materials, were reviewed by the UC Davis Institutional Review Board, as is required for University of California research involving human subjects. The survey was developed and implemented using the online survey tool called Qualtrics (SAP, Provo, Utah).

Phase 2

The goal of this phase was to demonstrate a solution to reduce HVAC energy consumption and simultaneously improve indoor air quality in California classrooms. The field data were used to document real-world performance of these systems and to inform the final phase of the project: conducting simulation-based analysis of HVAC systems in varying environments that reflect California's range of climate zones and outdoor pollutant levels.

School Selection

Two schools were selected for the field study, an elementary school located in the Bakersfield region and a high school located in the Sacramento region. The regions were chosen for the significant heating and cooling loads and distinct differences in outdoor air quality, with Bakersfield having some of the highest average annual levels of $PM_{2.5}$. Portable classrooms with wall-mounted HVAC systems — also called single packaged vertical units (SPVU) — were selected for HVAC retrofits for a variety of practical and scientific reasons, including that Phase 1 of the project identified portable classrooms as more likely than permanent ones to have ventilation and thermal comfort problems.

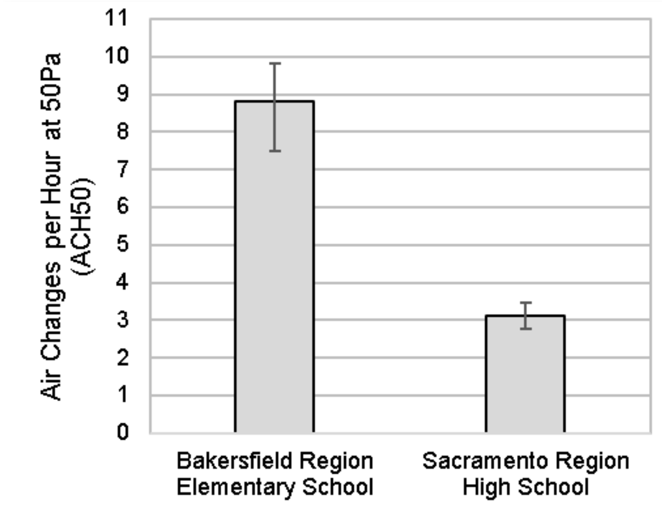
At the Sacramento region high school (SAC), the study included seven portable classrooms used for grades 10 – 12. The classrooms were arranged in a single row. The year of construction and manufacturer are unknown. Each door was located on the south face, and the HVAC unit, before and after replacement, was wall-mounted on the north face. There were two 2-foot by 8-foot (2'x8') double-paned operable windows on the north face and two 4'x8' double-paned operable windows on the south face. Each classroom was 30' wide by 32' long with 960 square feet (ft^2) of floor area. The ceiling was vaulted, measuring 7.75' at the lowest point and 15.5' at the highest point. There was no supply air ducting; the supply and return grills were located on the north wall. Each classroom had 18 2'x'4 light emitting diode (LED) dimming light fixtures with a maximum output of 33 watts (W) each, for a maximum lighting power density of 0.6 W/ft^2. Classrooms 1 – 4 were carpeted and classrooms 10 – 12 had vinyl flooring.[1] Each room was occupied between four and seven periods per day, and the number of students per period varied from 20 to 36. Six classrooms had a single teacher, while one had a different teacher in the morning and afternoon.

At the Bakersfield region elementary school (BAK), the study included six portable classrooms used for grades 1 – 3. The classrooms were arranged in a single row and were constructed in the year 2000 by Pacesetter Industries. Each door was located on the west face, and the HVAC unit, before and after replacement, was wall-mounted on the east face. There were two 4'x8' double-paned operable windows, one on the east and one on the west face. Each classroom was 24' wide by 40' long with 960 ft^2 of floor area. The ceiling height was 8.5' with supply air ducts located above the drop ceiling. Five classrooms had two supply registers spaced equally along the length of the classroom, while one classroom had four supply registers. There were 10 2'x4' lighting troffers with four T8 lamps in each, for an estimated lighting power density of 1.3 W/ft^2. All rooms were carpeted. Each classroom had 20 – 24 students and one teacher during school hours. Unlike the high school site, room occupancy did not vary much throughout the school day.

A blower door test was conducted to estimate envelope leakage of each classroom at SAC and BAK. The envelope leakage was approximately three times greater in Bakersfield compared to Sacramento (Figure 3).

[1] This report refers to classroom numbers assigned to the rooms by the district, rather than project-specific numbers.

Figure 3: Average, Minimum, and Maximum Air Change Results for Each School



The air changes per hour at a pressurization of 50 Pascals averaged 8.8 at the Bakersfield region elementary school and 3.1 at the Sacramento region high school.

Source: Western Cooling Efficiency Center, University of California at Davis

HVAC Equipment Selection and Installation

Both schools selected for the study were in the process of replacing their HVAC equipment with newer SVPUs, manufactured by Bard. UC Davis worked with Geary Pacific, the distributor for Bard, to select specific upgrades to the schools' planned orders to facilitate comparisons across equipment. The upgrades were provided by Bard at no cost to the district.

The HVAC replacements involved selecting and installing heating and cooling equipment, ventilation equipment, air filters, and control systems (summarized in Table 1 and Table 2). The room number in the table is abbreviated as "Room#-HVAC model-Ventilation Type-Filter Type." The research team selected the HVAC equipment and control system settings, while the control system hardware was determined by the school districts.

Table 1: Sacramento Region HVAC Equipment by Classroom

Room #	HVAC Compressor/Fan Type	HVAC Ventilation Type	HVAC Model #	Filter MERV Rating
2-WG-CRV-MERV8	WG: Single-speed scroll compressor, PSC blower motor	Commercial Room Ventilator*	W36G*AN AEX4XXH	8
3-WGS-CRV-MERV8	WGS: Two-speed scroll compressor, ECM blower motor	Commercial Room Ventilator*	WG3SANA EX4XXH	8
12-WGS-CRV-MERV13	WGS: Two-speed scroll compressor, ECM blower motor	Commercial Room Ventilator*	WG3SANA EX4XXH	13
1-WGS-ERV-MERV8	WGS: Two-speed scroll compressor, ECM blower motor	Energy Recovery	WG3SANA RX4XXH	8
10-WGS-ERV-MERV13	WGS: Two-speed scroll compressor, ECM blower motor	Energy Recovery	WG3SANA RX4XXH	13
4-WGS-ECON-DCV-MERV8	WGS: Two-speed scroll compressor, ECM blower motor	Economizer and Demand Control Ventilation	WG3SANA EX4XXH	8
11-WGS-ECON-DCV-MERV13	WGS: Two-speed scroll compressor, ECM blower motor	Economizer and Demand Control Ventilation	WG3SANA EX4XXH	13

WG and WGS are manufacturer specified model numbers for the HVAC system, where the WG series has a single speed compressor and permanent split capacitor (PSC) fan motor and the WGS series has a two speed compressor and electrically commutated motor (ECM) driving the fan. All rooms have Delta Controls thermostat model eZNS-T100 with CO_2 sensor.
***The ventilation systems were economizer hardware configured to operate like a fixed-position damper system.**

Source: Western Cooling Efficiency Center, University of California at Davis

Table 2: Bakersfield Region HVAC Equipment by Classroom

Room #	HVAC Compressor/Fan Type	HVAC Ventilation Type	HVAC Model #	Filter MERV Rating
27-TS-CRV-MERV8	TS: Two-speed scroll compressor, ECM blower motor	Commercial Room Ventilator	T48SA04VP4	8
24-TS-CRV-MERV13	TS: Two-speed scroll compressor, ECM blower motor	Commercial Room Ventilator	T48SA04VP4	13
26-TS-ERV-MERV8	TS: Two-speed scroll compressor, ECM blower motor	Energy Recovery	T48SA04RP4	8
29-TS-ERV-MERV13	TS: Two-speed scroll compressor, ECM blower motor	Energy Recovery	T48SA04RP4	13
28-TS-ECON-DCV-MERV8	TS: Two-speed scroll compressor, ECM blower motor	Economizer and Demand Control Ventilation	T48SA04SP4XXE	8
23-TS-ECON-DCV-MERV13	TS: Two-speed scroll compressor, ECM blower motor	Economizer and Demand Control Ventilation	T48SA04SP4XXE	13

TS is a manufacturer specified model number for the HVAC system, where the TS series has a two speed compressor and an ECM driving the fan. . All rooms have Pelican Wireless thermostat model # TS250 with CO_2 sensor.

Source: Western Cooling Efficiency Center, University of California at Davis

In SAC, natural gas heating/electric air conditioning packaged units were replaced. For the study, the baseline (that is, lowest efficiency) Bard's WG model was installed in one classroom while six classrooms were upgraded to Bard's WGS model , which has two main improvements over the WG model:

1. A two-speed compressor for cooling, instead of a single speed compressor
2. A variable-speed electrically commutated motor (ECM) for the indoor blower, instead of a standard single-speed induction motor

The ECM motor is higher efficiency than an induction motor and is programmed to maintain a fixed airflow rate for each equipment mode (that is, ventilation, cooling 1, cooling 2, and heating) even with varying resistance in the airflow delivery system (for example, due to differences in duct work, filters, and filter loading).

In BAK, electric heat pumps were replaced with Bard's high efficiency TS series equipment with a two-speed compressor and an ECM indoor blower. Six classrooms were selected for observation as part of the study.

Three ventilation system options were tested at each school: commercial room ventilators (CRV), energy recovery ventilators (ERV), and economizer and demand control ventilation units (ECON-DCV), which followed these basic principles of operation:

- CRV: Has a fixed-position (that is, open or closed) damper that allows outside ventilation air, up to 50 percent of the total airflow rating of the unit, to be introduced through the air inlet openings. It includes built-in exhaust air relief. When the damper opens, the outdoor air flow rate is increased, the return airflow is decreased, and the exhaust airflow in increased. The ventilation air flow rate is set by adjusting the setting for the outside air-inlet/exhaust damper actuator that opens when the call for ventilation is activated. The actuator has a spring return that closes the damper on power loss or deactivation, meaning that there is no ventilation on loss of power.
- ERV: Allows 200 to 450 CFM, depending upon the model, of fresh air and exhaust through the unit while maintaining indoor comfort and humidity levels. The ERV consists of a rotary energy recovery cassette with manufacturer-reported heat transfer efficiency of up to 67 percent during summer and 75 percent during winter conditions.
- ECON-DCV: Allows the amount of outdoor air to vary in response to the system controls and settings defined by the end user. The ECON-DCV system is similar to the CRV system, except the ECON-DCV system allows the damper position to be continually adjusted by a controller. The ventilation air rate is continually adjusted by the outside air-inlet/exhaust damper actuator. In the case of this study, it was configured to:
    - Economize and provide "free cooling" when outside air conditions were cool and dry enough to satisfy cooling requirements without running the compressor.
    - Control outdoor air rate as a function of indoor CO_2 levels, termed "demand control ventilation."

The ventilation settings for each system were commissioned and recorded by the research team. The supply air flow rate in each classroom was measured using a flow capture hood (Alnor model #EBT731, TSI Incorporated, Shoreview, Minnesota). After the supply airflow rate measurements were completed, a tracer-gas measurement procedure was used to calculate the ventilation air flow rate for each classroom at each fan speed, and for the ECON-DCV rooms, at a range of damper positions (totaling three to five measurements in each mode). Detailed supply air and ventilation air flow rate measurement results are available in Appendix B, sections "Supply Air Flow Rate Measurements" and "Ventilation Air Flow Rate Measurements." In ventilation mode, the ERV ventilation rates were up to 30 percent lower than the comparable CRV units. The research team could not achieve the target 450 CFM of ventilation air for the ERV systems even with the ERV supply fans set to the highest speed.

Air filtration was another element controlled and tested in the study. At each school, each ventilation system type was tested using 2"-deep filters, which had a MERV of either 8 or 13. The MERV13 filter, when new, was estimated to consume an additional 17 watts of fan power compared to the MERV8 filter based on the manufacturer-reported pressure drop data (Table 3). For more detail on how this estimate was calculated, see Appendix B, section "Air Filters."

Table 3: Manufacturer-Reported Values for Air Filters

Filter Model	MERV	Rated Air Flow (CFM)	Initial Pressure Drop at Rated Airflow (InWC)	Media Area (sq.ft.)	Alpha [pa/ ((m³/s)$^{1.4}$)]	Initial Pressure Drop at 1,000 CFM (InWC)	Fan Power Estimate at 1,000 CFM (w)
Airguard DP Pleat	8	2085	0.19	12.4	48.3	0.06	19
Airguard DP-G13EEN	13	2085	0.37	12.4	94.1	0.11	36

The rated airflow is measured in cubic feet per minute (CFM) at a measured initial pressure drop for a clean filter in inches of water column (InWC). The fan power in watts (w) consumed by the filter per 1,000 CFM of airflow is estimated based on a coefficient "alpha", which is further described in Appendix B in the section "Air Filters".

Source: Western Cooling Efficiency Center, University of California at Davis

Thermostats were replaced as part of the retrofits and chosen by the districts. Teachers had control of the temperature settings in accordance with district policies. In both schools, when the building was scheduled to be unoccupied, the ventilation systems were turned off and the heating/cooling was shut off (BAK) or thermostat setpoints were set back (SAC). An override button was programmed in each classroom to allow teachers to resume ventilation and heating or cooling for 30-minute intervals when the room was occupied outside normal hours.

All thermostats in monitored classrooms were upgraded to include CO_2 sensors, though the CO_2 level was not displayed to the teacher. CO_2 levels were tracked and logged by the EMS and used to control the ventilation in the ECON-DCV units.

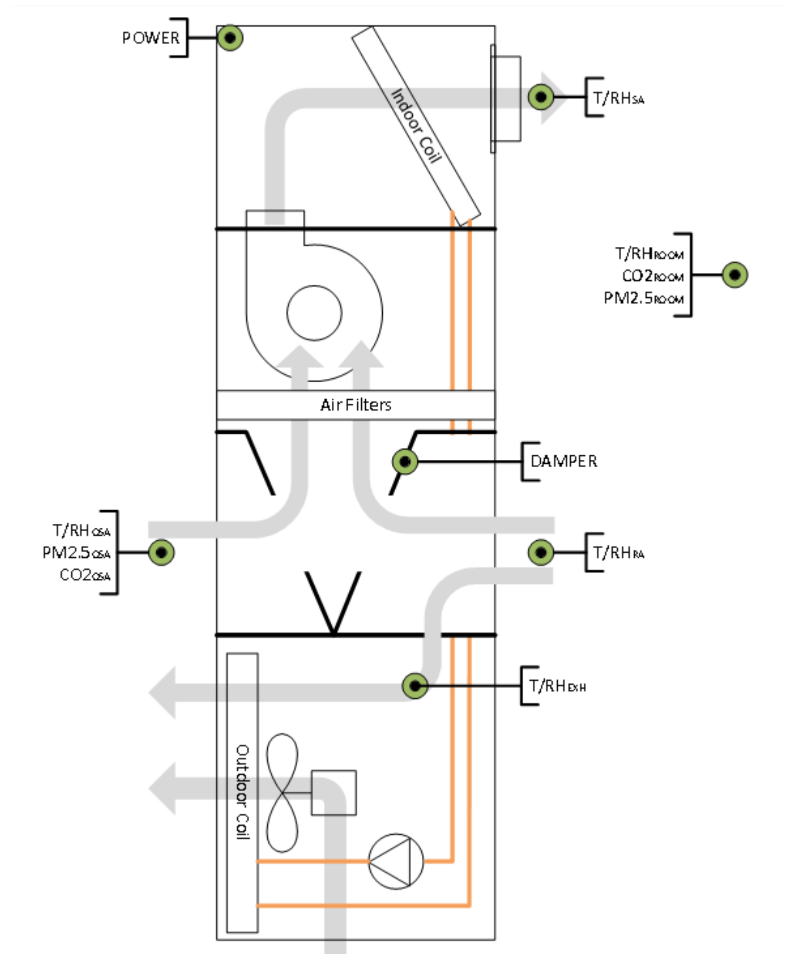
In the two SAC classrooms with ECON-DCV, the CO_2 level was outputted from the Delta Controls EMS system to the Honeywell Jade controller installed inside the Bard unit. The Jade controller was programmed to target an indoor CO_2 level of 800 ppm and modulate the ventilation rate between a programmed minimum (approximately 150 CFM) and maximum (approximately 450 CFM) based on the current CO_2 level. Observations of early equipment operation showed that a Jade controller target of 800 ppm was needed to keep room CO_2 levels under 1,000 ppm, which is the California Title 24 requirement for spaces with demand control ventilation. Each school day, the maximum ventilation rate was provided from 7:00 to 8:00 a.m. as a pre-occupancy flush. Cooling was provided by the outdoor air economizer when certain conditions were met. Specifically, when the outdoor air temperature was below 65°F (4.4°C), the enthalpy was below 22 British thermal units per pound (Btu/lb), and the dew point was below 51°F (10.6°C) (the conditions that define setting "D" of the Honeywell Jade controller), the economizer would open the outdoor air damper to the maximum position, regardless of indoor CO_2 level, when the thermostat called for cooling.

In the two BAK classrooms with ECON-DCV, the CO_2 level was output from the thermostat to the Pelican Wireless Pearl Economizer Controller. The Pelican system was programmed to modulate the ventilation rate between a programmed minimum (approximately 150 CFM) and maximum (approximately 450 CFM) based on the CO_2 level. The target CO_2 level was set in the Pelican system to be 800 ppm. Observations of early equipment operation showed that Pelican controller target of 800 ppm was needed to keep room CO_2 levels under the required 1,000 ppm. On school days, the maximum ventilation rate was provided from 7:30 – 8:30 a.m. as a pre-occupancy flush. Originally, the Pelican wireless software was not capable of providing the pre-occupancy flush at the maximum ventilation rate, as required by Title 24. Pelican implemented this capability partway through the study (on May 18, 2018) after it was requested by WCEC. After 8:30 a.m., the CO_2 level was used to control the ventilation rate. If the thermostat called for cooling when the outdoor air temperature was less than 75°F (23.9°C), the economizer opened the outdoor air damper to the maximum position, regardless of indoor CO_2 level.

Classroom Environment and HVAC Monitoring (Long-Term)

The research team installed sensors to continuously measure power and air enthalpy for each HVAC system as well as temperature, humidity, CO_2, and particulate matter for each classroom (Figure 4).

Figure 4: Approximate Instrumentation Location in HVAC System



Source: Western Cooling Efficiency Center, University of California at Davis

More details on the instrumentation are available in Appendix B, section "HVAC Equipment Instrumentation." All sensors were wired to a DataTaker 85M data logger and sensor readings were logged once per minute. Data was transferred daily from the data logger to an off-site FTP server. The outside air damper position for HVAC systems was recorded directly (BAK) or calculated based on CO_2 sensor data and the documented demand control ventilation algorithm (SAC). Data from the Vaisala CO_2 and Plantower $PM_{2.5}$ sensors were corrected based on comparisons to laboratory-grade instruments that were deployed to classrooms for one-week periods, as described in the following section.

The research team analyzed the data collected at each school to compare the performance differences between CRV, ERV, and ECON-DCV, as well as MERV8 and MERV13 outdoor air filters. The analysis for each unit was limited to school days between 7:00 a.m. and 4:00 p.m. based on each school's academic calendar. After-school hours and non-school days were excluded from the analysis because classroom use varied widely outside of school hours.

The performance of each HVAC system was characterized for the entire analysis period during school hours for the following metrics: total daily natural gas consumption, total daily electricity usage, peak daily power draw, and average indoor air conditions (that is, air temperature, absolute humidity, CO_2 concentration, and $PM_{2.5}$). HVAC system standby power was estimated between 9:00 p.m. and 5:00 a.m. during periods when the heating/cooling was not running.

The performance analysis for the seven HVAC units installed at SAC was conducted on data collected between February 8, 2018 and March 22, 2019.

The performance analysis for the six HVAC units installed at BAK was conducted on data collected between May 1, 2018 and April 12, 2019.

Details on the analysis methods and equations are available in Appendix B.

Classroom Environment Monitoring (Short-Term Intensive)

Intensive indoor environmental quality monitoring, which includes air quality, temperature, and relative humidity data, was performed during three approximately one-week periods in each classroom between December 2017 and November 2018 (Table 4). The three visits were scheduled to collect data from different seasons that correspond to differences in HVAC operation (early fall, winter, and spring).

Table 4: Dates of Indoor Environmental Quality Monitoring

	Bakersfield Region Elementary School	Sacramento Region High School
Visit 1	December 5–19, 2017	February 1–9, 2018
Visit 2	May 7–14, 2018	May 29–June 5, 2018
Visit 3	October 10–18, 2018	October 30–November 8, 2018

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

In each of the studied classrooms, the research team used the instrumentation listed in Table 5 to measure the concentrations of CO_2, $PM_{2.5}$, ozone, black carbon, and formaldehyde, which are each briefly described as follows:

- CO_2 is emitted by occupants, is a marker of bio-effluents, and is used as an indicator to determine the adequacy of ventilation.
- $PM_{2.5}$ and ozone are the air pollutants that most often exceed both national and state ambient air quality standards with consequent morbidity and mortality. Whereas outdoor air should be the only source of ozone in the classroom, $PM_{2.5}$ is also generated by some indoor activities, such as resuspension of dust and soil particles, textile fibers and skin flakes, chalk, and breakdown of building materials.
- Black carbon is an indicator of diesel particulate matter. Exposure to ambient concentrations of black carbon was estimated to cause 1,500 – 2,400 deaths per year in California between 2005 and 2008,[2] the most recent period for which such data are available.
- Formaldehyde is a regulated, toxic air contaminant that is present in classrooms at levels that often exceed the chronic reference exposure levels set by the California Environmental Protection Agency. Although formaldehyde is present in outdoor air, the majority of formaldehyde found in indoor environments comes from indoor emissions. Thus, ventilation is highly (negatively) associated with formaldehyde levels in classrooms.

Table 5: Instrumentation Used to Monitor Indoor Environmental Quality

Sensor	Instrument	Sampling Frequency	Sampling Location
CO_2	Vaisala CARBOCAP GWM94	3-minute	Indoor Only
$PM_{2.5}$	TSI DustTrak II 8530	10-second	Indoor & Outdoor
$PM_{2.5}$	Gravimetric Filter	7-day	Indoor & Outdoor
Ozone	2BTech Ozone Monitor 202/205	1-minute	Indoor & Outdoor
Black Carbon	Aerosol Black Carbon Detector	2-second	Indoor & Outdoor
Formaldehyde	Graywolf (Shinyei) Formaldehyde Multimode Monitor (FM-801)	30-minute	Indoor Only
Formaldehyde	SKC UMEx-100 Passive Sampler	7-day	Indoor & Outdoor

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

CO_2 data measured from the three sampling visits were used to determine the adjustment factors for the long-term monitoring data. Adjustment is needed for the long-term monitoring of CO_2 because the sensors used can drift overtime. Linear fits between the CO_2 measured from the three sampling visits and the long-term monitoring data showed that the two sets of

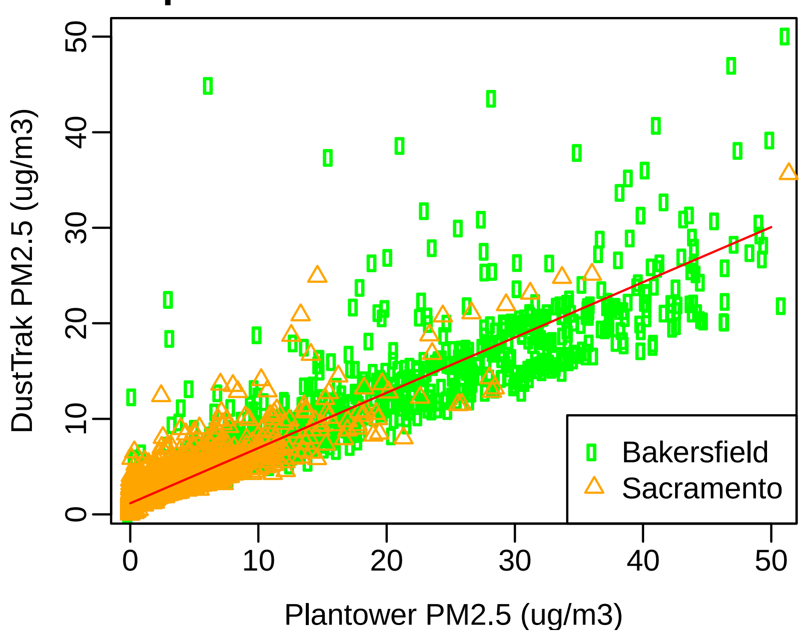
[2] Overview: Diesel Exhaust and Health. http://www.arb.ca.gov/research/diesel/diesel-health.htm. Accessed September 23, 2019.

measurements were highly correlated. R-squared (R^2) values from least squares regression were mostly greater than 0.99. However, the Vaisala used for long-term monitoring tended to read higher values compared to the concentrations measured during the three sampling visits, so the values of the long-term monitoring sensors were adjusted accordingly. Adjustment factors are available in Appendix B in the section "Adjustment Factors for Long Term Monitoring of CO_2."

On visits #2 and #3 in Bakersfield and visits #1 and #3 in Sacramento, $PM_{2.5}$ mass concentrations determined from the gravimetric analysis of filter weights were used to calibrate average DustTrak concentrations. The calculated correction factors suggested that DustTrak overestimates $PM_{2.5}$ concentrations, which is an expected result because of the difference in characteristics between the standard particles used by the DustTrak manufacturer for calibration and the typical size and composition of particulate matter found in ambient air. The mean correction factor was 2.4, which was applied to all DustTrak measurements.

A correction factor for the long-term monitoring Plantower sensors was computed from a least squares regression to determine the slope relating the Plantower sensor readings to the adjusted DustTrak data. An offset of 1.16 micrograms/meter cubed (μg/m^3) was determined from laboratory calibration. Figure 5 shows the results of the linear fit using all available $PM_{2.5}$ data from the two schools.

Figure 5: Comparison of DustTrak and Plantower Sensors



Red line shows the best-fit linear regression with an assumed offset = 1.16 μg/m3 as determined from lab testing of Plantower sensors. The R^2 value was 0.88. The slope is 0.58.

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

While there may be some differences between classrooms, the available data for making the concentration correction is too limited to support computing a correction factor specific to each classroom. Instead, concentration corrections were calculated by pooling all available data and calculating an average slope of 0.58 (Figure 5). All Plantower data were corrected using this correlation (Corrected_$PM_{2.5}$ = 0.58*Measured_$PM_{2.5}$+1.16). More details on the correction factor calculation are available in Appendix B in the section "Adjustment Factors for Long-Term Monitoring of $PM_{2.5}$."

Teacher Survey

A survey was conducted among teachers in the study classrooms to assess occupants' experiences with the equipment, including general satisfaction with temperature and air quality. Comparisons were drawn between teacher experiences across the different types of HVAC equipment, with particular focus on potential differences in perceptions of air quality and thermal comfort by ventilation type. In addition, results of this survey were compared to those from Phase 1 of the project to determine whether proper commissioning of HVAC equipment could be credited with improved occupant experience.

The 14 teachers who taught in the 13 classrooms in the study — two teachers shared a room — were invited to participate in an online survey roughly one year after the new HVAC equipment was installed in their classroom. Teachers were asked to report on their experiences with and perceptions of thermal comfort and air quality during the most recent heating and cooling seasons since the upgrade. Gift certificates were offered as an incentive to participate. All but one teacher (13 out of 14) completed the survey, providing us with occupant data on 12 classrooms.

Phase 3

The energy and air quality implications of HVAC systems and control strategies were modeled using a co-simulation-based approach. EnergyPlus modeled the equipment, control system, and energy consumption while CONTAM performed mass and contaminant balances. The research team used the co-simulation model to analyze the impact of:

- Three HVAC equipment types (CRV, ERV, ECON-DCV)
- Two filter types (MERV8 and MERV13)
- Four climate and outdoor air conditions representative of California's regional variation (Sacramento, Bakersfield, Riverside, and South Lake Tahoe)
- Two different classroom vintages, representative of 1998 and 2008 construction years
- Two grade levels, representing occupancy by elementary and high school aged children

In total, 96 cases were simulated.

Energy Model

The thermal interaction of the building with its environment and internal loads was simulated with EnergyPlus (U.S. Department of Energy, n.d.). EnergyPlus was used to model the building envelope, HVAC system and controls, and occupancy schedule. The geometry for the EnergyPlus model was developed using OpenStudio (Alliance for Sustainable Energy, n.d.) and the simulations were executed on a 15-minute time-step, with hourly time-series reporting.

EnergyPlus fixes indoor temperatures at the thermostat setpoints, with the HVAC system energy consumption modulated to meet that exact temperature. EnergyPlus ensures that the thermostat setpoint is always met; therefore, it does not account for the real-world dynamics of indoor temperature cycling above and below the setpoint as the conditioning portion of the

HVAC system turns on and off. This assumption is likely to fractionally underestimate the energy use, as actual HVAC systems operating intermittently are not expected to operate optimally.

Airflow Model

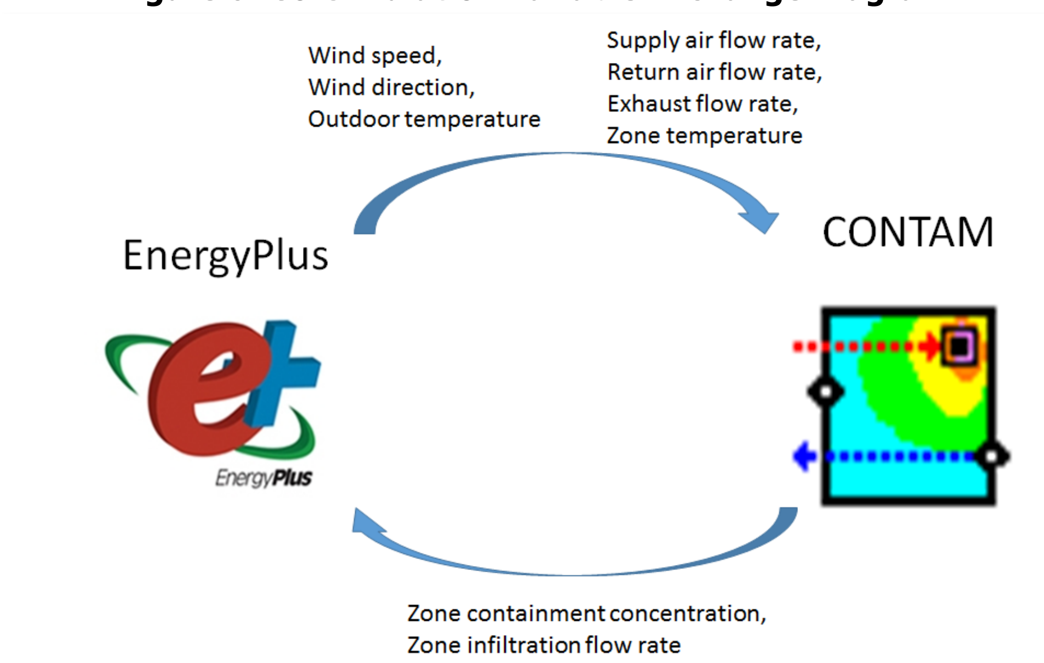
Airflow and contaminant filtration were modeled using CONTAM, which was developed by the National Institute of Standard and Technology (Dols & Polidoro, 2015). CONTAM cannot model building energy use but has sophisticated and flexible models for contaminant transport and loss. It was used to model the air flow mass balance including inter-zonal air flow, mechanical air flow and infiltration, and contaminant transport. The CONTAM simulation platform has a detailed accounting of infiltration at each 15-minute time-step through solutions to pressure-flow relationships.

Airflow models were built in CONTAM using the same geometry, aspect ratio floor area, and zone heights of the classroom specified in the EnergyPlus model. In total, six different CONTAM files were developed: two levels of air tightness and four different outdoor pollutant profiles. Each model effectively had one well-mixed thermal zone to match the corresponding EnergyPlus model.

Implementation of the EnergyPlus and CONTAM Co-Simulation

Performing a co-simulation involves running the two simulation engines in parallel, with critical data connections passed back and forth at each time step, as shown in Figure 6. The approach was based on a method developed and validated by Dols et al. (2016). Dols et al. used a Functional Mockup Interface (FMI, http://fmi-standard.org/) based implementation of CONTAM, which is then coupled with EnergyPlus via its FMI implementation (Nouidui et al., 2014).

Figure 6: Co-Simulation Variable Exchange Diagram



Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

At each timestep, environmental data (wind speed, direction, and outdoor temperature), and system operation data (mechanical system flows) are sent from EnergyPlus to CONTAM. The EnergyPlus EMS is used to manage this interchange and to implement required calculations and control strategies.

The HVAC system flow rates are calculated in EnergyPlus using system operation schedules, defined in the EnergyPlus model file. Once transferred to CONTAM via the FMI, they are represented in CONTAM as "flow paths." CONTAM then calculates the resultant infiltration and inter-zonal mass flows, considering these mechanical flows, along with wind driven and stack effects to determine the resultant mass flow rate. This infiltration is then returned to EnergyPlus to align the two models' air change rates.

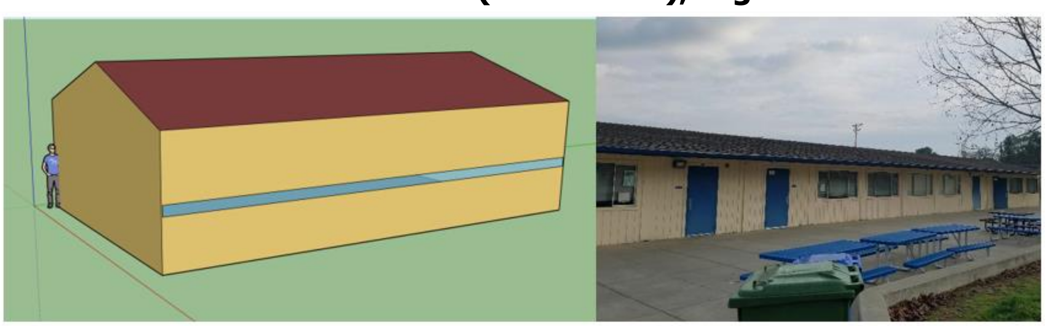
Simulation Model Descriptions

The following sections describe the models and input parameters used in the simulation program and the specifics of the simulation protocol.

Classroom Models

Classrooms were modeled using specifications derived from published data and from the research team's field measurements from Phases 1 and 2. Figure 7 Left shows a single classroom intended to represent the central classroom in a row of several as per Figure 7 Right. The specific model input values for the two prototypes are summarized in Table 1. Envelope performance is based on Table 143-C from the 2008 Title 24 Building Energy Efficiency Standards (California Energy Commission, 2008) and Section 143 from the 1998 Building Energy Efficiency Standards. Classroom building envelope air leakage was modeled using measurements from the two schools that were studied in Phase 2 (Table 6). Heating and cooling setpoints were 70.5 and 73.4°F (21.4 and 23°C) respectively; these setpoints were supported by the field data collected in Phase 2.

Figure 7: Left: Modeled Classroom (Front View), Right: Classrooms in Series



Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Table 6: Model Input Values for Classrooms

Element	Classroom T24 2008	Classroom T24 1998
Ceiling height (ft)	10 peak of 13.8	10 peak of 13.8
Conditioned floor area (ft^2)	958	958
Conditioned volume (ft^3)	11,500	11,500
Roof slope (percent)	20	20
Roof deck (U-Value)	0.039 Btu/hr-sf-°F	0.057Btu/hr-sf-°F
Ceiling insulation(U-Value)	0.048 Btu/hr-sf-°F	0.057Btu/hr-sf-°F
Radiant barrier	No	No
Wall (U-Value)	0.059 Btu/hr-sf-°F	0.092Btu/hr-sf-°F
Window (U-Value)	0.47 Btu/hr-sf-°F	0.72Btu/hr-sf-°F
Window relative solar heat gain	0.36	0.44
Window area	8 percent wall area	8 percent wall area
Lighting power density	1 W/ft^2	1.4 W/ft^2
Equipment power density	1 W/ft^2	1.4 W/ft^2
Envelope leakage (ACH50)	3	9

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

HVAC Design

The HVAC system was represented in EnergyPlus using the AirLoopHVAC:UnitarySystem model. For cooling, the equipment performance was dependent on a biquadratic relationship between the outside air dry-bulb temperature (X) and mixed air wet-bulb temperature (Y). For heating, the performance depended on a cubic relationship with the outdoor air dry-bulb temperatures (X). The biquadratic and cubic curves were taken from a unitary, multi-speed heat pump model in EnergyPlus (Table 7). The curves taken from EnergyPlus were normalized based on the gross capacity or energy intensity ratio (EIR) at the rated conditions of 95°F/67°F (35°C/19°C) (outdoor dry-bulb/mixed air wet-bulb) for cooling and 47°F/70°F (8°C/21°C) (outdoor dry-bulb/mixed air dry-bulb) for heating. The gross capacity and EIR (Table 7) were calculated using data with one-minute resolution from Phase 2 for the six heat pumps installed at BAK. The sensible heat ratio was modeled as 0.76 for Cooling Stage 1 and 0.86 for Cooling Stage 2.

The three ventilation system options were modeled as follows:

- CRV: A fixed percentage of the supply airflow rate was forced to be outside air. For all simulations when the supply fan ran, 50 percent of the volumetric flow was outside air and the remainder was return air from the room.
- ERV: The ERV systems in the field test had four components: the supply-side fan motor, exhaust-side fan motor, enthalpy wheel, and a motor to rotate the enthalpy wheel. To model the power consumption of the ERV and add the heat to the appropriate air streams, an extra 156.5W were added to the supply fan power consumption and 116W were consumed by the enthalpy wheel. The enthalpy wheel

was given a sensible and latent effectiveness of 74 percent for all airflow rates. For all simulations when the supply fan ran, 50 percent of the volumetric flow was outside air and the remainder was return air from the room.

- ECON-DCV: For the economizer with demand control ventilation, the outdoor air flow rate changed based on the equipment schedule and the CO_2 level in the classroom. For each school day, the outside air flow was forced to be 50 percent for one hour to complete the required pre-occupancy flush. After the flush, the flow modulated based on a CO_2 setpoint of 1,000 ppm in the classroom, while always providing at least 0.166 cubic meters per second (m^3/s) (150 CFM) of ventilation. The simulation used the Ventilation Rate Procedure from ASHRAE Standard 62.1-2007/2010 to calculate the ventilation rate based on the classroom floor area, the number of occupants, and the CO_2 generation rate of each occupant. When cooling was required and the outdoor air was less than 75°F (24°C), the economizer function was enabled, and the outdoor air rate increased to up to 100 percent to satisfy the cooling setpoint.

Table 7: Cooling and Heating System Performance Model

Mode	Type	Value at Rating Condition	Con-stant	X	X^2	X^3	Y	Y^2	XY
Cool 1	Capacity (W)	10964	4.76 E-01	4.01 E-02	2.26 E-04		–8.27 E-04	–7.32 E-06	–4.46 E-04
Cool 1	EIR (W/W)	0.237	6.32 E-01	–1.21 E-02	5.08 E-04		1.55 E-02	2.73 E-04	–6.79 E-04
Cool 2	Capacity (W)	15664	4.76 E-01	4.01 E-02	2.26 E-04		–8.27 E-04	–7.32 E-06	–4.46 E-04
Cool 2	EIR (W/W)	0.248	6.32 E-01	–1.21 E-02	5.08 E-04		1.55 E-02	2.73 E-04	–6.79 E-04
Heat 1	Capacity (W)	8348	7.59 E-01	2.76 E-02	1.49 E-04	3.50 E-06			
Heat 1	EIR (W/W)	0.280	1.19 E+00	–3.00 E-02	1.04 E-03	–2.33 E-05			
Heat 2	Capacity (W)	11302	7.59 E-01	2.76 E-02	1.49 E-04	3.50 E-06			
Heat 2	EIR (W/W)	0.281	1.19 E+00	–3.00 E-02	1.04 E-03	–2.33 E-05			

Performance curves for each mode of HVAC system operation, where the values are the coefficient of the specified variable. X represents the outdoor air dry-bulb and Y represents the mixed air wet bulb temperature.

Source: Western Cooling Efficiency Center, University of California at Davis

The supply fan system air flow rates and power draw were modeled based on the field data as shown in Table 8. Extra supply fan power was added for the ERV system, as described above, and for MERV13 filters, based on the manufacturer-reported pressure drop data at rated air flow and typical fan system efficiency (Table 3).

Table 8: Fan System Model

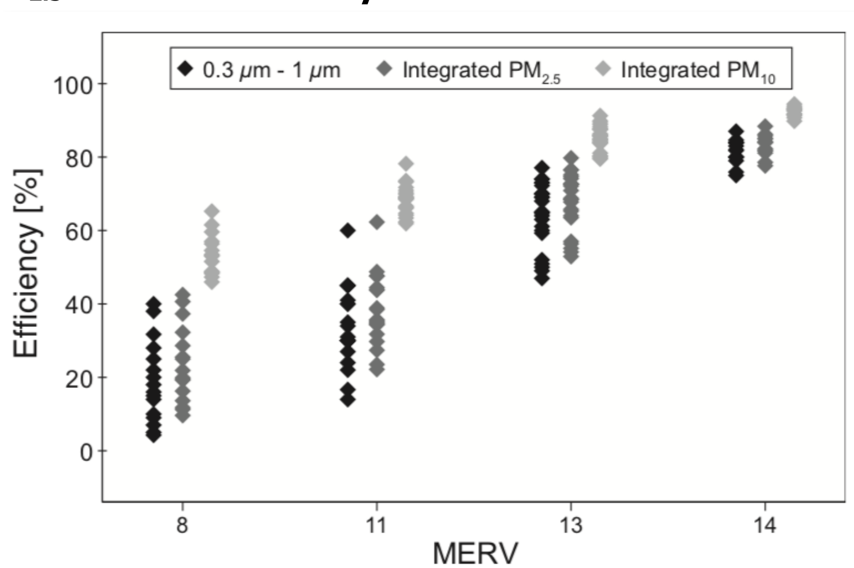
Mode	Airflow (m^3/s)	Supply Fan Power	Additional Supply Fan Power for ERV (W)	Additional Supply Fan Power for MERV13 Filter (W)
Ventilation	0.42664	127	156.5	13
Cool 1 / Heat 1	0.49997	204	156.5	21
Cool 2 / Heat 2	0.75181	695	156.5	61

Source: Western Cooling Efficiency Center, University of California at Davis

Air Filter Removal Efficiency

$PM_{2.5}$ removal efficiency was obtained from published data (Zattari et al., 2014): 20 percent for MERV8, and 70 percent for MERV13 (Figure 8). Removal efficiency depends strongly on particle size. There is a range in initial removal efficiency from different filter manufacturers when filters are new. With use, removal efficiency increases. Limited data suggest that MERV8 air filters increased to MERV12-equivalent removal efficiency when loaded, and MERV13 air filters increased to MERV15-equivalent when loaded (Rivers and Murphy, 1999). This improvement in removal efficiency as the particle loading on filter accumulated was not modeled.

Figure 8: $PM_{2.5}$ Removal Efficiency of Various MERV8 and MERV13 Air Filters



Source: Zattari et al., 2014

Climate Models

Locations were selected to represent the broad range of climatic conditions in California. It was important to capture a variety of heating, cooling, and moisture regimes that exist throughout the state to facilitate statewide estimates by interpolating between the results of these limited locations. The research team used coincident sets of weather and pollutant data to capture the relationship between the two. Weather data for the year 2018 was obtained from White Box Technologies for the four representative locations (Table 9).

Table 9: Selected Climate Zone Models

Climate Location	California Climate Zone	Cooling Degree Days	Heating Degree Days
Riverside	CZ10	2331	1469
Sacramento Region	CZ12	1588	2781
Bakersfield	CZ13	3052	1836
South Lake Tahoe	CZ16	549	8199

Selected climates including Fahrenheit-based five-year-average (2014 to 2018) heating and cooling degree days with a base temperature of 65°F (18°C).

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Outdoor $PM_{2.5}$

Outdoor $PM_{2.5}$ hourly data were obtained from California Air Resources Board (ARB) Air Quality and Meteorological Information System (AQMIS)[3] for the year 2018. A main monitoring station was selected for each of the four modeled locations. Data from additional secondary monitoring stations were used to impute missing data. The secondary stations were selected to represent the regional air quality of the modeled location. In cases where there is more than one secondary station, median hourly $PM_{2.5}$ data were used to impute the missing data. Table 10 shows the ARB station identification number [4] of the main and secondary air quality monitoring sites. More secondary sites were used for the South Lake Tahoe location than the other three locations because the main station has the most missing data.

[3] https://www.arb.ca.gov/aqmis2/aqmis2.php

[4] https://ww3.arb.ca.gov/qaweb/siteinfo.php

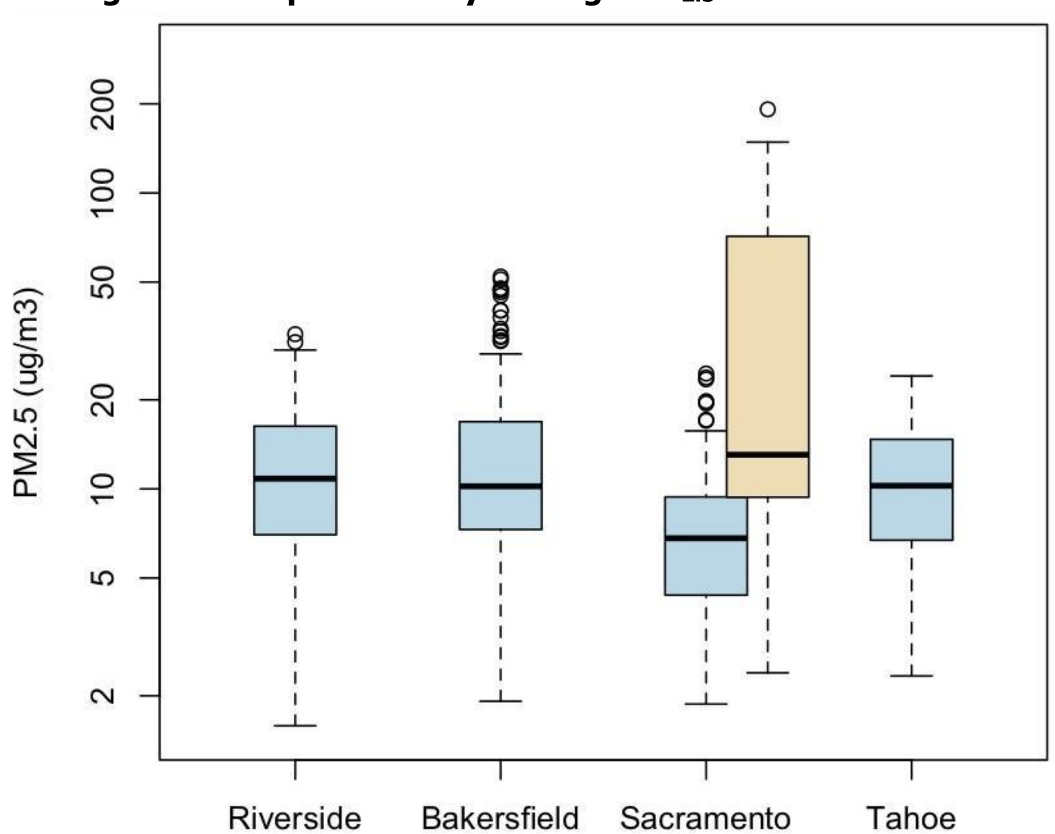
Table 10: ARB Station Identification Number of Air Monitoring Sites with Hourly $PM_{2.5}$ Data

	Riverside Area	Bakersfield Area	Sacramento Area	South Lake Tahoe Area
Main Station	33144	15255	57577	29794
Secondary Stations	33158, 33164, 33165, 33154, 33602	15252, 10240, 15301	57582	22742, 31818, 32821, 29800, 32823, 35633, 32826

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Figure 9 shows the 2018 daily average outdoor $PM_{2.5}$ concentrations at the four modeled locations during typical school hours (8:00 a.m. to 4:00 p.m.). Overall, Riverside and Bakersfield had the highest daily average $PM_{2.5}$ concentrations. Very high concentrations of hourly $PM_{2.5}$ were measured in Sacramento during November 2018 (plotted separately in Figure 9) as a result of a wildfire. Because of this abnormality, November data were excluded from the analysis for the Sacramento area location.

Figure 9: Boxplot of Daily Average $PM_{2.5}$ at Four Locations



For the Sacramento area, November data were plotted separately from the other months due to a wildfire.

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Indoor $PM_{2.5}$ Sources

Indoor particulate matter emission rate was assumed constant during school hours. Chan et al. (2015) estimated the effect of ventilation and filtration on chronic health risks in schools and other commercial building types (office and retail stores). The study used input parameters from 67 California schools (California Air Resources Board, 2004). The median value of 3 milligrams per hour was modeled (10th to 90th percentiles: 0.2 to 5.3 m) in CONTAM.

Deposition Rate and Penetration Factor

Building envelope penetration factor, P, and indoor deposition rate, kdep, are both highly dependent on particle size. El Orch et al. (2014) summarized the available data to derive central estimates of penetration factor as a function of particle diameter, determining a penetration factor of about 0.8 for particle size about 1 μm; this value was specified in the CONTAM model. A recent modeling study by Martenies and Batterman (2018) used a similar value of P = 0.7 to model the effectiveness of enhanced filtration in Detroit, Michigan schools. The value of 0.7 was based on an earlier study by Riley et al. (2002) that considered typical ambient particle size distribution in urban areas for predicting the resulting indoor exposure in different building types.

The deposition rate (k) describes how the concentration (C) of particles in the space deposit onto interior surfaces over time (t)[5]. A deposition rate of 0.3 per hour (was specified in CONTAM for particles with a diameter of about 1 μm. The modeling by Martenies and Batterman (2018) used a somewhat lower deposition rate of 0.1 per hour. A review by Lai (2008) on deposition rate shows values ranging between 0.1 and 1.0 per hour for particles approximately 1 um in diameter, with higher deposition rates found with higher indoor air speeds and increased levels of indoor furnishings. The value used in this study (0.3 per hour) is a reasonable estimate, understanding that the deposition rate of $PM_{2.5}$ can change according to indoor conditions inside the classroom.

Occupancy Schedule

Occupancy schedules were based on an informal survey of school district calendars in California and the required number of instructional minutes specified by the California Department of Education. School days were Monday — Friday, except for the following breaks, for a total of 185 school days:

- 01/01/2018 – 01/07/2018
- 06/04/2018 – 08/19/2018
- 11/19/2018 – 11/25/2018
- 12/17/2018 – 12/31/2018

The elementary schedule included students occupying the classroom from 8:50 a.m. – 3:10 p.m. with a 45-minute lunch break and two 15-minute recesses, except for a minimum day on Wednesday (8:50 a.m. – 2:30 p.m., with only one recess). The schedule assumed 24 students and one teacher during class sessions and one teacher during lunch and recess.

[5] Deposition rate formula: t (hours) = ln ($C_t/C_{initial}$)/-k

The secondary school schedule included students occupying the classroom from 8:15 a.m. – 3:30 p.m. with seven class periods, 5-minute passing periods, and one 42-minute lunch break. The schedule assumed 31 students and one teacher during six class periods, and one teacher during one preparation period, lunch, and passing periods. To represent that the timing of preparation periods varies across teachers, the time of the preparation period was rotated based on the day of the week.

CO_2 Generation Rate

Persily and de Jonge (2017) provided CO_2 generation rates for building occupants of different ages, activity levels, and gender. An average teacher (aged 21 to 60) is expected to generate 0.33 L CO_2/min at 1.6 MET activity level, where 1 MET is roughly the energy expended sitting quietly. Students' CO_2 generation rates were determined at 1.4 MET for these two age groups: 0.20 L CO_2/min for ages 6 to 11 (elementary) and 0.27 L CO_2/min for ages 11 to 16 (secondary — middle/high schools). The following CO_2 generation rates were modeled in CONTAM, given an assumed class size typical for California classrooms:

- Elementary school = 25 students @ 0.201 L CO_2/min each + 1 teacher @ 0.332 L CO_2/min = 5.357 L CO_2/min
- Secondary school = 32 students @ 0.267 L CO_2/min each + 1 teacher @ 0.332 L CO_2/min = 8.876 L CO_2/min

CO_2 generation rates were converted to units of meters cubed per second (m^3/s) per W per person in CONTAM. Each occupant is assumed to generate 120 W of heat.

CHAPTER 3: Project Results

Phase 1

HVAC Equipment Selection and Maintenance

An objective of this research was to better understand decision-making processes and contexts concerning HVAC equipment selection and maintenance in California's K-12 schools. Interviews with district facilities staff regarding their decision to upgrade HVAC equipment included discussion of five overarching topics: (1) HVAC replacement decision, (2) technology selection, (3) installation and commissioning, (4) assessment of new equipment performance, and (5) using and maintaining the equipment.

HVAC Replacement Decision

When asked why the decision was made to replace HVAC equipment, most interviewees discussed the need to replace "old" equipment (that is, equipment past its life expectancy and failing). Beyond poor performance, respondents mentioned several other issues, particularly with older equipment. For example, equipment was inefficient, units required frequent servicing — in some cases on a weekly or daily basis, parts were difficult to find and expensive, and the equipment used obsolete refrigerants. In one case, lack of fresh air was cited as an additional driving factor.

Technology Selection

Several districts relied heavily on third parties (for example, consultants and contractors) for selecting their HVAC retrofits. Other districts relied on an experienced and knowledgeable staff person (such as an HVAC technician or energy manager) to lead the technology selection process. District staff most frequently involved in the technology selection process were those at the administrative or management levels (for example, lead of maintenance/maintenance operations director, head/chief of business, construction coordinator, director of facilities, energy manager, executive committee, and superintendent). Field staff were sometimes involved in decisions such as prioritizing which units would receive upgrades. One interviewee mentioned involving lower level technicians in the process. Several noted the different perspectives held by "office" staff versus "field" staff. The former were noted as being primarily focused with the up-front costs, while the latter expressed concerns about long-term performance and maintenance requirements, as informed by their experience on school sites.

Researchers asked interviewees how energy efficiency, air quality considerations, and cost influenced technology selection. Interviewees were also asked to identify and explain any other factors that influenced HVAC technology selection. The following themes were identified:

- Consistency. Consistency with regard to uniformity and standardization of equipment was important for several reasons related to equipment maintenance. For example, consistent equipment creates efficiencies in training staff, access to parts, and filter changes. Districts also tended to favor certain manufacturers and technologies with which they were familiar and have had positive experiences. Negative experiences with new technologies and poor support and accountability among manufacturers influenced which technologies districts tended to avoid.

- Compatibility. Replacing "like with like" was also important for issues related to compatibility. New equipment needed to fit where and how the old equipment was situated to avoid costly structural changes such as wiring or roof penetrations. Compatibility of new equipment with existing or new control systems was another critical factor. One interviewee gave an example of serious problems resulting from incompatibility between equipment and controls. Some districts also avoided proprietary controls.
- Energy Efficiency. Energy efficiency of equipment factored in strongly, particularly if the HVAC replacement was part of a Proposition 39 project that had to meet certain savings to investment ratio requirements.
- Cost. Districts were working within confined budgets, and since higher efficiency tends to carry a higher price, maximizing efficiency reduced the number of classrooms that could be upgraded. Many favored quantity over efficiency of units.
- Air Quality. Air quality was not frequently cited as a factor in technology selection. Only one interviewee explicitly cited air quality issues as a reason for HVAC retrofits. This case involved a school with air conditioning units that did not introduce any outside air into the classrooms, and therefore, stale air was a problem. Other interviewees did not consider the projects as addressing air quality and were not aware of any problems with air quality prior to retrofits.

Installation and Commissioning

Most districts contracted with a third party to install the HVAC replacements. Interviewees described how school districts are required to "bid out" each sub-contracted job, rather than hire a single contractor for all work.

Perhaps because the installation process was largely handled by third parties, the interviewees did not have much knowledge regarding how ventilation rates were commissioned with the new equipment. Two interviewees assumed testing/calibration was done after installation, one reported they did not do testing, and one reported that they tested if there were complaints.

Assessment of New Equipment Performance

In general, interviewees reported that their HVAC replacements were satisfactory in terms of space conditioning performance. A couple interviewees were certain there had been energy savings since the replacements; others assumed so or were unsure due to confounding factors, such as concurrent adoption of new energy-consuming classroom technologies. When asked about the effect on air quality, most interviewees were not aware of any pre-existing problems or any effects of the replacements. Two interviewees from the same district noted improved ventilation in portable classrooms where economizers were installed.

Indirectly related to HVAC efficiency and air quality with the new systems, several interviewees expressed enthusiasm for their EMS. Interviewees mentioned the capacity to monitor or receive alerts regarding energy waste and air quality issues, as well as control HVAC systems remotely.

We also asked interviewees what they knew about teachers' satisfaction with the new systems. Although most did not have any information, several interviewees were aware that teachers were unhappy with the district's decision to limit teachers' control of the HVAC system upon installation of new equipment. One interviewee reported that with new thermostats the teachers could not see the setpoint. Even though the setpoint had not changed (it was still 76°F (24°C)) some of the teachers disapproved of the new thermostats for this reason. One interviewee noted that fan noise is a problem for teachers. He said that teachers do not understand why the fan is on without cooling (it runs all day to provide ventilation, regardless of space conditioning). In one case, buffers were added to mitigate the noise from the new HVAC system. By contrast, in another case, the noise level reportedly improved compared to the old systems.

Using and Maintaining the New Equipment

HVAC replacements sometimes improved control for facilities at the expense of teachers' control. In other cases, teachers gained some flexibility. In most cases, systems allowed teachers a little control, with setpoints that could be adjusted 2°F (1.1°C) to 4°F (3.3°C). Facilities staff reported heating setpoints ranging from 64°F to 69°F (18°C to 21°C), and cooling setpoints ranging from 72°F to 76°F (22°C to 24°C).

According to interviewees, filter replacement (or reusable filter cleaning) schedules typically followed manufacturer recommendations, ranging from 3 to 12 months, or district standards informed by feedback on filter condition from maintenance crew and school location. For example, some schools near agricultural fields or roadways changed filters more often. One interviewee reported a rolling schedule, as opposed to a fixed interval at which all filters were changed. Two interviewees reported that filter changes were not always done as frequently as they should be. Another interviewee reported that filter replacement frequency is specified in teachers' contracts as an assurance of environmental quality in the workplace and is reported out for accountability. Filter replacement is typically the responsibility of a small maintenance crew or HVAC technicians (typically one or two staff) from the district.

Classroom and Heating, Ventilation, and Air Conditioning Characterization

Classroom Characteristics

Data was collected for 104 classrooms, all of which were generally in good condition based on visual inspection. The field team did not observe any visible mold. Evidence of pests (for example, cockroaches) was reported in two classrooms. The sample was weighted to lower grades, with 42 of the classrooms from seven schools serving grades K-3 and 43 classrooms from schools assigned to grades 4 – 8. Only 19 of the 104 classrooms were occupied by upper grades (9 – 12), and 16 of those were from the two high schools (Table 1). The studied classrooms had a mean floor area of 893 ft^2 (range of 721 – 1098 ft^2). The mean class size was 28 students (range of 14 – 37), which is typical for California classrooms.

Heating, Ventilation, and Air Conditioning Equipment and System Controls

The study included 63 RTUs and 41 wall-mount HVAC systems. Most of the portable classrooms (31 of 33) had wall-mount systems and most of the permanent classrooms (61 of 71) were serviced by an RTU. All wall-mount units used electric heat pumps, whereas all but two RTUs used gas heating. The RTUs had higher efficiency ratings (EER 11.2 – 13.0) than the wall-mount heat pumps (EER 9.0 – 11.0).

The ventilation systems can be divided into five technology groups. The HVAC units serving 19 classrooms with constant rate ventilator systems could provide the code-required ventilation rate per Title 24 if configured correctly. These systems have a damper for outdoor air that is either continuously open or is powered to open to a fixed position when the air handler fan operates and have an exhaust air path for pressure relief from the room. Six classrooms had non-powered, spring-based outdoor air dampers without an exhaust air pathway for pressure relief; this equipment is designed for spaces with lower outdoor air requirements (such as modular offices with lower occupant density) and cannot provide the code-required ventilation for 30 students and a teacher even when set to the maximum opening position. Five of the HVAC systems had energy recovery ventilators that provide constant, balanced (supply and exhaust) airflows that transfer sensible and latent heat through an enthalpy wheel. Seventy-four systems were equipped with economizer (ECON) units that use outdoor air in place of mechanical cooling when the outdoor air temperature or enthalpy is below a set value. These units had the capacity to pull up to 100 percent of the air that they supply to the room from the outdoors. Twenty-five of the systems with economizers were additionally equipped with DCV.

The field inspection found incorrect equipment or other serious installation problems in 16 classrooms. The field team measured outdoor airflow for the six ventilator systems with non-powered, spring-based outdoor air dampers and found that they provided very little ventilation (range of 0 – 40 L/s; mean of 17 L/s [35 CFM]. In three of the systems with the fixed-position ventilator, the low voltage electric power and control signal were not connected, so the outdoor air damper was always closed. Seven of the economizers (without DCV) systems were wired incorrectly or were not configured properly such that they were always closed. No obvious hardware problems were found in the systems with either DCV or an ERV. However, it is possible that installation problems were under-reported because the field team did not directly measure outdoor airflow or check the damper position setting in all classrooms. Therefore, the absence of an identified problem does not mean that the ventilation rate to the classroom was sufficient.

Most of the classrooms (96 of 104) had a thermostat that was networked to an EMS, where the school district controlled the allowable heating and cooling setpoint range and fan operation schedule. Eight classrooms had no EMS. In 79 of the 96 classrooms with an EMS, the teacher had some control of room temperature within a range set by the school district. The thermostat had a manual override button, enabling heating/cooling and ventilation for 30 to 60 minutes at a time outside of the scheduled occupied hours. In the other 17 systems linked to an EMS, the teacher had no control of room temperature. All of the equipment examined in this study requires the ventilation fan to run continuously during occupied hours to deliver adequate ventilation to the classroom. However, in 22 classrooms, the ventilation fan was incorrectly set to "auto" mode and operated only when the system was heating or cooling. This occurred in classrooms with and without an EMS. One classroom without EMS had the fan set to run continuously (24 hours a day/7 days a week). In this case, the thermostat was locked so that the teacher could not turn off the fan.

Filter Characteristics

The majority of the classrooms (85 of 104) had 2-inch pleated air filters with either a MERV 7 or MERV 8 rating. About one-third of the classrooms with wall-mount systems (13 out of 41) had non-pleated polyester media filters with no MERV rating. One RTU had no air filter. It was unclear why the filter was missing; similar classrooms and equipment inspected at the same school all had air filters. Three air filters in wall-mount units could not be evaluated because they were inaccessible (the screws on the filter compartment cover could not be removed), and so presumably had not been replaced since installation of the unit.

The condition of each filter was rated on a scale of 1 (like new) to 5 (past service life) by visual inspection. Thirty of the 100 filters that could be inspected fell into categories 4 and 5, and most of these (26 of 30) were found in wall-mount units.

Occurrences of Observed Heating, Ventilation, and Air Conditioning Problems

The number of occurrences of each of the common HVAC problems observed by HVAC type and ventilation system type are shown in Table 11 and Table 12.

Each problem contained one or more of the following:

- Hardware: Inadequate ventilation equipment and/or improper installation resulting in no or minimal outside air to the classroom
- Controls: Fan not operating continuously during occupied hours, resulting in reduced fan run hours and reduced outside air to the classroom
- Maintenance: Filter due for change or past service life, possibly resulting in reduced airflows and reduced outside air to classroom

Table 11: Summary of HVAC Problems and Type That Could Result in Inadequate Ventilation

Problems: Hardware (H), Control (C), and/or Filter (F)	RTU	Wall-Mount	Total
None identified	48	3	51
Hardware only	2	3	5
Control only	7	6	13
Hardware + Control	1	—	1
Filter only	3	14	17
Hardware + Filter	—	9	9
Control + Filter	1	6	7
Hardware + Control + Filter	1	—	1
Total	63	41	104

Source: Western Cooling Efficiency Center, University of California at Davis

Table 12: Summary of HVAC Problems and Ventilation System Type That Could Result in Inadequate Ventilation

Problems: Hardware (H), Control (C), and/or Filter (F)	CRV	Spring Damper	ERV	ECON	ECON-DCV	Total
None identified	4	–	–	23	24	51
Hardware only	1	–	–	4	–	5
Control only	7	–	–	6	–	13
Hardware + Control	–	–	–	1	–	1
Filter only	4	–	4	8	1	17
Hardware + Filter	2	6	–	1	–	9
Control + Filter	1	–	1	5	–	7
Hardware + Control + Filter	–	–	–	1	–	1
Total	19	6	5	49	25	104

Source: Western Cooling Efficiency Center, University of California at Davis

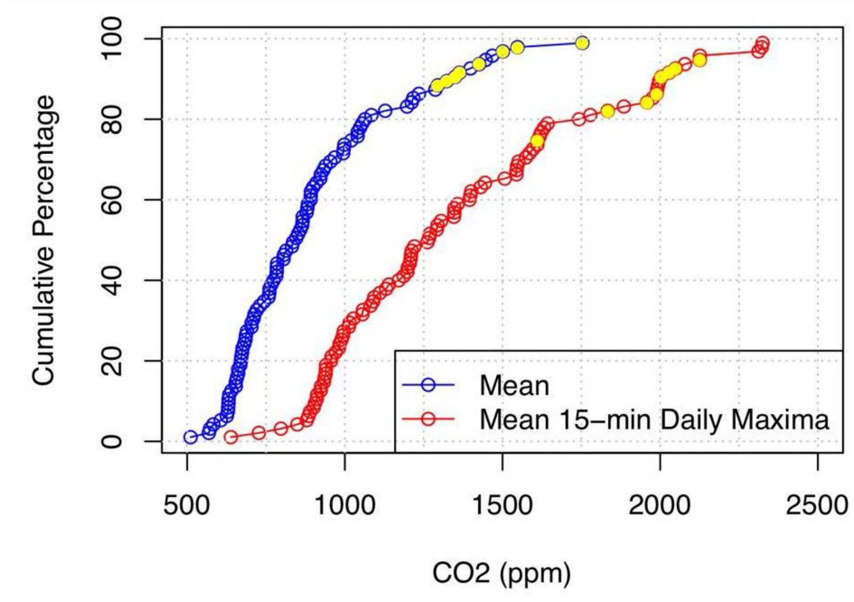
More than half of the classrooms had at least one problem identified. Problems were more commonly found in wall-mount units (93 percent had one or more problems) than in RTUs (24 percent). Ventilation systems with economizer only or ECON-DCV had fewer problems identified during field inspection, in comparison to the other ventilation system types. The low frequency of problems in the 25 classrooms with ECON-DCV may be the result of being in (two) districts with full-time energy managers who were involved with HVAC equipment installation and commissioning. Also, the DCV systems collected and reported CO_2 data to the facilities staff, so ventilation problems could be easily identified and fixed.

Indoor Environmental Quality Monitoring

Figure 10 shows the distribution of mean CO_2 concentrations across classrooms measured during school hours. Also shown is the distribution of the means of the 15-minute highest daily average CO_2 concentrations. Because of data loss in 10 classrooms (for example, monitor became unplugged), data from only 94 classrooms were available for this analysis.

The mean and median CO_2 concentrations across all measurements during school hours were 895 ppm and 897 ppm, respectively. The distribution of the mean concentration plotted in this figure assumed the value of 2,000 ppm during times when CO_2 concentrations exceeded this upper limit in schools 1 and 2. Among the 18 classrooms from those two schools, 8 had CO_2 concentrations above 2,000 ppm for a substantial amount of the time, varying from 17 percent to 69 percent of the occupied hours. As a result, the plotted distributions likely underestimate the true CO_2 statistics of the classrooms measured.

Figure 10: Indoor CO_2 Concentrations

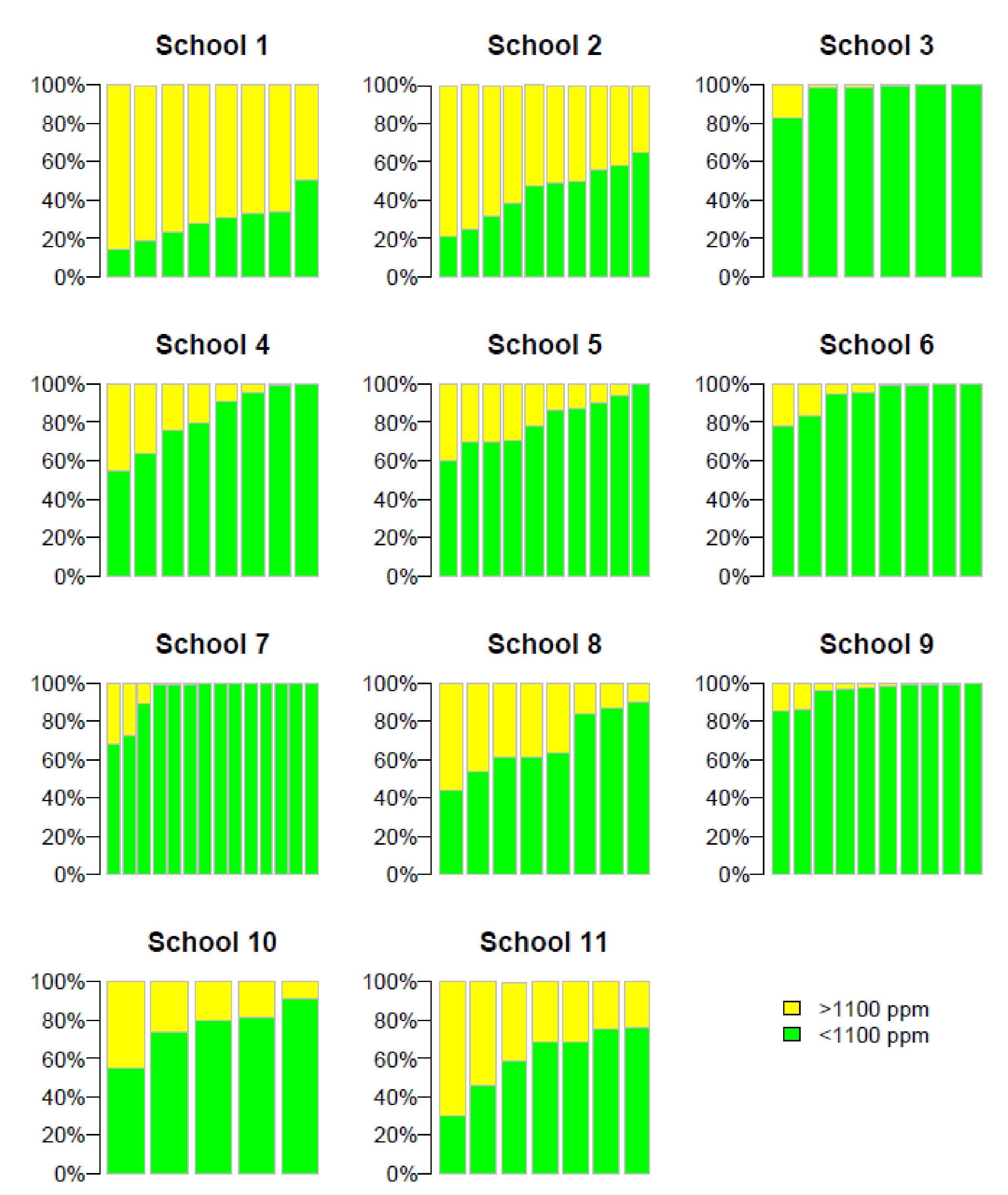


Yellow circles indicate classrooms that frequently had CO_2 at or above the sensor limit of 2,000 ppm; the values presented for these eight classrooms may therefore be an underestimate.

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

California's Title 24 (California Energy Commission, 2012) has no requirement to maintain CO_2 below a specified concentration. However, as a reference point, the CO_2 concentration that would occur in spaces that meet the minimum ventilation rate requirement of 7.1 L/s-person was calculated. For a CO_2 generation rate of 0.27 L/min-person (corresponding to 7 – 8th grade students), a space ventilated at the Title 24 minimum would have a steady-state CO_2 concentration of 1,100 ppm, or 700 ppm above the concentration of CO_2 (400 ppm) in outdoor air. Figure 11 shows the percent of time when CO_2 concentrations exceeded 1,100 ppm in each classroom. There were variations across classrooms within each school and large differences between schools. This shows that in schools where under-ventilation is a problem, it tends to occur not as an isolated case, but rather as a common problem that affects many classrooms within a school.

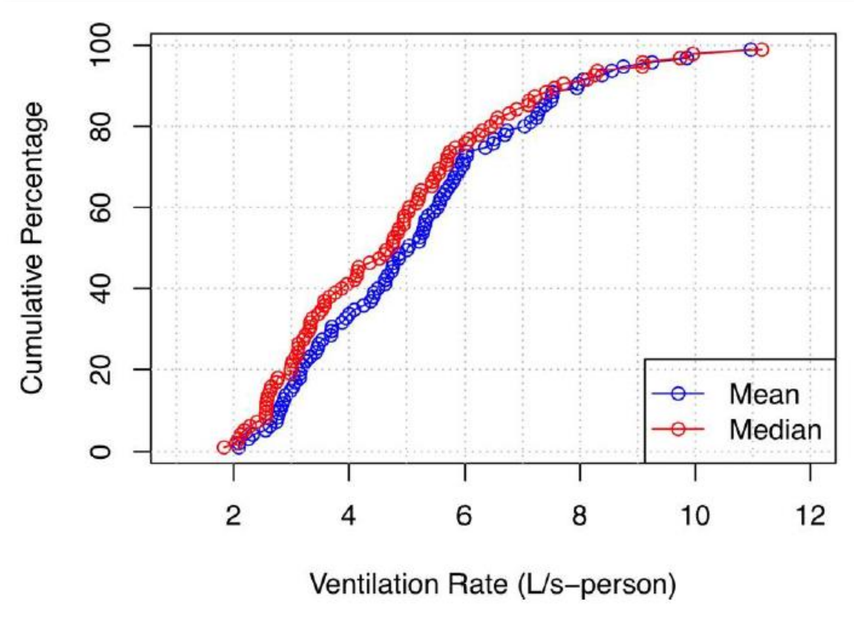
Figure 11: Percent of Time During School Hours When CO_2 Exceeded 1,100 ppm



Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Researchers calculated the daily ventilation rate for each classroom (see Appendix A for more detail on the equation used). Figure 12 shows the distributions of the mean and median of the calculated daily ventilation rates for each classroom. Across the 94 classrooms with CO_2 data, the 50th percentiles of mean and median ventilation rates were 5.2 L/s-person and 4.8 L/s-person, respectively. Only around 15 percent of the classrooms had a median daily ventilation rate estimate that met the 7.1 L/s per person code requirement.

Figure 12: Cumulative Probability of Ventilation Rates

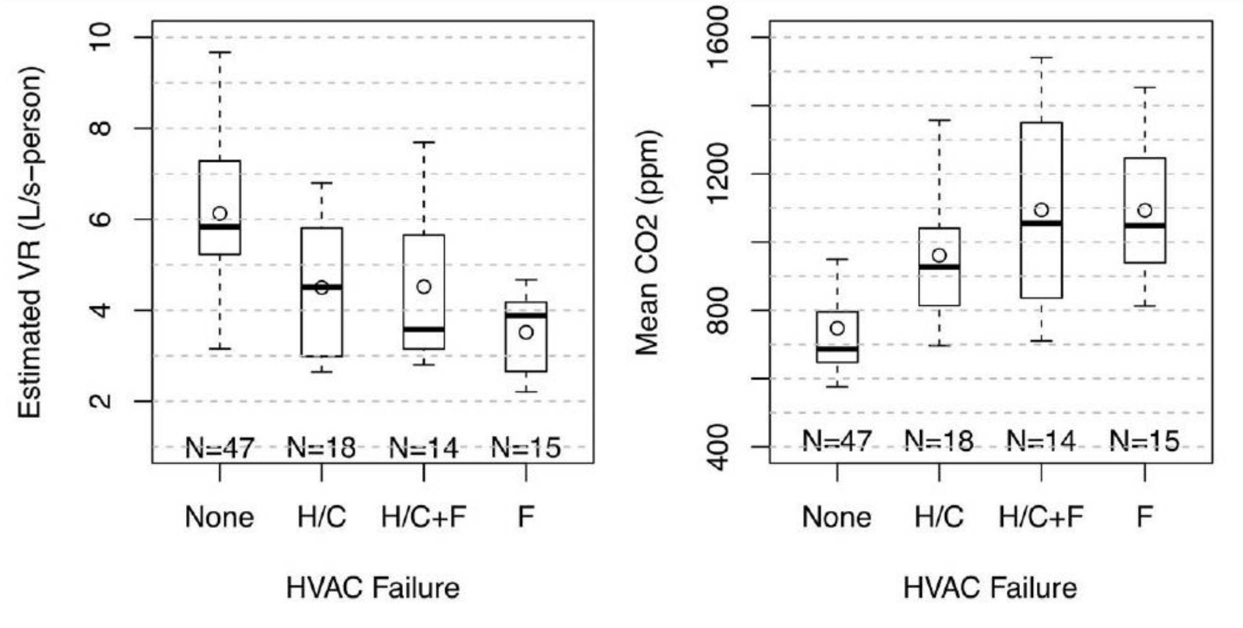


Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Portable classrooms that used wall-mount HVAC systems tended to have higher CO_2 concentrations and lower estimated ventilation rates compared to permanent classrooms, which tended to use rooftop units. Lower CO_2 concentrations were observed in classrooms with economizers. Classrooms with demand control ventilation had lower CO_2 concentrations, and all classrooms in this category had average mean CO_2 concentrations below 1,000 ppm.

Figure 13 shows results for the classrooms with one or more problems identified from HVAC inspection during site visits. Classrooms with any one or more of the HVAC problems tended to have lower ventilation rates and higher mean CO_2. The difference in mean estimates is statistically significant at the 0.05 level in all cases, with respect to classrooms with no observable problems. The research team found no statistically significant difference in the mean estimates between classrooms that had hardware and/or control problems alone and classrooms that had hardware and/or control problems in addition to having filters due for change or past service life. This result is expected: if the HVAC system is not providing sufficient ventilation because of hardware and/or control problems, the filter condition may not be as important. On the other hand, heavily loaded air filters alone are associated with lower ventilation rates and higher mean CO_2. A possible explanation is that HVAC systems with heavily loaded air filters also had other problems that were not identified during the field inspection, such as incorrect damper position settings resulting in inadequate ventilation. It is also possible that heavily loaded air filters can reduce airflow and outdoor air ventilation for some HVAC systems, though additional tests were not performed to confirm this.

Figure 13: Boxplots of CO_2 Concentration and Ventilation Rate by HVAC Failure

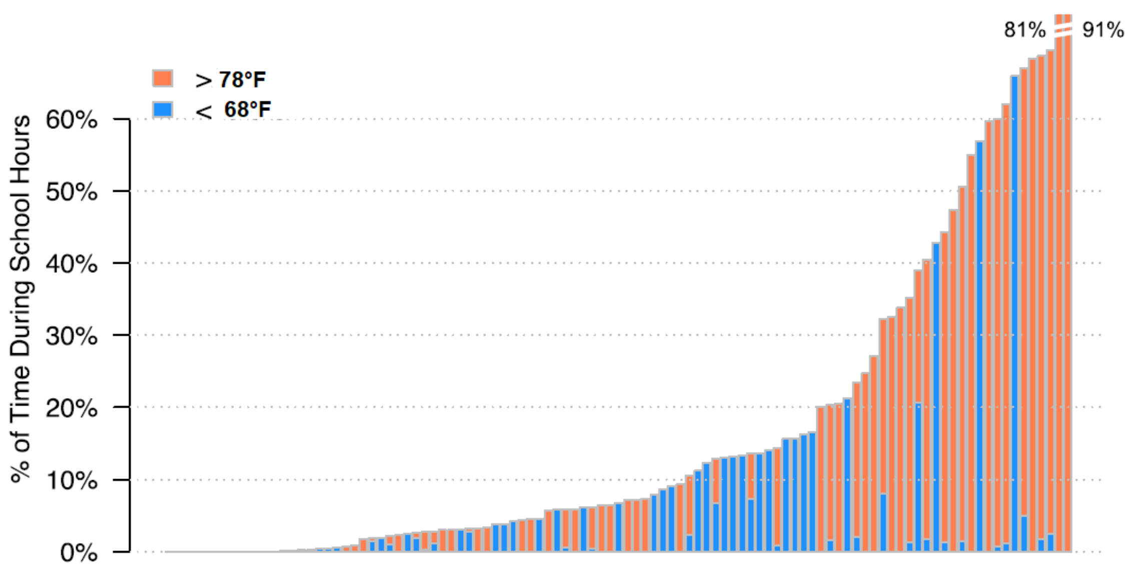


Identified failure modes include hardware (H), controls (C), and filter (F).

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Figure 14 shows the percent of school hours where indoor air temperature was outside of the typical range for thermal comfort, defined as less than 68°F (20°C) or greater than 78°F (26°C). The majority of the classrooms with a large percent of school hours outside the desired thermal comfort range were too warm. There were 23 classrooms with indoor air temperature above 78°F (26°C) for more than 20 percent of the school hours. In comparison, there were five classrooms with indoor air temperature below 68°F (20°C) for more than 20 percent of the school hours.

Figure 14: Percent of Time When Classroom Was Too Cold or Too Warm



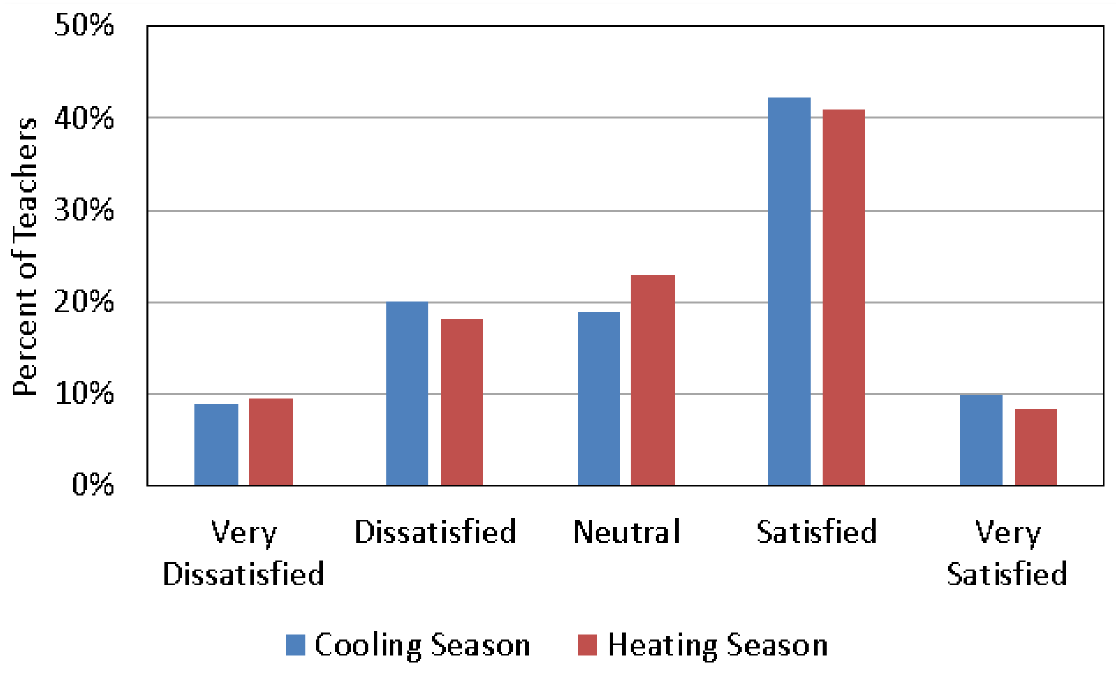
Each bar represents one classroom. Data is missing from one classroom because of a sensor problem.

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Teacher Surveys

Teachers' satisfaction with the room temperature varied; roughly half were satisfied, 30 percent were dissatisfied and 20 percent were neutral (Figure 15). Specific complaints were related to lack of control over thermostat setpoints, temperature swings, and uncomfortable supply air temperatures. Teachers reported using alternative means to achieve comfort, including overriding the thermostat, adapting (for example, adjusting clothing, drinking hot or cold beverages), using supplemental heating or cooling devices, and complaining to the district. Teachers reported that some of their students also engaged in adaptive behaviors.

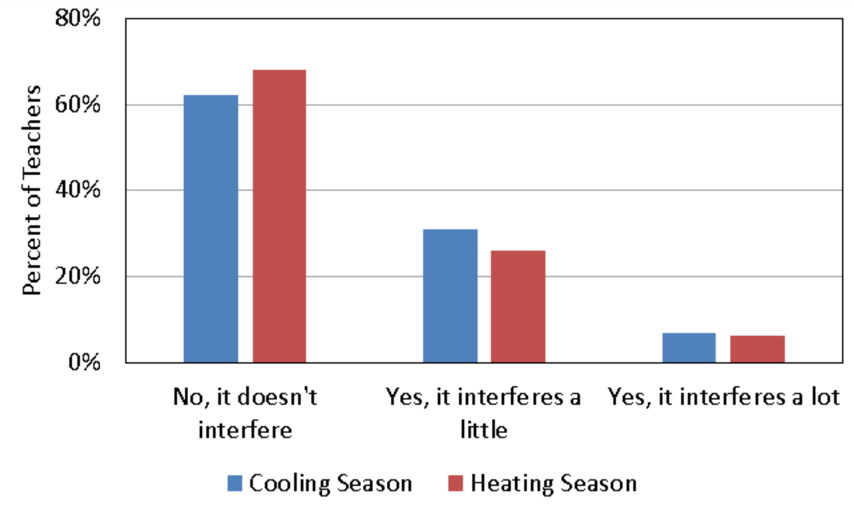
Figure 15: Teacher Satisfaction with Temperature



Source: Western Cooling Efficiency Center, University of California at Davis

As shown in Figure 16, about half of the teachers reported that the classroom temperature interfered with the learning environment, in part because of the activities they engage in to adapt to the temperature to achieve comfort. Unsurprisingly, perception of temperature interfering with the classroom environment strongly correlated with lower satisfaction with temperature (cooling season: $r = -.69$, $p < .001$; heating season: $r = -.63$, $p < .001$). A general sense of dismay, and sometimes resignation, among teachers regarding their lack of control over classroom conditions was also evident among some surveyed.

Figure 16: Interference of Temperature with the Learning Environment



Source: Western Cooling Efficiency Center, University of California at Davis

Teachers were most often "neutral" when asked to rate their satisfaction with air quality, and more reported being satisfied than dissatisfied. Although only one-quarter reported dissatisfaction with classroom air quality, one-third reported that the air quality interfered with the learning environment and 59 percent said the HVAC system did not provide enough fresh air. Stuffiness was the most common complaint (50 percent), although some also reported negative health effects for themselves and students (for example, headaches, allergies, sinus infections, and dizziness). Interestingly, satisfaction with air quality was not correlated to monitored CO_2 levels, suggesting that air quality problems are difficult for most teachers to detect.

Triangulating findings across the survey, classroom audits, and IEQ monitoring revealed that teachers' control over HVAC operations is correlated with greater satisfaction with environmental conditions. Teachers reported they are often limited in their ability to gain access to outdoor air due to non-operable windows and school policies that require doors to remain shut. It also appeared that many teachers did not understand that the HVAC system provides needed ventilation, in addition to conditioning the air.

Phase 2

A summary of results including indoor conditions and energy effects are presented for both schools. In figures, the equipment type is labeled "Ventilation type-filter MERV" to reduce space used. "Base-8" refers to the baseline WG model equipment with CRV. The economizer with demand control ventilation (ECON-DCV) is shortened to "DCV."

Indoor conditions and energy use are affected by the occupancy of the classroom. The class sizes reported by the school office are reported in Table 13. In Sacramento, the day was divided into seven class periods and the number of students reported is the average over seven periods.

Table 13: Number of Students by Classroom

School	Unit Type	Average # Students	Grade
SAC	Base-8	22.3	10-12
SAC	CRV-8	23.1	10-12
SAC	CRV-13	28.7	10-12
SAC	ERV-8	16.9	10-12
SAC	ERV-13	23.0	10-12
SAC	DCV-8	32.0	10-12
SAC	DCV-13	23.9	10-12
BAK	CRV-8	20	1
BAK	CRV-13	23	2
BAK	ERV-8	25	3
BAK	ERV-13	22	2
BAK	DCV-8	23	2
BAK	DCV-13	24	3

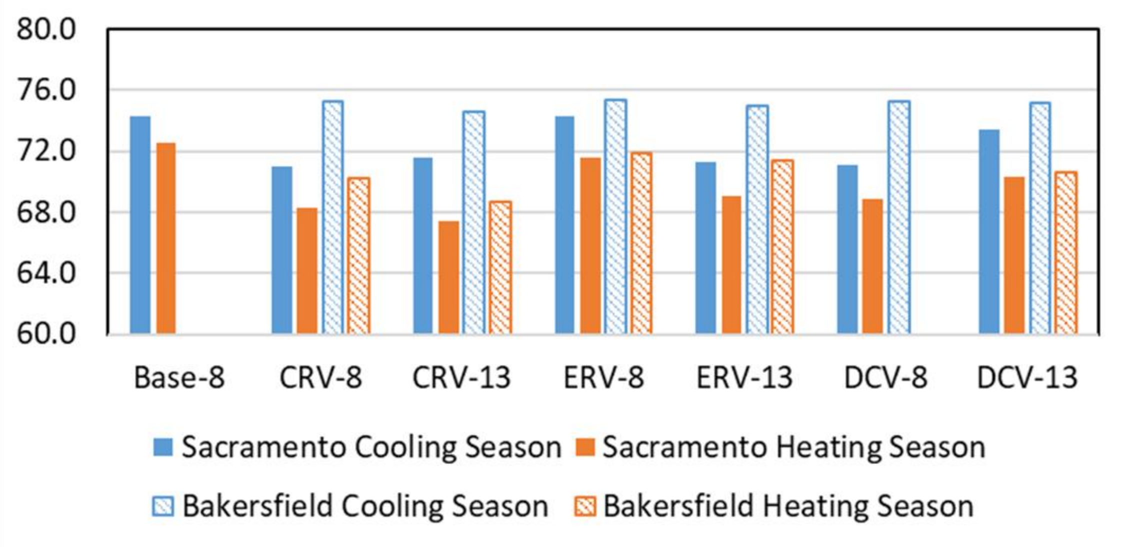
Source: Western Cooling Efficiency Center, University of California at Davis

Indoor Temperature

Cooling season average indoor air temperatures varied widely between classrooms at SAC, between 71.1 and 74.3°F (21.7 and 23.5°C). Heating season average indoor temperatures also varied widely, between 67.4 and 72.5°F (19.7° and 22.5°C) (Figure 17).This variation is not surprising, as teacher-controlled thermostats allow teachers to meet their individual preferences. Generally, the rooms that were conditioned to be warmer in the winter were also conditioned to be warmer in the summer.

Variations in indoor air temperatures in classrooms at BAK were less pronounced than in SAC (Figure 17). Cooling season average indoor air temperatures varied between 74.6 and 75.4°F (23.7 and 24.1°C). Heating season average indoor air temperatures varied between 68.7 and 71.9°F (20.4 and 22.2°C).

Figure 17: Average Indoor Temperature (°F) by Season

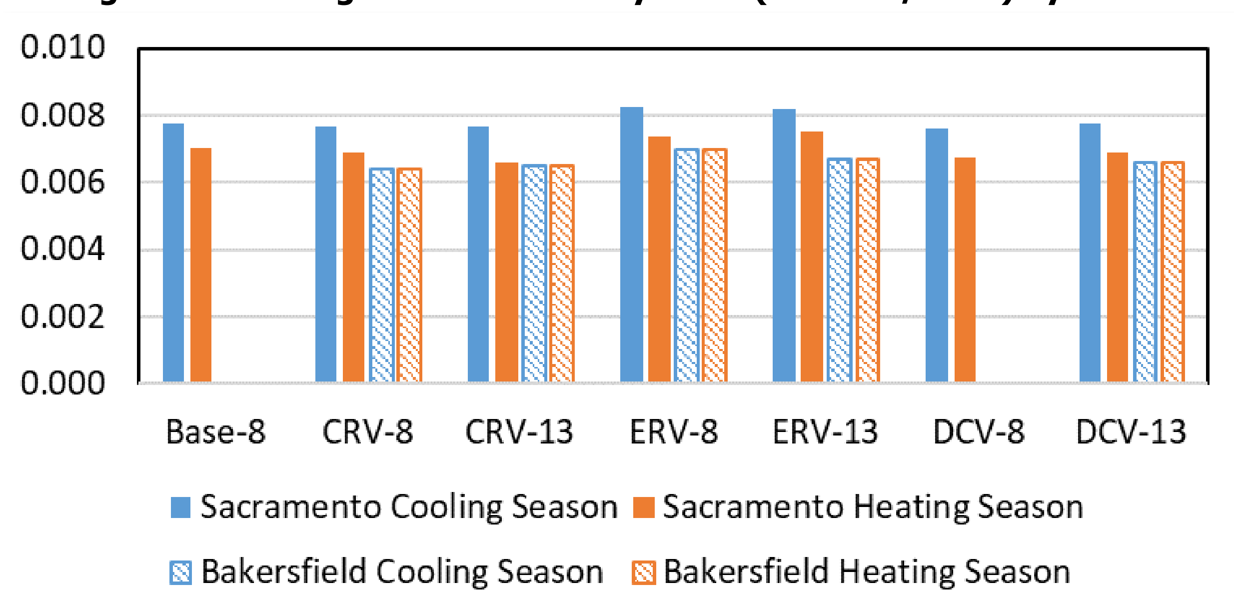


Source: Western Cooling Efficiency Center, University of California at Davis

Indoor Humidity

The indoor humidity ratio was similar between the classrooms at each school, with a slight increase in humidity in cooling season versus heating season, which is expected due to increases in outdoor humidity in warmer months (Figure 18). In both schools, the indoor humidity ratio was highest in classrooms with ERVs. This is because the ERV recovers both latent heat and sensible heat. This is a disadvantage in California's dry climate, where the humidity level outdoors in summer is generally more favorable than indoors. However, recovering the humidity from indoors is likely to improve occupant comfort in the winter by preventing the air from feeling too dry (that is, maintaining a comfortable relative humidity and avoiding the need for a humidifier).

Figure 18: Average Indoor Humidity Ratio (lb water/lb air) by Season



Source: Western Cooling Efficiency Center, University of California at Davis

CO_2 Concentrations

Outdoor CO_2 concentrations during school hours averaged 462 ppm at SAC and 477 ppm at BAK. Analysis of the hourly data shows the outdoor concentration did not vary significantly between occupied and unoccupied hours. This average was higher than 400 ppm, which is generally assumed for outdoor CO_2 concentrations.

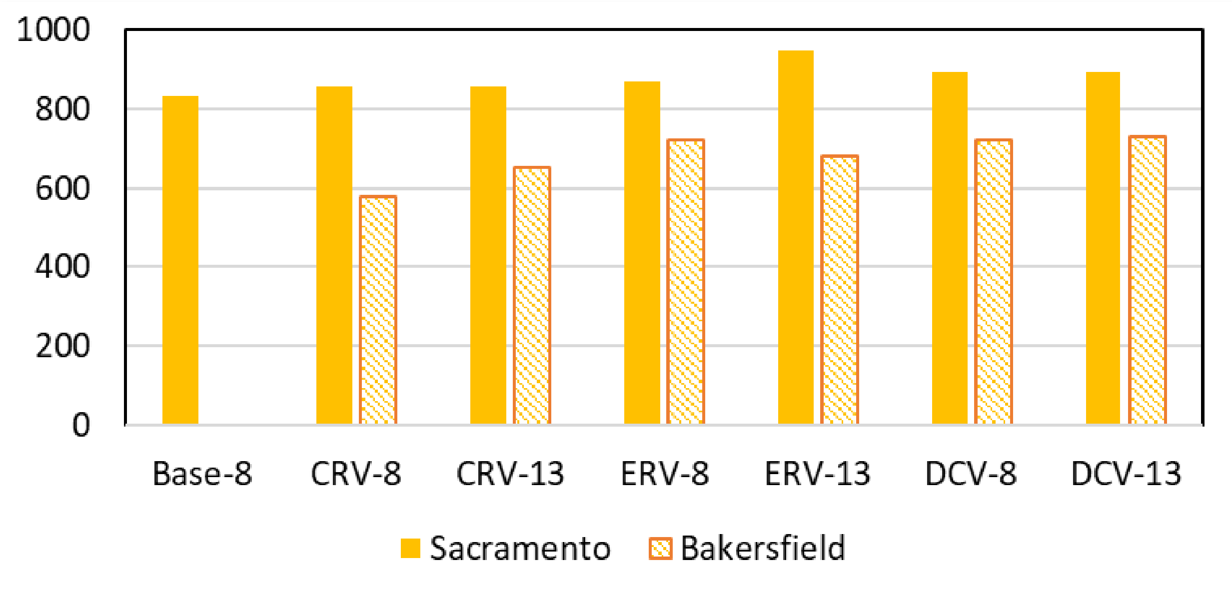
Indoor CO_2 levels were higher at SAC (mean 833 – 949 ppm) due to the larger class size and older students compared to BAK (mean 580 – 731 ppm), as shown in Figure 19. Title 24 building energy efficiency standards specify that buildings with demand control ventilation systems must control the ventilation air flow rate to keep the indoor CO_2 concentrations below 1,000 ppm (or 600 ppm greater than outdoors).

At SAC, average CO_2 concentrations were comparable between rooms. While the ERV ventilation rate measured during the commissioning process was lower than the CRV rooms, this did not result in a significant problem because the ERV classrooms were only occupied four or five periods a day. Still, the ERV-13 room had the highest average CO_2 concentrations, which in some months exceeded an average of 1,000 ppm.

Review of the hourly data for the ECON-DCV classrooms showed that the CO_2 levels were not tightly controlled (see Appendix B: CO_2 Concentration by Hour and by Month). Upon further investigation, the research team determined that the damper response time of the Jade controller was too slow to respond quickly to the large range of damper movement required for the equipment to respond to the normal occupancy changes that occur in school settings (for example, between class periods, lunch). The damper response characteristics are part of the Jade controller's firmware and could not be adjusted by the research team. Further discussion with Honeywell after the field study was completed determined that the damper speed can be adjusted using a supplementary PC tool. UC Davis is following up with Honeywell and Bard to advocate for ensuring that HVAC equipment ships with the controller configured with a damper response speed appropriate to the range of damper movement required.

At BAK, class sizes were smaller and the CRV systems, which were commissioned for a typical occupancy of 30 people, over-ventilated the classrooms relative to minimum standards. CRV-8 had the lowest CO_2 levels; however, there were only 20 first-grade students in the classroom, which was the lowest among the classrooms in the study (Figure 19). CO_2 concentrations were higher in the ERV rooms because the ventilation rates were lower than in the CRV rooms. The ECON-DCV systems responded to classroom CO_2 concentrations; however, review of the hourly data shows that the CO_2 levels were not tightly controlled. The damper response characteristics are part of Pelican's cloud-based software and could not be adjusted by the research team.

Figure 19: Average Indoor Carbon Dioxide (ppm)



Source: Western Cooling Efficiency Center, University of California at Davis

Particulate Matter ($PM_{2.5}$)

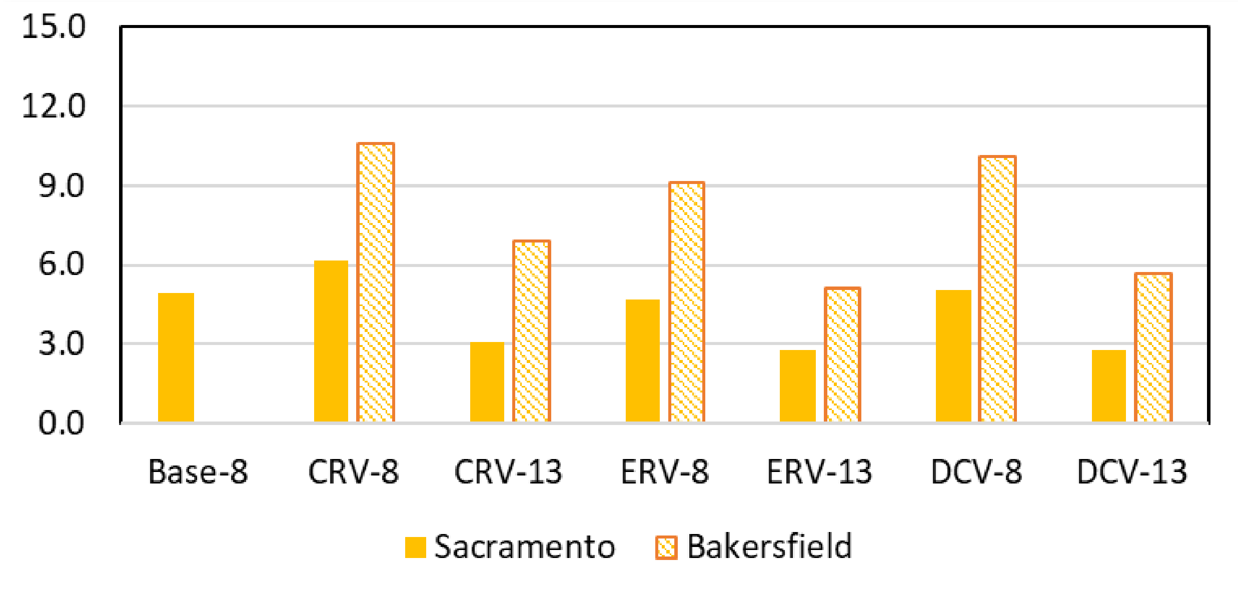
Both the California Air Resources Board and United States Environmental Protection Agency (U.S. EPA) set the annual average standard for $PM_{2.5}$ at 12 µg/m^3. The U.S. EPA also has a 24-hour average standard set at 35 µg/m^3 for $PM_{2.5}$.

Classrooms at both schools with MERV13 air filters had substantially lower $PM_{2.5}$ concentrations compared to classrooms with MERV8 air filters. The three intensive one-week monitoring periods using the DustTrak sensors showed that the MERV13 filters reduced $PM_{2.5}$ by one-half to two-thirds compared to MERV8 filters. Measured indoor $PM_{2.5}$ was 0.37 – 0.55 of outdoor $PM_{2.5}$ for classrooms with MERV8 filters, and indoor $PM_{2.5}$ was 0.14 – 0.27 of outdoor $PM_{2.5}$ for classrooms with MERV13 filters.

At SAC, over a one-year period reported by the Plantower sensor, the average outdoor $PM_{2.5}$ during school hours was 9.3 µg/m^3, whereas indoor $PM_{2.5}$ during the same time period averaged 5.2 µg/m^3 for rooms with MERV8 filters and 2.9 µg/m^3 for rooms with MERV13 filters, a 45 percent reduction relative to MERV8 filters (Figure 20). The results at BAK were similar. The average indoor $PM_{2.5}$ from rooms with MERV13 filters was 5.9 µg/m^3 compared to 9.9 µg/m^3 for MERV8, a 41 percent reduction, similar to what was measured in SAC (Figure 20). An annual outdoor average $PM_{2.5}$ concentration for the Bakersfield region school was not calculated due to intermittent problems with the outdoor $PM_{2.5}$ sensor at that site.

Outdoor $PM_{2.5}$ levels from air quality monitoring stations near the field sites show that average $PM_{2.5}$ values were higher in the Bakersfield region than the Sacramento region, except for mid-November 2018, when the Sacramento region experienced unusually poor air quality from a wildfire that burned about 100 miles north.

Figure 20: Average Indoor $PM_{2.5}$ (µg/m³)



Source: Western Cooling Efficiency Center, University of California at Davis

Black Carbon

The difference in black carbon concentrations between classrooms with MERV8 and MERV13 air filters were less significant than $PM_{2.5}$. In some cases, classrooms with MERV13 air filters had indoor black carbon concentrations about 60 percent to 75 percent lower compared to classrooms with MERV8 air filters (Table 14 and Table 15). But there were also cases where there were no discernable differences in indoor black carbon concentrations between classrooms with MERV8 and MERV13 air filters. Measurement uncertainty may be a contributing factor.

Table 14: Black Carbon, Bakersfield Region Elementary School

Room	Visit 1 (µg/m³)	Visit 2 (µg/m³)	Visit 3 (µg/m³)
Outdoor	0.47	0.38	0.47
CRV-8	0.42	No data	0.52
ERV-8	0.44	No data	0.49
DCV-8	0.75	0.49	0.60
Average	0.53	0.49	0.53
CRV-13	0.45	0.30	0.34
ERV-13	0.56	0.23	0.39
DCV-13	0.57	0.37	0.45
Average	0.53	0.30	0.39

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Table 15: Black Carbon, Sacramento Region High School

Room	Visit 1 (µg/m^3)	Visit 2 (µg/m^3)	Visit 3 (µg/m^3)
Outdoor	0.23	No data	0.45
Base-8	0.10	0.21	0.43
CRV-8	0.16	No data	0.44
ERV-8	-	0.25	No data
DCV-8	0.09	No data	No data
Average	0.11	0.23	0.44
CRV-13	0.11	No data	0.33
ERV-13	No data	0.25	0.32
DCV-13	0.14	0.17	No data
Average	0.12	0.21	0.21

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Ozone

Overall, the measured indoor ozone concentrations were low relative to the California ambient air quality standard, which is an annual average below 70 parts per billion (ppb) and a one-hour average below 90 ppb (Table 16 and Table 17). However, any ozone introduced can contribute to indoor chemistry that generates irritants. Therefore, reduced introduction of outdoor ozone into classrooms represents an improvement in indoor air quality.

Table 16: Ozone, Bakersfield Region Elementary School

Room	Visit 1 Time-Average Ozone (ppb)	Visit 1 1-Hour Max Ozone (ppb)	Visit 3 Time-Average Ozone (ppb)	Visit 3 1-Hour Max Ozone (ppb)
Outdoor	32	46	41	53
CRV-8	13	22	21	32
ERV-8	9	16	17	27
DCV-8	13	22	12	20
CRV-13	15	21	16	24
ERV-13	8	16	13	21
DCV-13	8	16	12	22

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Table 17: Ozone, Sacramento Region High School

Room	Visit 1 Time-Average Ozone (ppb)	Visit 1 1-Hour Max Ozone (ppb)	Visit 3 Time-Average Ozone (ppb)	Visit 3 1-Hour Max Ozone (ppb)
Outdoor	30	43	34	48
Base-8	8	12	11	20
CRV-8	11	19	12	19
ERV-8	No data	No data	No data	No data
DCV-8	No data	No data	No data	No data
CRV-13	9	21	13	23
ERV-13	9	17	No data	No data
DCV-13	9	17	10	16

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Formaldehyde

Formaldehyde concentrations were low in measured classrooms, especially during school hours with ventilation, compared to California's health guideline of 7 ppb[6] (Table 18 and Table 19).

Table 18: Formaldehyde, Bakersfield Region Elementary School

Month	Statistic	Weekday School Hours (ppb)	Weekday Off Hours (ppb)	Weekday Average (ppb)	Weekend Average (ppb)	Period Average (ppb)	School Hours / Period Average
Dec 2017	Mean (N=6)	1.0	5.6	3.6	5.5	4.1	0.23
Dec 2017	Range (N=6)	0.2–1.6	5.1–7.4	3.0–4.7	3.9–9.2	3.3–6.0	0.05–0.35
May 2018	Mean (N=4)	4.3	11.6	7.9	4.4	6.9	0.59
May 2018	Range (N=4)	2.6–8.4	10.9–13.2	6.6–10.5	2.4–6.0	5.9–9.0	0.39–0.92
Oct 2018	Mean (N=5)	2.1	8.5	5.4	12.6	7.0	0.30
Oct 2018	Range (N=5)	1.6–3.0	7.4–10.5	4.6–7.0	10.0–16.4	5.9–8.9	0.25–0.37

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

This points to the importance of ventilation to ensure that the formaldehyde concentrations in classrooms during school hours are maintained to meet health guidelines. Data show seasonal dependency, where higher formaldehyde concentrations were measured in warmer seasons compared to cooler seasons. Temperature dependency means that the need for purge

[6] California Office of Environmental Health Hazard Assessment chronic inhalation reference exposure level. https://oehha.ca.gov/air/chemicals/formaldehyde

ventilation, which ventilates the building one hour prior to expected occupancy to remove indoor pollutants emitted from building materials and surfaces, may not be as great in winter. There may be energy benefits by reducing the purge ventilation requirement in certain circumstances.

Table 19: Formaldehyde, Sacramento Region High School

Month	Statistic	Weekday School Hours (ppb)	Weekday Off Hours (ppb)	Weekday Average (ppb)	Weekend Average (ppb)	Period Average (ppb)	School Hours / Period Average
Feb 2018	Mean (N=5)	1.9	9.4	6.1	10.3	7.5	0.25
Feb 2018	Range (N=5)	1.3–2.5	7.8–10.3	4.8–6.8	9.5–11.4	6.4–8.4	0.2–0.29
May 2018	Mean (N=5)	2.5	10.7	6.6	4.3	6.0	0.42
May 2018	Range (N=5)	1.9–3.4	8.8–14.9	5.4–9.1	2.5–7.2	4.9–8.6	0.33–0.56
Oct/Nov 2018	Mean (N=7)	2.3	6.7	4.6	7.7*	5.1*	0.45*
Oct/Nov 2018	Range (N=7)	1.8–3.1	5.4–8.0	3.8–5.5	5.8–9.8*	4.2–5.9*	0.39–0.54*

*** N=6, excluding Base-8 because ventilation system operated on occupied mode scheduled throughout the week regardless of weekday or weekend due to control system programming error.**

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Fan Power

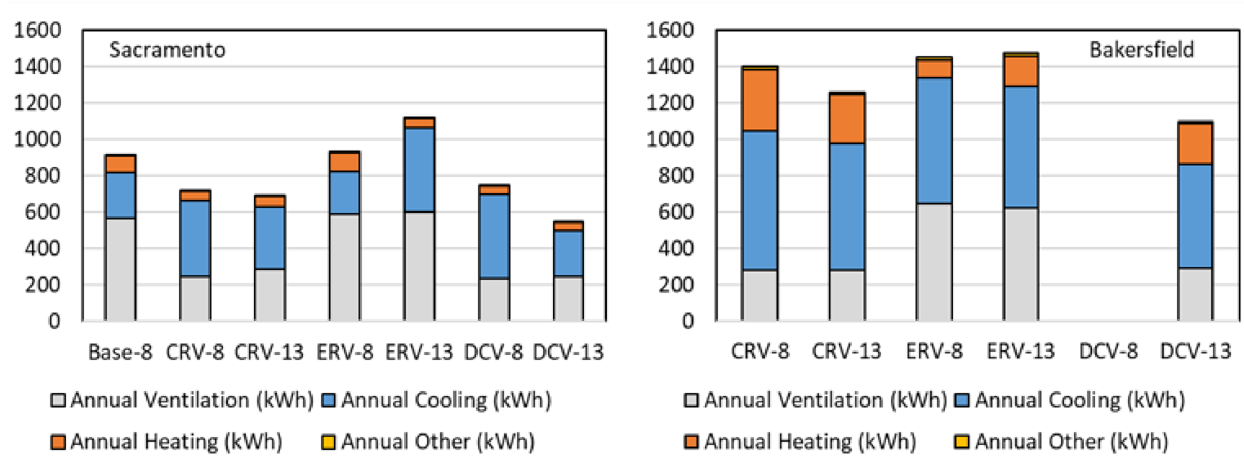
An increase in fan power consumption for the MERV13 filters was expected due to their higher initial resistance and their greater particle capture efficiency. The average fan power consumption during the first hour of ventilation system operation each school day was analyzed. The first hour of the day was chosen to reduce likelihood that the cooling coil would be wet (since cooling in early morning hours is unusual). Two periods of monitoring data in Sacramento covering two sets of filters (first: three months, second: four months) showed that, on average, the MERV13 filters increased fan power consumption by 18W over the life of the filters. Calculation of fan power consumption over six months in Bakersfield (with no filter changes) showed an average increase in power consumption of 20W due to MERV13 filters. This increase includes power consumption attributed to the extra initial resistance of new filters (estimated at 14 – 16W) plus extra resistance from the increased collection of particulates (estimated at 4W). This field result is consistent with the estimate made from the manufacturer data that predicted the additional extra initial resistance would increase fan power by 17W. Over an estimated 1,620 required ventilation hours per year, an extra 20W of power consumption equates to 32 kWh.

Total Electricity and Gas Consumption – School Hours

The total electricity and gas consumed by each HVAC system was summed for the entire study period during school hours. In SAC, this equated to 195 school days. In BAK, this equated to 170 school days. The reported results were linearly scaled to estimate the natural gas and electricity consumption for a standard 180 school days.

The results estimate electricity consumption by mode: heating, cooling, ventilation, and other (Figure 21). Ventilation mode is the fan running to provide ventilation only. When heating or cooling is on, all the fan power is assigned to the heating/cooling mode (even though it is also simultaneously providing ventilation).

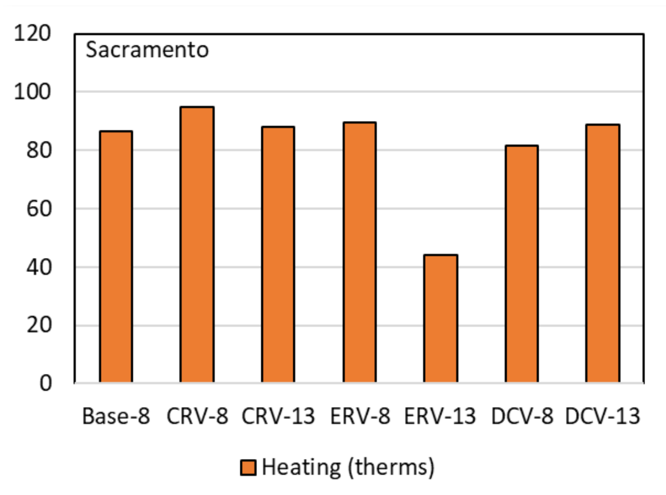
Figure 21: Electricity Consumption by Mode (kWh)



Source: Western Cooling Efficiency Center, University of California at Davis

For SAC, with natural gas heating, the estimated therms of natural gas consumed are reported along with the electricity for fan operation during heating mode (Figure 22).

Figure 22: Natural Gas Consumption (therms)



Source: Western Cooling Efficiency Center, University of California at Davis

ERV-13 had the lowest natural gas use, likely due to room temperature being one of the coldest. When the mode of the equipment could not be determined from the data or the equipment was off, the electricity consumed is reported as "other."

The instantaneous power draw (kW) at one-minute intervals was used to determine the mode and then the electricity consumed (kWh) for the minute preceding the power measurement was added to that sum for that mode. These results are highly accurate for total annual consumption (for all modes), but because mode changes are frequent, there is some uncertainty in allocating the entire kWh consumption for a particular minute to a mode based on an instantaneous power measurement.

Small differences in electricity consumption due to filter type are not seen in this analysis because the number of ventilation hours varies due to (1) differences in heating and cooling requirements for rooms, and (2) inaccuracies in assigning full-minute electricity consumption to specific modes, as described previously. Therefore, energy effects due to filter type are discussed in the previous Fan Power section. In general, electricity consumption differences due to filter type are small (approximately 30 kWh/year) compared to electricity consumption differences due to indoor temperature setpoints, interior loads (occupancy, for example), HVAC equipment type, and ventilation system type. Therefore, the average electricity consumption of the two rooms with different filter types is averaged when comparing the difference in electricity consumption for ventilation system types.

The annual energy consumption comparative analysis shows the following results for HVAC system model and ventilation system type.

- **"Base" Versus "CRV":** This compares the baseline unit with single speed compressor, permanent split capacitor blower motor to a high efficiency unit with two-speed compressor and ECM blower motor. Both systems have commercial room ventilators. The ECM motor in the high efficiency unit reduced ventilation fan energy consumption by 53 percent and heating fan energy consumption by 44 percent (Figure 21, left). Cooling energy consumption increased by 50 percent. This is likely due to the reduced indoor temperatures and higher occupancy for the CRV rooms, which were 3°F (2.2°C) colder than the Base room in the summer and had 16 percent higher occupancy (Figure 17 and Table 13). Overall, electricity reduction was 23 percent for the higher efficiency unit.
- **"CRV" Versus "ERV":** This compares the high efficiency unit with two different ventilation system options: commercial room ventilators versus energy recovery ventilation. Overall, the ERV systems were problematic in the climate tested; they increased electricity consumption by 46 percent in Sacramento and 10 percent in Bakersfield. The ERV used 122 – 126 percent more electricity in ventilation mode compared to the CRV at the same school. A separate, one-time measurement of the ERV system power showed that the ERV consumed between 272 and 424 watts, with the higher power consumption being measured at Bakersfield (Table 20). In both schools the ERV reduced the cooling energy consumption by 7 percent. During many hours of the cooling season in California, particularly cool mornings, the outside air temperature is lower than the room temperature. During these hours, the ERV is consuming additional electricity and reduces the cooling delivered to the room. This

penalty mostly offsets the times when the ERV saves electricity, for example during hot summer afternoons. In Sacramento, the ERV reduced heating therms used by 27 percent but increased heating fan energy used by 39 percent. In Bakersfield, the ERV reduced heating electricity consumption by 56 percent; however, since heating loads were small, this had a small effect on overall electricity consumption.

Table 20: ERV Settings and Power Consumption Measurements by Classroom

	SAC ERV-8 Fan Setting	**SAC ERV-8** Power (W)	**SAC ERV-13** Fan Setting	**SAC ERV-13** Power (W)	**BAK ERV-8** Fan Setting	**BAK ERV-8** Power (W)	**BAK ERV-13** Fan Setting	**BAK ERV-13** Power (W)
Supply ERV fan	high	155	high	158	high	193	high	180
Exhaust ERV fan	med	84	med	82	med	140	high	171
ERV wheel motor	N/A	33	N/A	33	N/A	77	N/A	73
Total		272		273		410		424

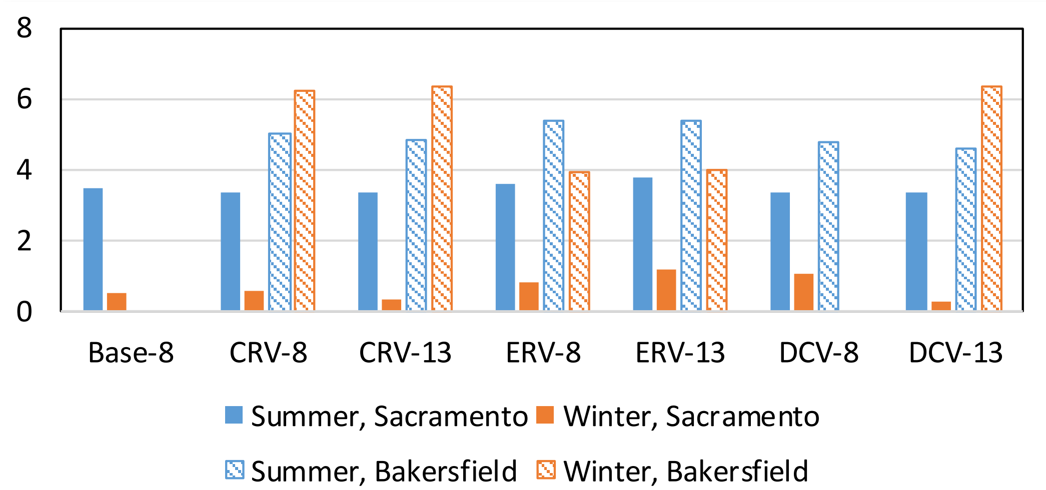
Source: Western Cooling Efficiency Center, University of California at Davis

- **"CRV" Versus "ECON-DCV":** This compares the high efficiency unit with two different ventilation system options: commercial room ventilator versus economizer with demand control ventilation. Overall, the ECON-DCV systems performed well and reduced electricity consumption by 8 percent in Sacramento and 18 percent in Bakersfield. Savings were greater in Bakersfield due to the smaller occupant load and more extreme climate. Changes in ventilation system electricity consumption were small. Annual cooling electricity consumption was reduced by 5 percent in Sacramento and 22 percent in Bakersfield. Compared to the CRV, the ECON-DCV systems performed well and reduced electricity consumption by 18 percent in Bakersfield (for the all-electric systems), and reduced electricity consumption by 8 percent and natural gas use by 7 percent in Sacramento (for the gas/electric systems).

Peak Demand

Peak demand is the customer's maximum power draw from the electrical grid during a fixed time period, typically 15 minutes. Reducing peak demand benefits ratepayers by lowering their monthly bill. The maximum 15-minute summer and peak demand for systems in Sacramento did not differ significantly by system type (Figure 23). The ERV systems had higher peak demand for both heating and cooling due to the extra fan electricity consumption. However, in Bakersfield, the ERV significantly reduced the winter peak demand because it prevented the backup electric resistance heat from operating.

Figure 23: Peak Demand, kW



Source: Western Cooling Efficiency Center, University of California at Davis

Standby Electricity Consumption

The average standby power for each unit between 9:00 p.m. and 5:00 a.m. is shown in Table 21. Differences between unit types were significant. In Sacramento, the average standby power for the WG series baseline unit (Base-8) was only 11W. In comparison, the higher efficiency WGS series units had average standby power of 38W – 43W. Assuming there are 7,140 non-school hours annually (8,760 hours per year, minus 180 9-hour school days), the average WGS system is predicted to consume approximately 200 kWh more than the WG system in standby power (Table 21). This is a significant loss compared to approximately 280 kWh the WGS system saved when operating during school hours. After reviewing the result with Bard (HVAC equipment manufacturer), it was determined that the WGS system has a crankcase heater that is always running to keep the compressor warm, while the WG does not. In the WG model, the crankcase heater is sold as an extra option.

In Sacramento, a small difference in standby power was seen between ventilation system types. The CRV/ECON-DCV systems had an average additional standby power of 3W relative to the ERV systems, which was likely due to the electronics associated with the Honeywell Jade controller. While a CRV system does not require a Honeywell Jade controller, the research team used a system with a Honeywell Jade controller to replicate the function of the CRV hardware.

In Bakersfield, Bard's TS series units had standby power ranging from 17 – 24W. A small difference in standby power was seen between ventilation system types. The CRV and ERV systems used the least standby power, and an additional 5W were consumed by the ECON-DCV systems on average, likely for the Pelican Wireless economizer controller. The TS series does not have a crankcase heater and end-use of the standby power consumption is unknown.

Table 21: Standby Power for Each HVAC System in Watts

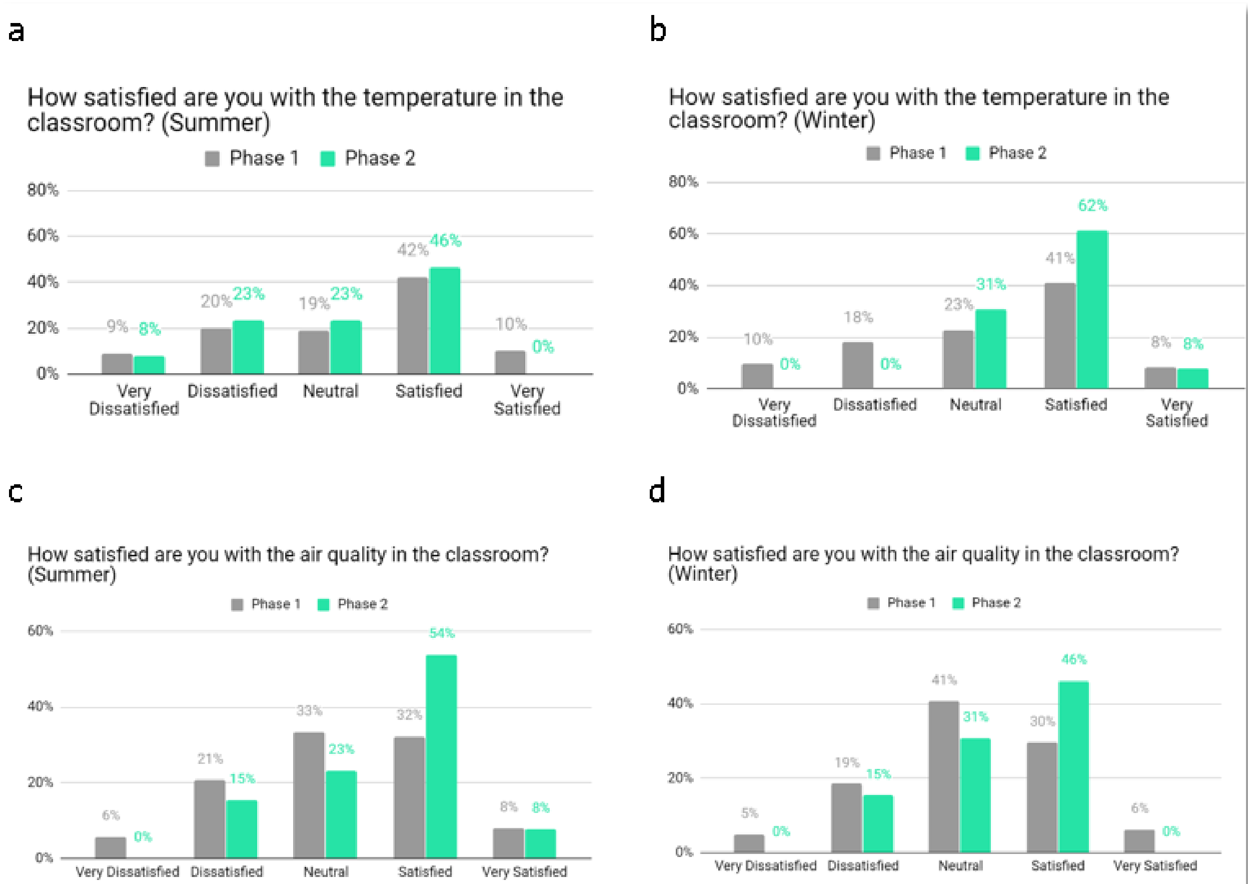
Site	Statistic	Base-8	CRV-8	CRV-13	ERV-8	ERV-13	DCV-8	DCV-13
Sacramento	mean	11	41	40	39	38	43	41
Sacramento	max	13	41	41	39	38	44	41
Sacramento	min	9	40	40	38	38	43	40
Bakersfield	mean	-	20	17	19	17	24	22
Bakersfield	max	-	23	20	23	20	33	28
Bakersfield	min	-	17	14	16	14	19	17

Source: Western Cooling Efficiency Center, University of California at Davis

Teacher Survey

Figure 24 presents classroom teachers' levels of satisfaction with temperature and air quality in the cooling and heating seasons from Phases 1 and 2.

Figure 24: Phases 1 and 2 Comparison of Teacher Satisfaction with Temperature and Air Quality



Source: Western Cooling Efficiency Center, University of California at Davis

The only statistically significant difference observed is that Phase 2 teachers were more satisfied with classroom temperature in the winter ($t[94]= -2.7$, $p = .011$). Either the HVAC equipment had no other effects on teacher satisfaction or other effects were not large enough to be detected given the small Phase 2 sample size of 13 teachers. In either case, it is safe to conclude that the commissioning of equipment with proper ventilation neither compromised comfort nor greatly enhanced it.

Satisfaction with comfort and air quality was also compared across teachers with different types of ventilation equipment within Phase 2 alone. Those with ERV systems appeared to be slightly more satisfied, but small sample sizes precluded significance testing.

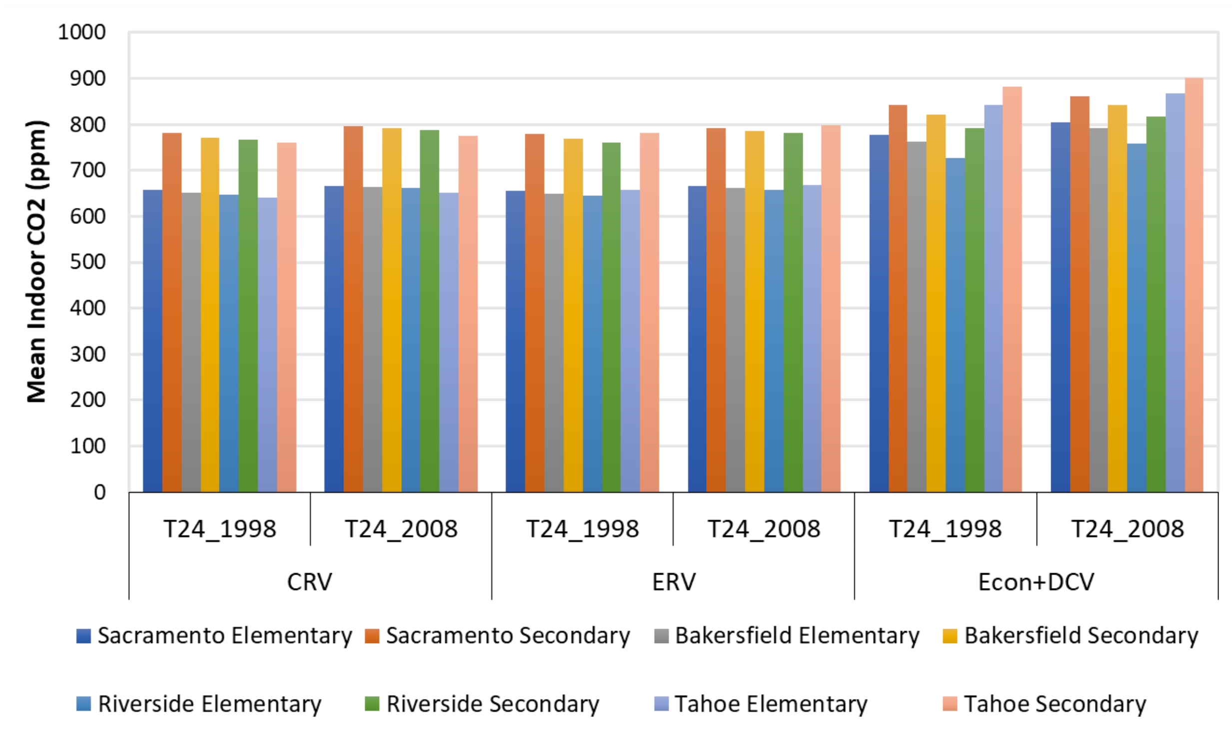
Phase 3

The EnergyPlus and CONTAM modeling results were analyzed to compare CO_2 and $PM_{2.5}$ concentrations and energy use by location, building vintage, grade level, ventilation system type, and filter type. Modeling results assumed the outdoor air CO_2 concentration was 400ppm and were compared to field results where possible.

Carbon Dioxide

Figure 25 shows the predicted indoor CO_2 concentrations for the four locations and two grade levels, averaged for all occupied hours.

Figure 25: Predicted Indoor CO_2 Mean Concentrations by Ventilation Type



Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Secondary school classrooms with higher CO_2 generation rates resulted in higher indoor CO_2 compared to elementary classrooms. Classrooms with CRV and ERV were predicted to have very similar indoor CO_2 concentrations because they were modeled to have the same ventilation rates. This result differed from the field study, which showed higher indoor CO_2 concentrations for the ERV systems. This is because, in the field, the research team could not achieve the target 450 CFM of ventilation air for the ERV systems even with the ERV supply fans set to the highest speed (see HVAC Equipment Selection and Installation). Classrooms with ECON-DCV were predicted to have indoor CO_2 concentrations closer to the setpoint of 1,000 ppm.

Particulate Matter ($PM_{2.5}$)

Figure 26 shows the predicted indoor $PM_{2.5}$ concentrations for the four locations, averaged for all occupied hours. Across all model scenarios, indoor $PM_{2.5}$ concentrations were lower in classrooms with MERV13 versus MERV8 filters. The mean $PM_{2.5}$ was higher in classrooms located in Bakersfield and Riverside as a result of higher outdoor $PM_{2.5}$ concentrations relative to the Tahoe and Sacramento regions.

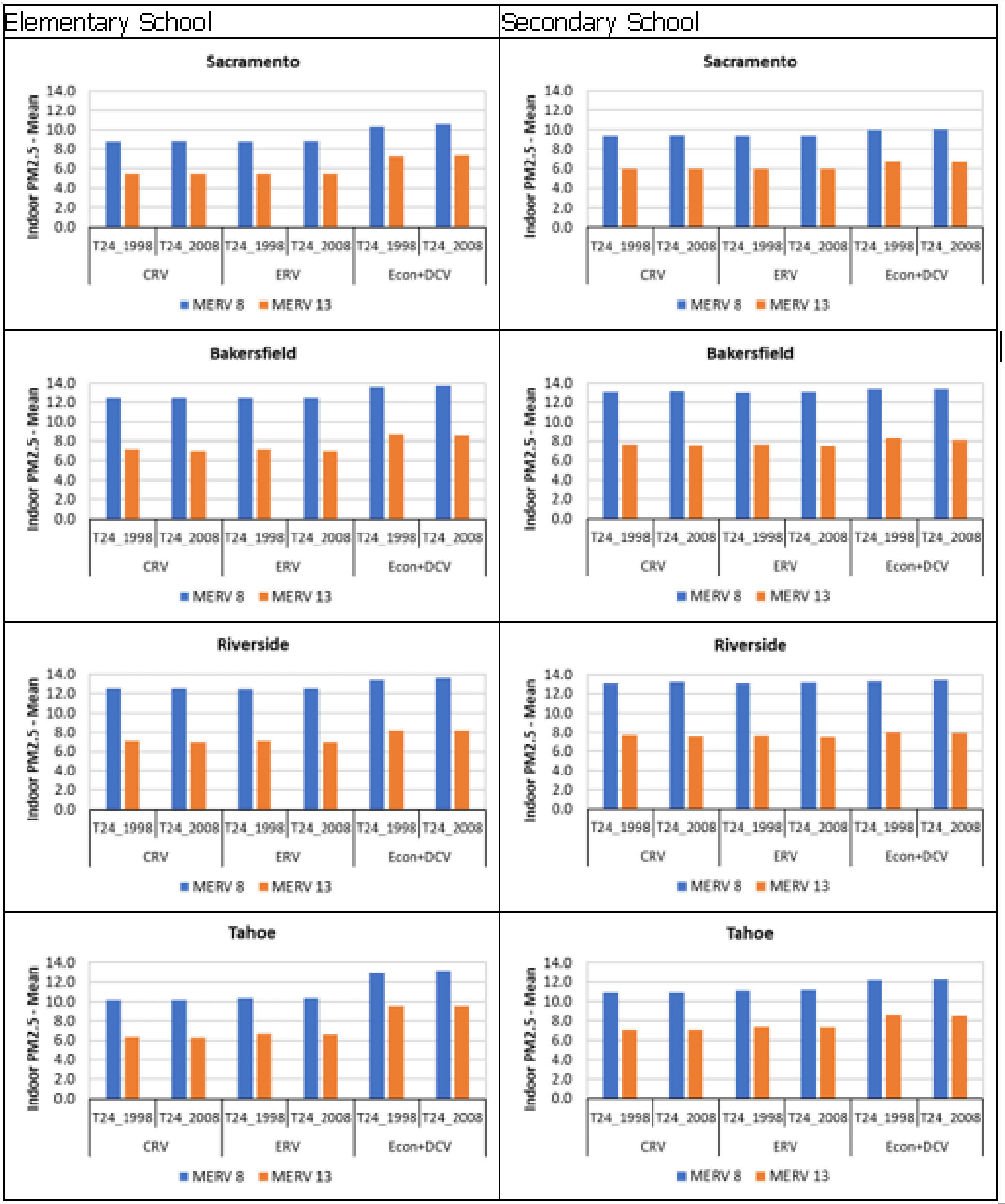
Figure 27 shows the predicted percent reduction in indoor $PM_{2.5}$ from the MERV13 filter compared to MERV8. These modeling predictions generally agree with the average reductions from MERV13 filters measured in the field study by the Plantower sensor:

- Bakersfield Region Elementary School: leaky envelope, 45 percent reduction averaged for all ventilation system types measured in field, compared to predicted 41 percent reduction
- Sacramento Region High School: less leaky envelope, 41 percent reduction averaged for all ventilation system types measured in field, compared to predicted 35 percent reduction

One possible reason for the slightly higher measured reduction is because filter loading is expected to increase filter performance. The model did not account for this and the performance was modeled to be constant over time.

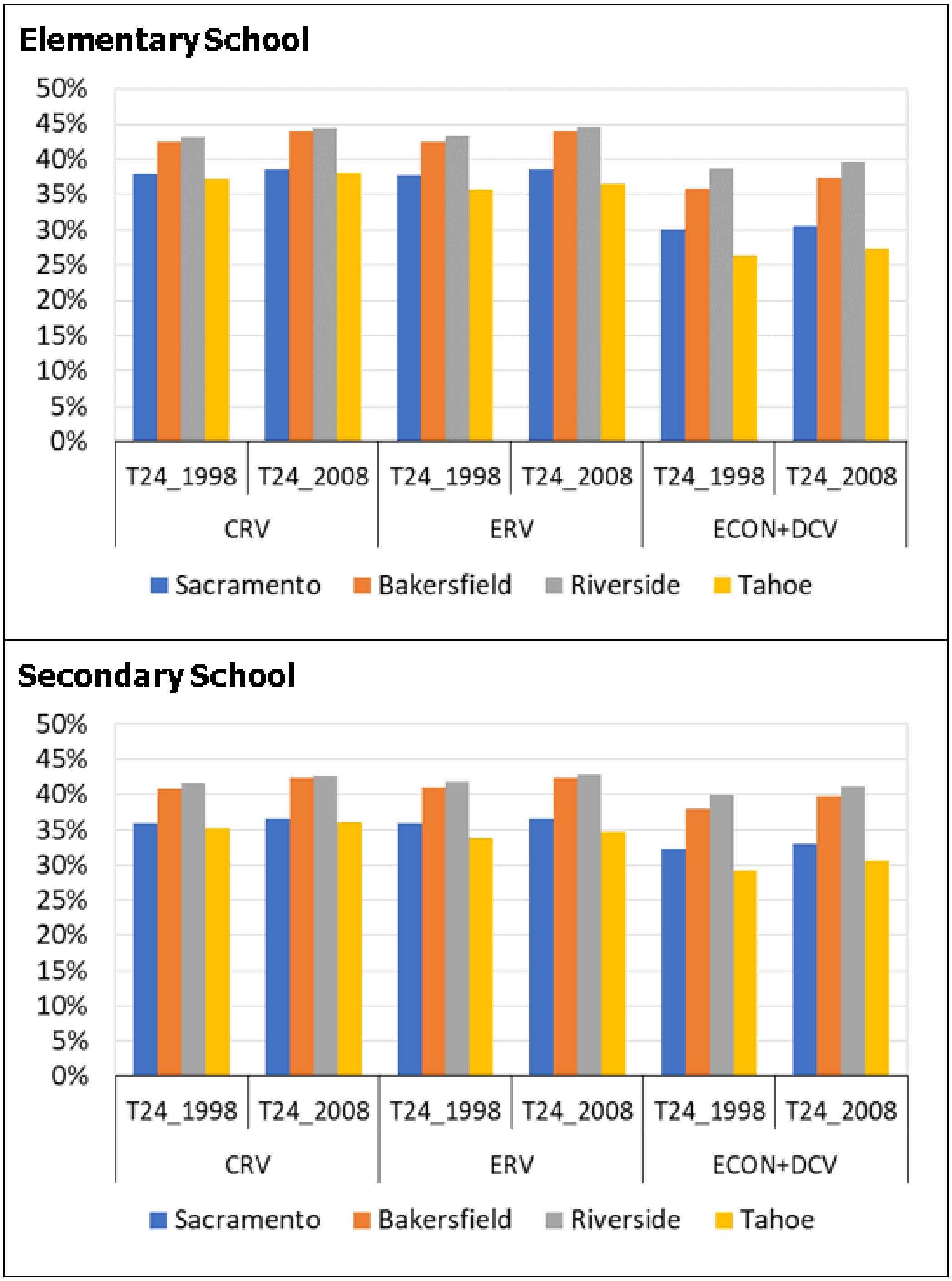
The use of MERV13 air filters was predicted to substantially reduce the number of days with indoor mean $PM_{2.5}$ greater than the annual average ambient standard of 12 $\mu g/m^3$ (Table 22 and Table 23). At three of the four locations (Sacramento, Riverside, and Tahoe), the number of predicted days with indoor mean $PM_{2.5}$ greater than 12 $\mu g/m^3$ was reduced by about 90 percent when using MERV13 air filters. Bakersfield was the most challenging location in terms of maintaining days with indoor mean $PM_{2.5}$ below 12 $\mu g/m^3$. Even with the use of MERV13 air filters, 22 school days were predicted to exceed the 12 $\mu g/m^3$ level. This is because Bakersfield has the highest outdoor $PM_{2.5}$ concentrations (as measured in 2018), compared to the other modeled locations (see Figure 20).

Figure 26: Predicted Indoor $PM_{2.5}$ Annual Mean Concentrations in Four Locations



Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Figure 27: Percent Reduction in Indoor $PM_{2.5}$ Mean



Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Table 22: Number of Elementary School Days with Indoor $PM_{2.5}$ Over 12 µg/m3

	CRV T24_1998	CRV T24_2008	ERV T24_1998	ERV T24_2008	ECON+ DCV T24_1998	ECON+ DCV T24_2008
Sacramento*, MERV 8	23	22	24	24	34	35
Sacramento*, MERV 13	1	0	1	0	4	3
Bakersfield, MERV 8	63	63	63	63	79	82
Bakersfield, MERV 13	20	16	21	16	31	27
Riverside, MERV 8	80	80	79	79	99	102
Riverside, MERV 13	7	5	7	5	18	11
Tahoe, MERV 8	53	52	57	58	104	107
Tahoe, MERV 13	1	1	3	1	22	19

***2018 November excluded from Sacramento results due to the unusual effects from wildfire.**

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Table 23: Number of Secondary School Days with Indoor $PM_{2.5}$ Over 12 µg/m3

	CRV T24_1998	CRV T24_2008	ERV T24_1998	ERV T24_2008	ECON+ DCV T24_1998	ECON+ DCV T24_2008
Sacramento*, MERV 8	25	26	24	27	31	31
Sacramento*, MERV 13	2	1	1	1	4	3
Bakersfield, MERV 8	66	66	66	66	72	74
Bakersfield, MERV 13	22	19	22	19	25	23
Riverside, MERV 8	89	90	89	89	93	93
Riverside, MERV 13	12	8	11	8	12	10
Tahoe, MERV 8	67	68	71	72	88	87

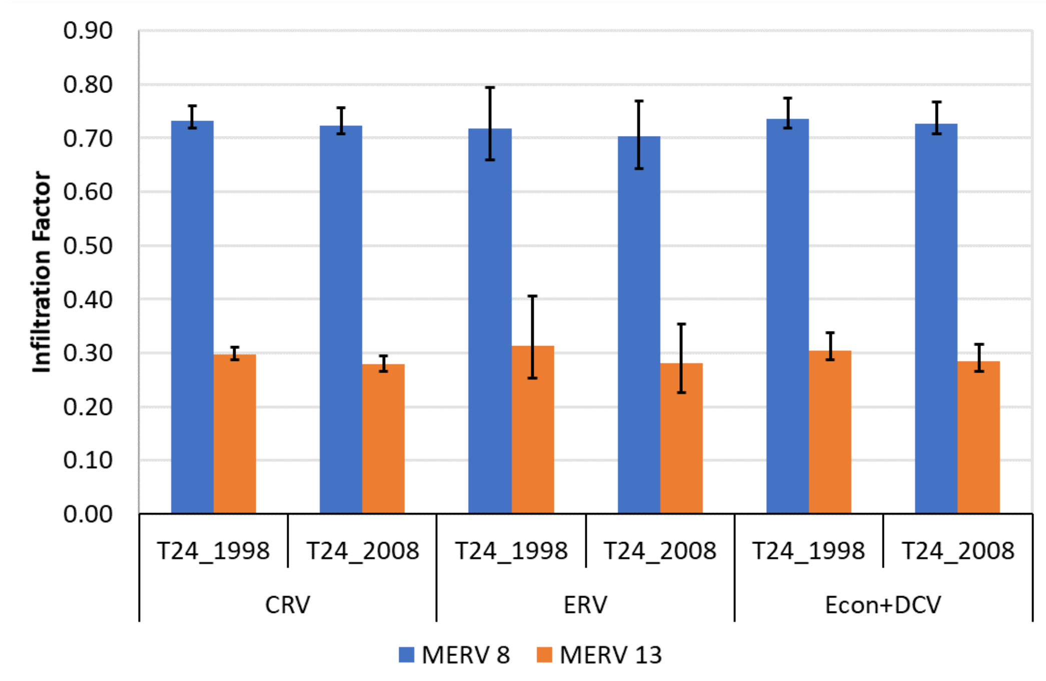
***2018 November excluded from Sacramento results due to the unusual effects from wildfire.**

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Least-square linear regression was used on the simulation results to calculate the intercept and infiltration factor to relate outdoor to indoor $PM_{2.5}$ levels[7]. The infiltration factor represents the percentage of outdoor $PM_{2.5}$ that enters the classroom. The intercept represents the baseline indoor $PM_{2.5}$ level when the infiltration factor is zero. Figure 28 shows the average infiltration factors for each building vintage, ventilation type, and filter type.

The infiltration factor calculated from the simulation results of $PM_{2.5}$ were slightly higher than the measured results from the three IEQ intensive monitoring periods in Phase 2 (measured result of 0.37 – 0.55 for MERV8 filters and 0.14 – 0.27 for MERV13 filters). However, in terms of the relative differences between MERV 8 and MERV 13 classrooms, simulation results agreed well with measured data. The measured data showed an average reduction of 58 percent in the infiltration factor between classrooms that used MERV 13 compared to MERV 8 air filters. Similarly, the simulation results showed an average reduction of 59 percent in the infiltration factor.

Figure 28: Infiltration Factor Relating Indoor and Outdoor $PM_{2.5}$



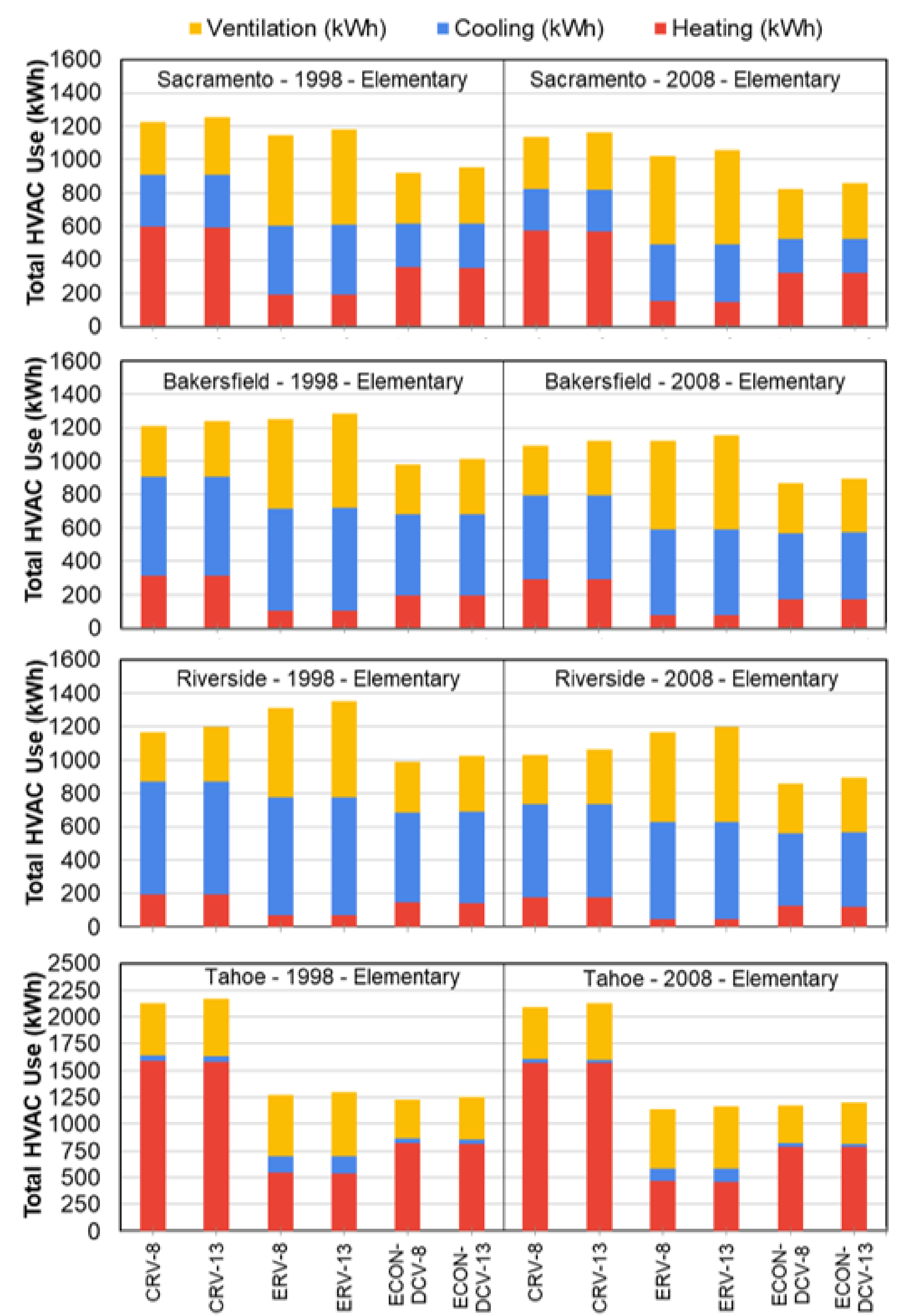
Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Electricity Consumption

Total predicted annual HVAC energy use during school hours for all 96 simulations is shown for the elementary school (Figure 29) and the secondary school (Figure 30). The six bars on the left side of each chart are for the 1998 vintage classroom, and the bars on the right side are for the 2008 vintage classrooms. Scenarios are identified first by their ventilation system identifier (CRV, ERV, or ECON-DCV), then by the HVAC filter MERV rating, 8 or 13. Overall, the modeling results showed that:

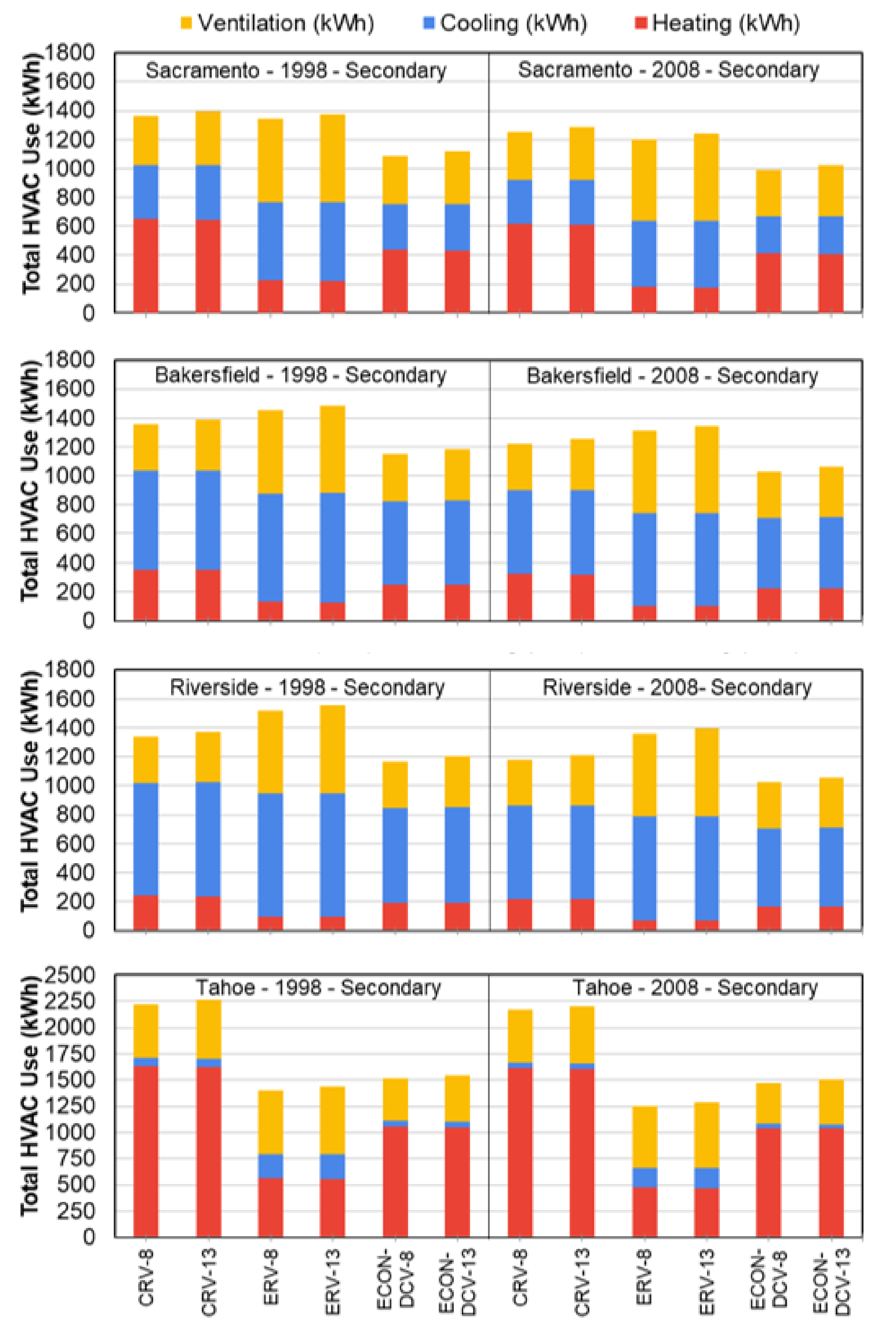
[7] Indoor $PM_{2.5}$ = Intercept + Infiltration Factor x Outdoor $PM_{2.5}$

Figure 29: Modeled HVAC Electricity Use for Elementary School in Four Locations



Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

Figure 30: Modeled HVAC Electricity Use for Secondary School in Four Locations



Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

- MERV13 filters increased HVAC energy consumption by 29 – 38 kWh annually, which was 2 percent to 4 percent of the total electricity consumed by the HVAC system during school hours.

- The ECON-DCV system had the lowest energy consumption in Sacramento, Bakersfield, and Riverside. In Tahoe in some scenarios, the ERV system used slightly less electricity than the ECON-DCV system.
- Percent savings of ERV or ECON-DCV systems compared to CRV varied significantly by climate and grade level, but not by building vintage or filter type (Table 24). Bakersfield and Riverside, savings were negative for the ERV system, due to the extra electricity used by the ERV and lack of economizer for free cooling.
- While single-speed induction motors were not modeled, field data show that using ECM motors contributes an additional savings of 300 kWh annually that are not accounted for in Table 24. Adding 300 kWh to the total savings for the ECON-DCV system equates to 28 percent to 57 percent savings compared to a minimum efficiency system.

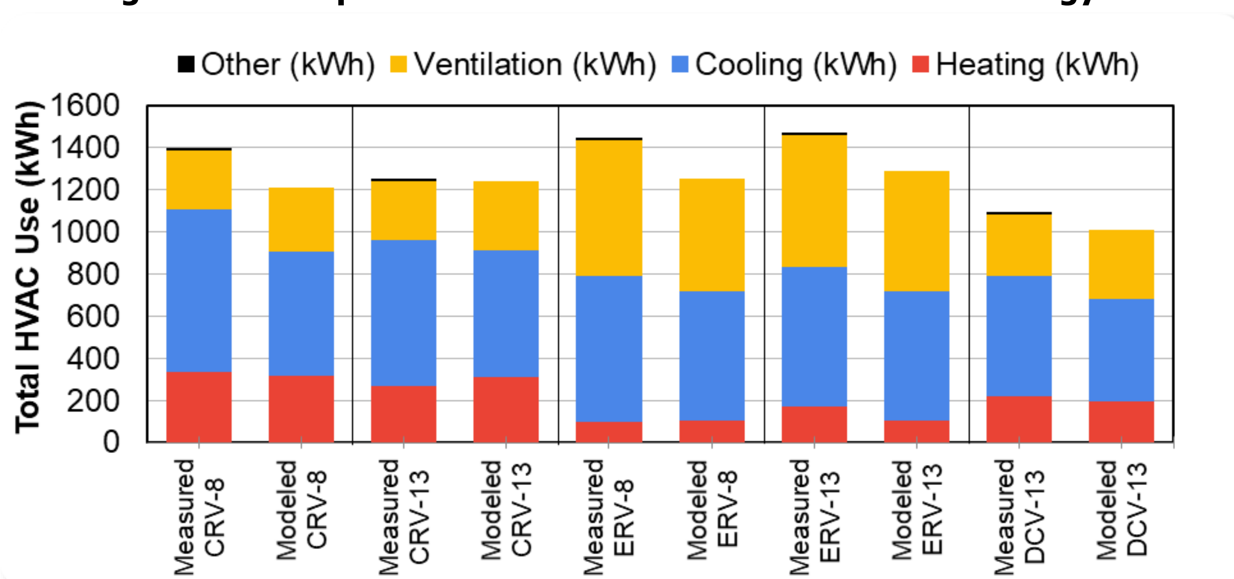
Table 24: Savings of ERV and ECON-DCV Savings Compared to CRV

	ERV – Elementary kWh (percent)	ERV – Secondary kWh (percent)	ECON-DCV – Elementary kWh (percent)	ECON-DCV – Secondary kWh (percent)
Sacramento	95 (8%)	34 (3%)	305 (26%)	268 (20%)
Bakersfield	–40 (-3%)	–92 (–7%)	228 (20%)	199 (15%)
Riverside	–143 (–13%)	–183 (–14%)	172 (16%)	163 (13%)
Tahoe	910 (43%)	870 (39%)	916 (43%)	705 (32%)

Source: Indoor Environment Group, Lawrence Berkeley National Laboratory

A comparison between the measured field data and simulation models was performed for Bakersfield (Figure 31).

Figure 31: Comparison of Modeled and Measured HVAC Energy Use



Source: Western Cooling Efficiency Center, University of California at Davis

It should be noted, however, that even though the models are broadly based on the field study classrooms, they are not calibrated to have identical load profiles. There are many factors that affect the classroom energy use that could not be accurately or cost effectively measured, such as day-to-day variations in occupancy levels, indoor setpoints, and use of equipment that generates interior loads.

The field measurements and models agree that the ERV increases overall HVAC electricity use in this climate. While the ERV reduced heating energy use, it did not save energy overall because of increased electricity use for ERV components. Additionally, the ERV energy use for ventilation in the field is greater than the model. Since there was a significant difference between the systems at the two sites, the research team used the average electricity consumption from ERVs in Sacramento for the model (Table 20).

CHAPTER 4: Conclusions and Recommendations

Problems with HVAC installation and maintenance were prevalent in the classrooms visited in Phase 1 of the project. Classrooms were frequently non-compliant with ventilation standards, which resulted in high CO_2 levels. Facilities staff weighed multiple factors in selecting the HVAC technologies to install but provided little oversight to the installation and maintenance of equipment, making them largely unaware of the problems the study documented. Teacher satisfaction with classroom heating and cooling was relatively low. Strict thermostat policies aimed at saving energy and money appeared to yield discomfort and disruption among students and teachers.

The Division of the State Architect (DSA), which has jurisdiction over building code enforcement in K-12 schools, and the California Energy Commission could consider ways to improve compliance with the ventilation requirements of California's 2016 Building Energy Efficiency Standards (Title 24, Part 6). Recommendations are for regulatory agencies to:

1. Train DSA inspectors in Title 24 ventilation requirements.
2. Require DSA oversight for HVAC replacements, which currently often qualify for an exemption under a procedure called "exempt concurrence."
3. Require certified technicians to complete acceptance testing, which will become required by Title 24 under the "Mechanical Acceptance Test Technician" program after the number of certified technicians passes a required threshold.
4. Require CO_2 sensors and/or demand control ventilation in classrooms in a future revision of Title 24.
5. Create a program with funding to improve ventilation rates in existing classrooms with existing equipment. This could include installing CO_2 sensors in existing classrooms and then retro-commissioning ventilation systems in classrooms with an identified ventilation problem.

In addition, recommendations for school districts are to:

1. Install demand control ventilation systems, or, at a minimum, thermostats with CO_2 sensors, to detect ventilation problems immediately.
2. Install and use energy management systems to set ventilation schedules and report high CO_2 levels to district facilities staff if CO_2 sensors are present in classrooms.
3. Allow teachers control over their heating and cooling setpoints for their thermostat, within a reasonable range.
4. Educate teachers on the need for continuous fan operation during occupied hours. Many teachers did not understand that the fan provides needed ventilation.

In addition to better oversight of installation and commissioning of ventilation systems, in Phase 2 and 3 researchers developed recommendations when purchasing new HVAC equipment:

1. High efficiency variable speed motors, which reduce fan energy by approximately 50 percent
2. Compressors without crankcase heaters, or with crankcase heater controls to reduce their operation, unless the manufacturer of the HVAC equipment specifically requires a crankcase heater for long-term compressor performance
3. Economizers with demand control ventilation controls to modulate the outdoor damper based on outdoor air conditions and indoor CO_2 levels (additional HVAC savings of 13 – 43 percent)
4. MERV13 filters, particularly in areas where outdoor particulates exceed recommended exposure levels for $PM_{2.5}$, to reduce indoor exposure to $PM_{2.5}$ by 40 percent or more.

The ERVs tested in this project were not recommended for most California climates. Because the analysis of ERV performance is climate specific, the results presented in this report are specific to California. It may be possible to develop an ERV that provides heat recovery benefits with less electricity consumption and the ability to bypass heat recovery and allow use of "free cooling." This is a difficult task because of the limited space available inside packaged HVAC systems and the cost associated with all the components. However, ERV technology would be more favorable in California under these circumstances.

Finally, the research team recommends further product development and research in the following areas:

1. Reduction of standby power in HVAC systems, including ways to reduce electricity use by compressor crankcase heaters
2. Standardized test methods to objectively compare and report the performance of demand control ventilation products and control algorithms

CHAPTER 5: Knowledge Transfer

During the project, the research team engaged in numerous activities to transfer the experimental results, knowledge gained, and lessons learned to the public and key decision makers. The team made shared project results at the following events:

- Behavior, Energy and Climate Change Conference, October 17, 2017
- Green Schools Summit, April 10, 2018
- New Building Institute Webinar, June 6, 2018
- Green Technology Webinar, June 22, 2018
- California School Boards Association Annual Education Conference; November 30, 2018 and December 5, 2019.
- CEC's EPIC Symposium (Poster Session), February 19, 2019
- UC Davis Energy and Efficiency Annual Forum (Poster), April 16, 2019
- Coalition for Adequate School Housing Conference, April 30, 2019

Written materials about the project have been disseminated. The WCEC website features a case study highlighting the results of the work. The project was also featured in the 2018 Annual Research Highlights (distribution of approximately 400) and WCEC monthly newsletters.

A technical paper documenting the results of indoor environmental quality monitoring in Phase 1 was published in the academic journal *Building and Environment*. A second paper on the (poor) reliability of occupants' ability to detect CO_2 is in process.

The research team convened numerous meetings with various school districts, the Division of the State Architect, Commissioner Andrew McAllister of the CEC, and CEC staff to explore existing and potential policies regarding oversight of installation and commissioning.

All reports resulting from this project will be made publicly available on the WCEC website (with approximately 1500 visitors annually), which also provides access to a case study and webinar.

Finally, analysis of the data in Phase 2 revealed that the controller on the demand control ventilation units was too slow to respond to the normal occupancy changes that occur in school settings. WCEC is working with the manufacturers to advocate for ensuring that HVAC equipment ships with the controller configured with a damper response speed appropriate to the range of damper movement required.

CHAPTER 6: Benefits to Ratepayers

Providing low-energy and robustly workable ventilation solutions will enable the improvements in HVAC energy efficiency needed to achieve California's goals of 50 percent reduction in energy use of existing schools and new carbon neutral schools while also protecting student health and learning. Ensuring adequate ventilation and reducing in-school exposure to $PM_{2.5}$, ozone, black carbon, and formaldehyde will lead to reduced illness and absence, resulting in improved funding for schools and improved performance and learning for students. This project demonstrates some of the benefits of installing energy efficient HVAC systems that provide code-compliant ventilation.

In isolation, raising ventilation rates to meet code-mandated minimums using the HVAC equipment currently installed in California classrooms would lead to an increase in HVAC energy use (Bennett et al., 2012; Dutton et al., 2015). However, advanced HVAC equipment can mitigate that perverse effect. Field testing and modeling of HVAC technologies from this study determined that variable speed motors for indoor blowers, two-speed compressors, economizers, and demand control ventilation technology combined can save 28 percent to 57 percent of HVAC electricity use, depending on climate. This recommended HVAC package is suitable for all of California's climates.

According to the 2006 California Commercial End-Use Survey, schools use 3,322 GWh annually with 30 percent consumed by HVACs. Assuming that 10 percent of California schools adopt these efficient technologies over the next 10 years, a 40 percent savings (central estimate, based on 28 percent to 57 percent savings modeled) would result in an aggregate reduction in energy use by 220 GWh, which is roughly equivalent to 63,000 metric tons of CO_2.

Mendell et al. (2013) estimated that increasing ventilation rates in California classrooms from the current estimated average of 4 L/s/person to the required 7.1 l/s/person would reduce illness-related absence by 3.4 percent and increase attendance-linked funding to schools by $33 million annually. The small increase in energy costs, estimated to be approximately $4 million if no upgrades are made to HVAC equipment, would further be reduced if the recommended HVAC package from this study is installed.

One estimate of the benefits from improved filtration is developed from the work of Chan et al. (2015), the lead author who also led the indoor environmental quality analysis for this study. Chan et al. estimated a national health burden of 1,100 disability-adjusted life years (DALYs) lost each year from $PM_{2.5}$ exposures in schools. They estimated that improved filtration could reduce the health cost by roughly one-third (360 DALYs per year). Considering that California has roughly 12 percent of the nation's K-12 population and using $120,000 as an estimated value of a DALY,[8] roughly $5 million of annual health benefits from reduced $PM_{2.5}$ exposure are expected by improving filtration to schools.

[8] Estimated based on a central estimate of $2.6 million (in 2008 US$) for a value of a statistical life (Mrozek and Taylor 2002) and an average loss of 22 DALYs per premature death.

LIST OF ACRONYMS

Term	Description
ARB	Air Resources Board
AQMIS	Air Quality and Meteorological Information System
ASHRAE	American Society of Heating Refrigeration and Air Conditioning Engineers
BAK	Bakersfield Region Elementary School
California ARB	California Air Resources Board
CFM	cubic feet per minute
CRV	commercial room ventilator
DALY	disability-adjusted life years
DCV	demand control ventilation
DSA	Department of State Architect
ECM	electronically commutated motor
ECON	Economizer
EIR	energy intensity ratio
EMS	energy management system
ERV	energy recovery ventilation
FMI	functional mockup interface
HVAC	heating, ventilation, and air conditioning
IEQ	indoor environmental quality
LBNL	Lawrence Berkeley National Labs
LED	light emitting diode
MERV	minimum efficiency reporting value
NIST	National Institute of Standards and Technology
PM	particulate matter
PSC	permanent split capacitor
RTU	rooftop packaged units
SAC	Sacramento Region High School
SVPU	single vertical package unit
U.S. EPA	United States Environmental Protection Agency
VOC	volatile organic compound
WCEC	Western Cooling Efficiency Center

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APPENDIX A: Phase 1 Ventilation Rate Calculation

This appendix describes how the ventilation rate was calculated for the 104 classroom surveyed during Phase 1 of the project.

Ventilation Rate Determination

All analyses of classroom ventilation rates and thermal comfort are limited to times when the classroom was occupied on weekdays and during school hours, according to the bell time schedule. CO_2 data suggested that some classrooms were routinely occupied for longer hours, such as during after-school activities. These additional occupied hours were not considered in our analyses, even though it is just as important to provide adequate ventilation during these times.

Equation A-1 is the mass balance model used to estimate ventilation rate per person using the indoor equilibrium and the outdoor CO_2 concentration. The equation assumes that CO_2 is generated for a sufficiently long time at a constant rate to reach an indoor equilibrium concentration in the classroom. Even though the steady-state condition is often not reached in classrooms because of variable occupancy, the ventilation rate calculated using Eq. 1 is a common metric used to indicate if a ventilation standard is met (Fisk 2017). The daily maximum value of a 15-minute moving average of indoor CO_2 concentration is used to estimate the indoor equilibrium value.

$$V_o = \dot{E}/(C_{15max} - C_o) \qquad \text{Eq. A-1}$$

Where,

V_o: ventilation rate per person (L/s-person)

$\dot{E}$: CO_2 generation rate per person (L/s-person)

C_{15max}: daily maximum value of 15-minute moving average classroom CO_2 concentration (ppm)

C_o: outside CO2 concentration (ppm), assumed as 400 ppm.

Batterman (2017) provided values of E for each grade level from pre-K (0.0025 L/s-person) to grade 12 (0.0057 L/s-person). E is determined for each classroom using grade(s) reported from the teacher survey and information gathered from the site visit.

Classroom ventilation rate (L/s) and air change rate (h^{-1}) were calculated using the number of students reported from the teacher survey and the volume of each classroom. If the teacher survey did not provide information on the number of students, the number of student chairs observed during the site visit was used to estimate the number of students.

APPENDIX B: Site Descriptions

Two schools were selected for the study, one located in the Bakersfield region and one located in the Sacramento region (Table B-1). These regions were chosen for the significant heating and cooling loads and distinct differences in outdoor air quality (**Error! Reference source not found.**). Both sites had a mix of portable classrooms and permanent construction. Portable classrooms with wall-mounted HVAC systems - also called single packaged vertical units (SPVU) - were selected for HVAC retrofits for the following reasons:

1. 35% of classrooms in California are portables [5].
2. Phase 1 of the project identified that portable classrooms are more likely to have ventilation and thermal comfort problems.
3. Portable classrooms are highly standardized, so solutions and recommendations from this project are replicable and scalable without customized engineering solutions.
4. Modification and/or replacements of roof top units were challenging to accomplish within the project timeline because increasing the weight of rooftop equipment requires a structural review process managed by the Department of the State Architect.

Table B-1: Participating School Sites

Site Name*	Location	Type	Construction Type
SAC	Sacramento Region	High School	Portable
BAK	Bakersfield Region	Elementary	Portable

***Nicknames assigned for clarity and anonymity in this report.**

Sacramento Region High School

At the Sacramento region high school (SAC), the study included seven portable classrooms used for grades 10-12. The room occupancy varied by period. Each room was occupied 4-7 periods per day (Table B-2), and the number of students per period varied from 20 to 36. Six classrooms had 1 teacher, while Classroom 4 had a different teacher in the morning and afternoon.

The classrooms were arranged in a single row. The year of construction and manufacturer is unknown. Each door was located on the south face and the HVAC unit (before and after replacement) was wall-mounted on the north face. There were two 2′x8′ double-paned operable windows on the north face and two 4′x8′ double-paned operable windows on the south face. Each classroom was 30′ wide by 32′ long with 960 ft^2 of floor area. The ceiling was vaulted, measuring 7.75′ high at the lowest point and 15.5′ at the highest point. There was no supply air ducting; the supply and return grills were located on the north wall. Each classroom had 18 2′x′4 LED dimming light fixtures with a maximum output of 33W each, for a maximum lighting power density of 0.6 W/ft^2. Classrooms 1-4 were carpeted and classrooms 10-12 had vinyl flooring.

Table B-2: Sacramento Region classroom list

Site Name	Class ID	Grade Levels	# of Class Periods per day	# of Students
SAC	1	10-12	4	Mean=29.5, Min=22, Max=33
SAC	2	10-12	5	Mean=31.2, Min=21, Max=36
SAC	3	10-12	5	Mean=32.4, Min=28, Max=36
SAC	4	10-12	7	Mean=32.0, Min=20, Max=36
SAC	10	10-12	5	Mean=32.2, Min=30, Max=34
SAC	11	10-12	5	Mean=33.4, Min=27, Max=37
SAC	12	10-12	6	Mean=33.5, Min=30, Max=36

Bakersfield Region Elementary School

At the Bakersfield region school, the study included six portable classrooms. The classrooms were used for grades 1-3 and had 20-24 students and 1 teacher (Table B-3) during school hours. Unlike the high school site, room occupancy did not vary much throughout the school day.

The classrooms were arranged in a single row and were constructed in the year 2000 by Pacesetter Industries. Each door was located on the west face and the HVAC unit (before and after replacement) was wall-mounted on the east face. There were two 4'x8' double-paned operable windows, one on the east and one on the west face. Each classroom was 24' wide by 40' long with 960 ft^2 of floor area. The ceiling height was 8.5' with supply air ducts located above the drop ceiling. There were two supply registers spaced equally along the length of the classroom. There were ten 2'x'4 lighting troffers with four T8 lamps in each, for an estimated lighting power density of 1.3 W/ft^2. All rooms were carpeted.

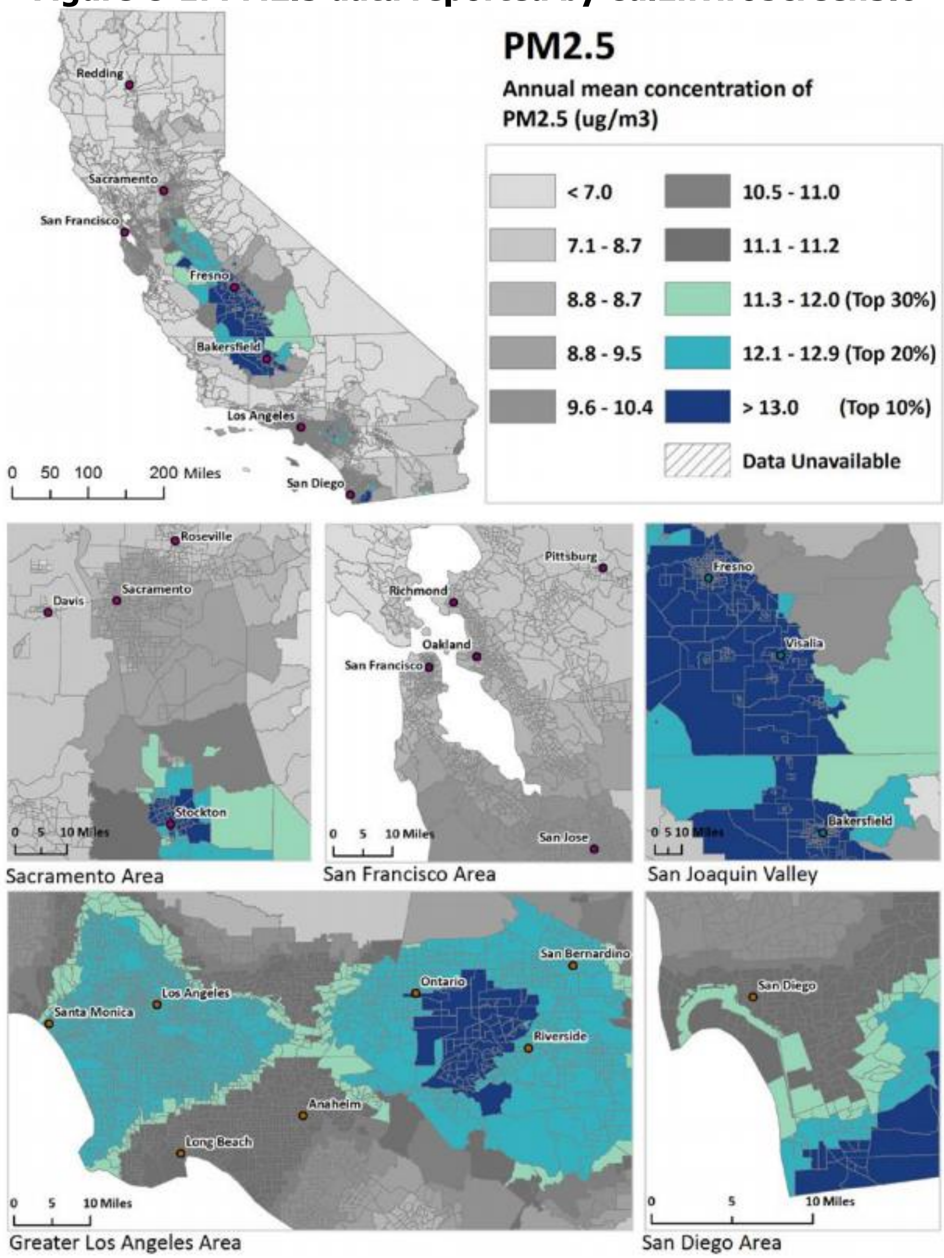
Table B-3: Bakersfield classroom list

Site Name	Class ID	Grade Level	# of Students
BAK	23	3	24
BAK	24	2	23
BAK	26	3	25
BAK	27	1	20
BAK	28	2	23
BAK	29	2	22

APPENDIX C:
PM2.5 distribution by location

PM2.5 is a measure of fine particle pollution (2.5 micrometers or less in diameter) that has significant health consequences at elevated levels. PM2.5 data reported by CalEnviroScreen 3.0 is shown in Figure C-1. PM2.5 levels are highest in Los Angeles and Riverside counties, south of San Diego, and the Central Valley, which includes the areas surrounding Stockton, Fresno, Visalia, and Bakersfield.

Figure C-1: PM2.5 data reported by CalEnviroScreen3.0



APPENDIX D: HVAC Equipment Selection and Installation

The HVAC replacements involved selecting and installing heating and cooling equipment, ventilation equipment, air filters, and control systems. The research team dictated selection of the first three to ensure the research aims could be met, while the control systems and thermostat settings were determined by the school districts. Details are described below.

Equipment Selection

Both schools selected for the study were in the process of replacing their HVAC equipment with newer Bard units. UC Davis worked with Bard, a manufacturer of SVPUs, to select specific upgrades to the schools' orders to facilitate comparisons across equipment. The upgrades were provided by Bard at no cost to the district. A summary of all installed equipment is provided is shown in Table D-1 (Sacramento) and Table D-2 (Bakersfield) with details provided in subsequent sections.

Table D-1: Sacramento region wall-mount HVAC unit equipment by classroom

Room #	HVAC Compressor/ Fan Type	HVAC Ventilation Type	HVAC Model #	Filter MERV Rating	Delta Thermostat Model #
2-WG-CRV-MERV8	WG: Single-speed scroll compressor, PSC blower motor	Commercial Room Ventilator[9]	W36G*ANAEX4XXH	8	eZNS-T100 with CO2
3-WGS-CRV-MERV8	WGS: Two-speed scroll compressor, ECM blower motor	Commercial Room Ventilator[9]	WG3SANAEX4XXH	8	eZNS-T100 with CO2
12-WGS-CRV-MERV13	WGS: Two-speed scroll compressor, ECM blower motor	Commercial Room Ventilator[9]	WG3SANAEX4XXH	13	eZNS-T100 with CO2
1-WGS-ERV-MERV8	WGS: Two-speed scroll compressor, ECM blower motor	Energy Recovery	WG3SANARX4XXH	8	eZNS-T100 with CO2
10-WGS-ERV-MERV13	WGS: Two-speed scroll compressor, ECM blower motor	Energy Recovery	WG3SANARX4XXH	13	eZNS-T100 with CO2
4-WGS-ECON-DCV-MERV8	WGS: Two-speed scroll compressor, ECM blower motor	Economizer and Demand Control Ventilation	WG3SANAEX4XXH	8	eZNS-T100 with CO2

9 Economizer hardware was configured to operate as a commercial room ventilator.

Room #	HVAC Compressor/ Fan Type	HVAC Ventilation Type	HVAC Model #	Filter MERV Rating	Delta Thermost at Model #
11-WGS-ECON-DCV-MERV13	WGS: Two-speed scroll compressor, ECM blower motor	Economizer and Demand Control Ventilation	WG3SANAEX4XXH	13	eZNS-T100 with CO2

Table D-2: Bakersfield region HVAC equipment by classroom

Room #	HVAC Compressor/ Fan Type	HVAC Ventilation Type	HVAC Model #	Filter MERV Rating	Pelican Wireless Thermostat Model #
27-TS-CRV-MERV8	TS: Two-speed scroll compressor, ECM blower motor	Commercial Room Ventilator	T48SA04VP4	8	TS250 with CO2
24-TS-CRV-MERV13	TS: Two-speed scroll compressor, ECM blower motor	Commercial Room Ventilator	T48SA04VP4	13	TS250 with CO2
26-TS-ERV-MERV8	TS: Two-speed scroll compressor, ECM blower motor	Energy Recovery	T48SA04RP4	8	TS250 with CO2
29-TS-ERV-MERV13	TS: Two-speed scroll compressor, ECM blower motor	Energy Recovery	T48SA04RP4	13	TS250 with CO2
28-TS-ECON-DCV-MERV8	TS: Two-speed scroll compressor, ECM blower motor	Economizer and Demand Control Ventilation	T48SA04SP4XXE	8	TS250 with CO2
23-TS-ECON-DCV-MERV13	TS: Two-speed scroll compressor, ECM blower motor	Economizer and Demand Control Ventilation	T48SA04SP4XXE	13	TS250 with CO2

Heating/Cooling System Selection

In the Sacramento region school, the school was in the process of replacing natural gas heating/electric air conditioning packaged units with Bard's lowest-efficiency equipment option, the WG series (**Error! Reference source not found.**). For the study, the baseline WG model was installed in one classroom and six classrooms were upgraded to WGS series (**Error! Reference source not found.**) equipment. The main improvements with the WGS series upgrade were:

1. A two-speed compressor for cooling, and
2. An electrically commutated motor (ECM) for the indoor blower.

The ECM motor has two advantages over a permanent split capacitor (PSC) motor. First, the efficiency of the ECM - in terms of airflow delivered versus power consumed - is higher. Second, the ECM is programmed to maintain a fixed airflow rate for each equipment mode (i.e., ventilation, cooling 1, cooling 2, and heating) even with varying resistance in the airflow delivery system (e.g. due to differences in duct work, filters, and filter loading).

In the Bakersfield region school, the school was in the process of replacing electric heat pumps with Bard's high efficiency TS series equipment with a two-speed compressor and an ECM indoor blower (Table D-3). Six classrooms were selected for the study.

Table D-3: Bard HVAC equipment specifications

Specification	Bard WG-3610	Bard WGS-3611	Bard TS-4812
Indoor blower motor	PSC	ECM	ECM
Natural gas heating input	45,000 btu/hr	50,000 btu/hr	-
Natural gas heating thermal efficiency	82%	82%	-
Stage 1 cooling capacity	-	24,000 btu/hr	27,000 btu/hr
Stage 2 cooling capacity	35,000 btu/hr	35,000 btu/hr	33,800 btu/hr
Stage 2 cooling EER[13]	10.2	11.2	11.3
Stage 1 and 2 IPLV[14]	-	14.6	14.7
Heat pump stage 1 heating capacity	-	-	22,600
Heat pump stage 2 heating capacity	-	-	33,000
Heat pump stage 1 COP at 47°F	-	-	Not reported
Heat pump stage 2 COP at 47°F	-	-	3.4

[10] Bard Manufacturing Company. The Wall-Mount Gas/Electric. http://www.bardhvac.com/digcat/S3364_TechDoc_CD/TechDoc-PDF/S3500.pdf

[11] Bard Manufacturing Company. The Wall-Mount Step Capacity Gas/Electric. http://www.bardhvac.com/digcat/S3364_TechDoc_CD/TechDoc-PDF/S3396.pdf

[12] The wall-mount step capacity "Quiet Climate" Heat Pumps. http://www.bardhvac.com/digcat/S3364_TechDoc_CD/TechDoc-PDF/S3447.pdf

[13] EER stands for Energy Efficiency Ratio, a rating that is certified in accordance with ARI Standard 390-2003. All ratings are based on fresh air intake being 100% closed.

[14] While the EER rating is measured at an outdoor air temperature of 95°F, the Integrated Part Load Value (IPLV) rating is measured at a lower outdoor air temperature (80°F) that is expected to occur at part load conditions.

APPENDIX E: Phase 2 Airflow Rate Measurements

Overview

The following sections describe how the research team made the various airflow measurements during phase 2 of the project.

Supply Air Flow Rate Measurements

The supply air flow rate in each classroom was measured using a flow capture hood (Alnor model #EBT731). The accuracy of the flow hood is ±3% of the reading. In the Sacramento region school, the supply air flow was measured at the single supply air register. In the Bakersfield region school, the air flows of each supply air register were measured and summed. The supply air flow rate was measured for each of three fan speeds (i.e., Vent, Cool 1, Cool 2). These measurements were only taken at one time during the study period with clean filters installed. Electronically commutated motors (ECMs) were used to drive the HVAC system's indoor blower in all but one classroom (2-WG-CRV-MERV8). The ECM driven indoor fan delivers a constant supply airflow, requiring increased fan power as system resistance increases with filter loading. In room 2-WG-CRV-MERV8, the indoor blower was driven by a single-speed permanent split magnet (PSC) motor. Therefore, as the system resistance increased with increased filter load, both the fan power and supply airflow rates dropped. The relationship between fan power and supply airflow for this classroom was measured at the field site and a linear relationship between the supply airflow and the cube root of the average fan power was calculated as:

Equation E-1: Relationship between fan power and supply airflow for room 2-WG-CRV-MERV8 only

$$\dot{V}_{SA} = 5709.7\sqrt[3]{P_{fan}} - 3052.5$$

Where:

$\dot{V}_{SA}$ is the supply airflow [cfm]

P_{fan} is fan power for room 2-WG-CRV-MERV8 [kW].

The measured supply air flow rates for Sacramento and Bakersfield are listed in Table E-1 and Table E-2. Each value represents the average of the measurements for the two classrooms with the same HVAC equipment type. All classrooms generally had supply air flow rates that were consistent across units and met or exceeded the manufacturer's specification.

Table E-1: Measured supply airflow rates for Sacramento region school classrooms compared to Bard Specification.

Mode	Bard Spec (WGS)	2-WG-CRV-MERV8 *	3-WGS-CRV-MERV8	12-WGS-CRV-MERV13	1-WGS-ERV-MERV8	10-WGS-ERV-MERV13	4-WGS-ECON-DCV-MERV8	11-WGS-ECON-DCV-MERV13
Vent/Cool1	800	Equation E-1	1051	1051	1006	1006	1022	1022
Heat	960	Equation E-1	1288	1288	1269	1269	1270	1270
Cool2	1100	Equation E-1	1092	1092	1044	1044	1101	1101

All numbers are cubic feet per minute (CFM). *This unit is a fixed speed motor and airflow rates were measured with clean filters. Airflow will reduce as filter loading increases.

Table E-2: Measured supply airflow rates for Bakersfield region school classrooms compared to Bard Specification.

Mode	Bard Spec	27-TS-CRV-MERV8	24-TS-CRV-MERV13	26-TS-ERV-MERV8	29-TS-ERV-MERV13	28-TS-ECON-DCV-MERV8	23-TS-ECON-DCV-MERV13
Vent	825	904	904	881	881	946	946
Cool/Heat 1	1000	1059	1059	979	979	1055	1055
Cool/Heat 2	1550	1593	1593	1551	1551	1616	1616

All numbers are cubic feet per minute (CFM)

Ventilation Air Flow Rate Measurements

A carbon dioxide tracer-gas measurement procedure was used to calculate the ventilation air flow rate for each classroom at each fan speed and three damper positions for the ECON-DCV rooms. For each HVAC system, CO_2 tracer gas was added to each empty classroom, then concentration measurements were taken at the following locations: the supply air outlet, the return inlet, the outdoor air damper inlet, and the outdoor ambient air measured approximately 30 feet from the unit. Only two high accuracy CO_2 gas analyzers were available, so each one was configured to switch between two of the four locations. Concentrations were measured for five to ten minutes while the unit operated in the desired mode. The data from each measurement location was fit with an exponential decay function, where the floor of the decay was set to the ambient CO_2 concentration. The outdoor air fraction was calculated using

Equation E-2, where the values were determined at each minute using the decay functions:

Equation E-2: Outside air fraction

$$OSA_{fraction} = \frac{RA - SA}{RA - OSA}$$

Where:

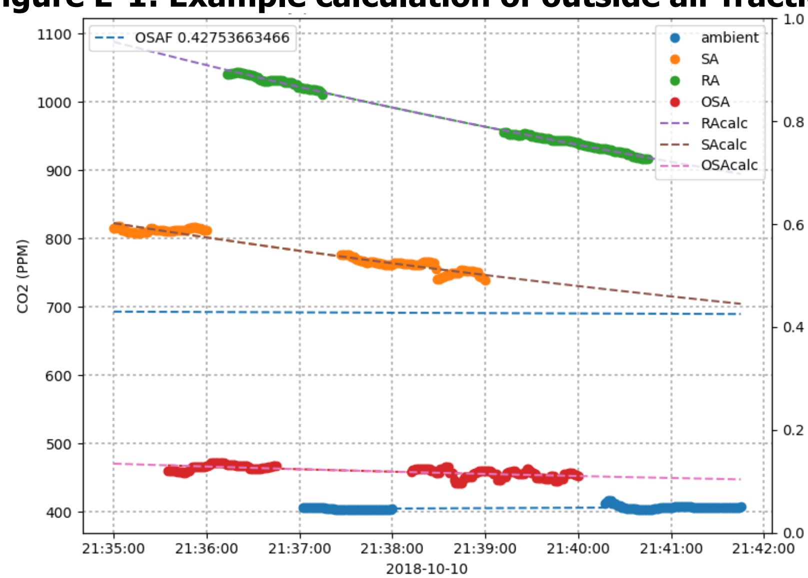
RA is the return air inlet CO_2 concentration in parts-per-million [ppm]

SA is the supply air outlet CO_2 concentration [ppm]

OSA is the outside air inlet CO_2 concentration [ppm]

The reported outside air fraction was calculated by averaging the results over each five to ten-minute test. An example calculation is shown in Figure E-1. For this operating mode, the outside air fraction was 43%. The ventilation rate was then calculated as the outside air fraction multiplied by the supply airflow. The reported ventilation air flow rates are the average of the measurements for the two classrooms with the same equipment type, except for rooms 26-TS-ERV-MERV8 and 29-TS-ERV-MERV13 because they had different exhaust fan settings on the ERV (see section Energy Recovery Ventilator and Table E-5). The results are shown for Sacramento and Bakersfield in Table E-3 and Table E-4.

Figure E-1: Example calculation of outside air fraction



For the ECON-DCV rooms, the Bakersfield region school had much higher outdoor air flow rates at the same damper position compared to the Sacramento region school (916 CFM versus 558 CFM). This is because the equipment used in Bakersfield was physically larger and had a larger outdoor air intake. This results in greater economizer functionality at the Bakersfield region school because higher outdoor airflow rates are possible.

Table E-3: Measured ventilation airflow rates for Sacramento region school classrooms.

Mode	Damper Position	2-WG-CRV-MERV8*	3-WGS-CRV-MERV8	12-WGS-CRV-MERV13	1-WGS-ERV-MERV8	10-WGS-ERV-MERV13	4-WGS-ECON-DCV-MERV8	11-WGS-ECON-DCV-MERV13
Vent/Cool1	NA	$0.425*\dot{V}_{SA}$	497	497	345	345	-	-
Heat	NA	$0.425*\dot{V}_{SA}$	629	629	407	407	-	-
Cool 2	NA	$0.425*\dot{V}_{SA}$	512	512	364	364	-	-
Vent/Cool1	30	-	-	-	-	-	194	194
Vent/Cool1	70	-	-	-	-	-	322	322
Vent/Cool1	100	-	-	-	-	-	558	558
Cool 2	30	-	-	-	-	-	240	240
Cool 2	70	-	-	-	-	-	418	418
Cool 2	100	-	-	-	-	-	738	738
Heat	30	-	-	-	-	-	208	208
Heat	70	-	-	-	-	-	351	351
Heat	100	-	-	-	-	-	570	570

All numbers are cubic feet per minute (CFM). *This unit is a fixed speed motor and airflow rates were measured with clean filters. Airflow will reduce as filter loading increases.

Table E-4: Measured ventilation airflow rates at the Bakersfield region school classrooms.

Mode	Damper Position	27-TS-CRV-MERV8	24-TS-CRV-MERV13	26-TS-ERV-MERV8	29-TS-ERV-MERV13	28-TS-ECON-DCV-MERV8	23-TS-ECON-DCV-MERV13
Vent	NA	442	442	306	381	-	-
Cool/Heat 1	NA	630	630	279	398	-	-
Cool/Heat 2	NA	897	897	316	471	-	-
Vent	19	-	-	-	-	238	238
Vent	35	-	-	-	-	391	391
Vent	69	-	-	-	-	700	700
Vent	100	-	-	-	-	916	916
Cool/Heat1	19	-	-	-	-	280	280
Cool/Heat1	35	-	-	-	-	483	483
Cool/Heat1	69	-	-	-	-	725	725
Cool/Heat1	100	-	-	-	-	1055	1055
Cool/Heat2	19	-	-	-	-	499	499
Cool/Heat2	35	-	-	-	-	953	953
Cool/Heat2	69	-	-	-	-	1196	1196
Cool/Heat2	100	-	-	-	-	1616	1616

All numbers are cubic feet per minute (CFM).

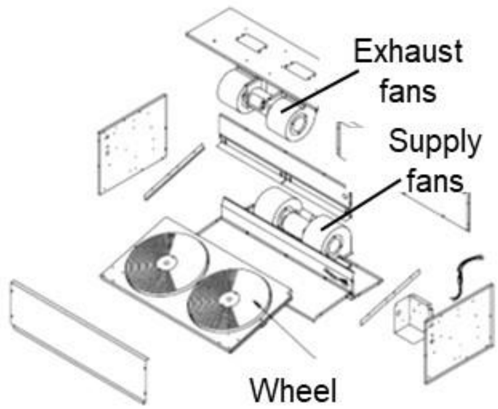
Energy Recovery Ventilator Airflow and Power Measurements

The ERV fan settings and power measurements for individual components were recorded after system commissioning and outdoor airflow measurements were taken. Each ERV system has switches to independently set the speed (i.e., low, med, high) of the supply and exhaust fans. All classrooms had the supply fan set to high and the exhaust fan set to medium to positively pressurize the classroom, except for BAK-29-TS-ERV-MERV13, which had the exhaust fan set to high. The difference in setting happened unintentionally during commissioning and was discovered partway through the study. The research team decided not to change the setting so that the performance would be consistent throughout the data analysis period. As a result, this room had higher outdoor air flow rates compared to the other ERV rooms.

The ERV in the Bakersfield region school used 50% more fan power to condition a similar amount of ventilation air when compared to the ERV classrooms in the Sacramento region school. The observable reasons for the power difference included physically larger equipment, the ERV was a different model and was constructed with two small wheels instead of one large wheel.

The ERV construction was documented to understand which air streams picked up heat from the ERV fan and wheel motor components (Figure E-2). The supply fan motor rejects heat to the supply airstream after the wheel, which is a benefit when heating ventilation air and a penalty when cooling ventilation air. The exhaust fan motor rejects heat to the exhaust airstream, which has no impact on heating or cooling of the ventilation air. The wheel motor rejects heat prior to the wheel in the supply airstream, so the impact on heating or cooling of ventilation air is minimal.

Figure E-2: ERV components



Several efforts were made to accurately measure heat transfer effectiveness of the ERV at each school. However, this proved to be a difficult task because there was limited space to isolate and measure each ERV airflow path before it mixed with another. While the minute-by-minute results were noisy, the average was consistent with the manufacturer's reported data:

- Sacramento region school: 73% effectiveness when cooling and 78% effectiveness when heating[15].
- Bakersfield region school: 66% effectiveness when cooling and 81% effectiveness when heating[16].

The heat transfer performance of the wheel is the same for heating and cooling. However, the difference in effectiveness is caused by fan and wheel motor heat in the supply airstream.

15 Bard Manufacturing Company. Energy Recovery Ventilator with Exhaust. Manual 2100-534A. 9-29-10.

16 Bard Manufacturing Company. Energy Recovery Ventilator with Exhaust. Manual 2100-513B. 3-28-12.

Table E-5: ERV settings and power consumption measurements by classroom

Motor	SAC-1-WGS-ERV-MERV8	SAC-1-WGS-ERV-MERV8	SAC-10-WGS-ERV-MERV13	SAC-10-WGS-ERV-MERV13	BAK-26-TS-ERV-MERV8	BAK-26-TS-ERV-MERV8	BAK-29-TS-ERV-MERV13	BAK-29-TS-ERV-MERV13
	Fan Setting	Power (W)	Fan Setting	Power (W)	Fan Setting	Power (W)	Fan Setting	Power (W)
Supply ERV fan	high	155	high	158	high	193	high	180
Exhaust ERV fan	med	84	med	82	med	140	high	171
ERV Wheel motor	N/A	33	N/A	33	N/A	77	N/A	73
Total		272		273		410		424

APPENDIX F: Air Filter Theoretical Impact Analysis

This appendix describes the theoretical calculation the research team used to estimate the increase in fan power due to MERV13 air filters during Phase 2 of the project.

Air Filters

Air filtration was another element controlled and tested in the study. At each school, each ventilation system type was tested using two 2” deep filters, which had a Minimum Efficiency Rating Value (MERV) of either 8 or 13 (Table F-1). Filters were manufactured by Airguard and sold by a local distributor. The manufacturer reported the initial pressure drop at an airflow of 2085 CFM, however the expected supply air flow rate was 800-1550 CFM, depending on HVAC system model and mode. The theoretical pressure drop at any airflow was calculated from the equation

Equation F-1: Theoretical pressure drop versus airflow

$$\Delta P = \alpha\, Q^n$$

Where:

ΔP is the pressure drop [pa]

α is a coefficient specific to the filter [$pa/((m^3/s)^n)$]

Q is the airflow [m^3/s]

n is a flow exponent, taken to be 1.4 based on data for typical air filters (California Energy Commission 2008)

The manufacturer data was used to calculate the coefficient α for each filter. The expected fan power consumed as a result of the filter was calculated from

Equation F-2: Theoretical pressure drop versus airflow

$$P = \frac{\Delta P\, Q}{e_{fan}}$$

Where:

P is the fan power [w]

e_{fan} is the combined efficiency of the fan and fan motor, taken to be 0.35[17] for a typical blower with ECM motor.

17 Department of Energy. Appendix 7-C. Calculation of furnace blower fan energy consumption. https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/ff_prelim_app_07_c_furnacefanconsumption_2012_06_22.pdf

The MERV13 filter, when new, was estimated to consume an additional 17w of fan power compared to the MERV8 filter based on the manufacturer reported pressure drop data.

Table F-1: Manufacturer reported values for air filters used in Sacramento and Bakersfield Region HVAC equipment

Filter model	MERV	Rated Air Flow (CFM)	Initial Pressure Drop at Rated Airflow (InWC)	Media Area (square feet)	Alpha [pa/((m^3/s)$^{1.4}$)]	Initial Pressure Drop at 1000 CFM (InWC)	Fan Power at 1000 CFM (w)
Airguard DP Pleat[18]	8	2085	0.19	12.4	48.3	0.06	19
Airguard DP-G13EEN[19]	13	2085	0.37	12.4	94.1	0.11	36

[18] Airguard DP Pleat. http://www.clcair.com/Portals/12/Documents/airguard/cut-sheets/DP-2IN-Cutsheet.pdf

[19] Airguard DP-G13EEN. http://www.clcair.com/Portals/12/Documents/airguard/cut-sheets/DP-Green13-Cut-Sheet2IN.pdf

APPENDIX G:
Phase 2 Field Study Instrumentation Plan

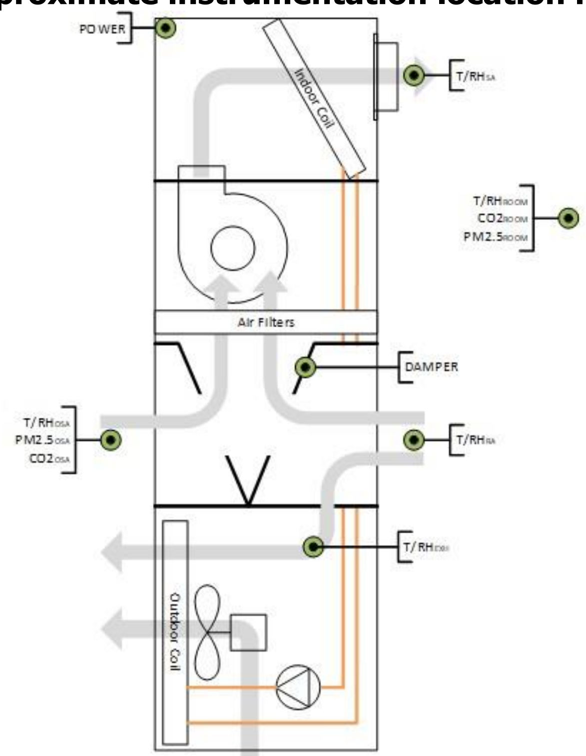
This appendix describes the sensors and sensor placement used to characterize the HVAC system performance during Phase 2 of the project.

HVAC Equipment Instrumentation Plan

The research team installed sensors to measure power and air enthalpy for each HVAC system as well as carbon dioxide (CO_2) and particulate matter (PM2.5) for each classroom. All sensors were wired to a dataTaker 85M data logger and sensor readings were logged once per minute. Data was transferred daily from the data logger to an off-site FTP server.

Table G-1 and Figure G-1 provide a detailed description and approximate placement for each sensor used to monitor the classroom conditions and HVAC performance. The air temperature and humidity, carbon dioxide concentration, and particulate matter were measured with a group of sensors installed in each classroom, as well as outdoors in a weather and radiation protected enclosure. For the Sacramento region school, outside temperature and humidity data from a local weather station approximately 20 miles away was used as a substitute for on-site data during 2018 due to failure of the on-site sensor. The latter was repaired and used to collect data onsite for 2019. For the Bakersfield region school, hourly PM2.5 outdoor concentrations for the study period were obtained from the closest ambient monitoring station approximately seven miles away due to inaccurate data from the on-site sensor (Air Quality and Meteorological Information System).

Figure G-1: Approximate instrumentation location in HVAC system



The outside air damper position for HVAC systems serving the two ECON-DCV classrooms was recorded. In the Bakersfield region school, this analog signal was recorded directly by the dataTaker. In the Sacramento region school, the proprietary digital signal could not be read by the dataTaker. Instead, the position of the damper was calculated using a correlation between the control system's CO_2 sensor and the research team's CO_2 sensor along with the documented demand control ventilation algorithm.

Data from the CO_2 and PM2.5 sensors were corrected based on comparisons to laboratory grade instruments that were deployed in the classrooms for one-week periods.

Table G-1: Instrumentation used to monitor Sacramento and Bakersfield region schools

Symbol	Measurement Type	Manufacturer, Model #	Accuracy	Classroom
T_{RA}	Return Air Temperature	Vaisala HMP110	±0.4°F	All
RH_{RA}	Return Air Relative Humidity	Vaisala HMP110	±1.5%	All
T_{SA}	Supply Air Temperature	Vaisala HMP110	±0.4°F	All
RH_{SA}	Supply Air Relative Humidity	Vaisala HMP110	±1.5%	All
T_{EXH}	Exhaust Air Temperature	Vaisala HMP110	±0.4°F	ERV rooms
RH_{EXH}	Exhaust Air Relative Humidity	Vaisala HMP110	±1.5%	ERV rooms
Power	HVAC System Power	Dent PowerScout	±1% of reading	All
Damper	Damper Position	Delta Controls (SAC) 2-10V output (BAK)	-	ECON-DCV rooms
T_{ROOM}	Room Air Temperature	Vaisala HMP110	±0.1°F	All
RH_{ROOM}	Room Air Relative Humidity	Vaisala HMP110	±1.6%	All
$CO2_{ROOM}$	Room Air CO_2 Concentration	Vaisala GMW93RD	± 30 ppm + 2% of reading	All
$PM2.5_{ROOM}$	Room Air Particulate Matter	Plantower PMS3003	± 10% of reading	All
T_{OSA}	Outside Air Temperature	Vaisala HMP110	±0.4°F	-
RH_{OSA}	Outside Air Relative Humidity	Vaisala HMP110	±1.5%	-
$CO2_{OSA}$	Outside Air CO_2 Concentration	Vaisala GMW80 or 90	GMW80 or 90	-
$PM2.5_{OSA}$	Outside Air Particulate Matter	Plantower PMS3003	± 10% of reading	-

APPENDIX H: HVAC Equipment Performance: Methodology for Analysis of Time Series Data

Overview

The research team analyzed the data collected at each school to compare the performance differences between constant-flow, energy-recovery, and demand control ventilation, as well as MERV 8 and MERV 13 outdoor air filters. The analysis for each unit was limited to school days between 7am-4pm based on each school's academic calendar. After school hours and non-school days were excluded from the analysis because classroom use varied widely outside of school hours.

The performance of each HVAC system was characterized for the entire analysis period and by month using the following metrics: total daily electricity usage, peak daily power draw, and average indoor air conditions (air temperature, absolute humidity, carbon dioxide concentration, and fine particulate matter (<2.5 µm). Carbon dioxide concentrations were also analyzed by calculating the hourly average for each sensor, then averaging each corresponding hour for each day of the analysis period. HVAC system standby power was estimated between 9pm – 5am during periods when the heating/cooling was not running.

The performance analysis for the seven HVAC units installed at the Sacramento region high school was conducted on data collected between February 8th, 2018 and March 22nd, 2019.

The performance analysis for the six HVAC units installed at the Bakersfield region elementary school was conducted on data collected between May 1st, 2018 and April 12th, 2019.

Performance metrics

Daily Electricity Use

The daily electricity use during school hours and the average daily electricity use per month during school hours was calculated from the sum of minute-average power measurements for each HVAC unit (Equation H-1).

Equation H-1: Electricity use during school hours from minute average power measurements

$$Electricity\left(\frac{kwh}{day}\right) = \sum_{t=07:00}^{t=15:59} P_t\,(kw) * \frac{1\,hr}{60\,min}$$

$$\widehat{Electricity}\left(\frac{kwh}{day}\right)_{month} = \frac{1}{n_{days}}\sum_{d=1}^{n_{days}} Electricity\left(\frac{kwh}{day}\right)_d$$

Where:

P_t is the measured average system power for each minute in a single day during school hours [kW]

$Electricity\left(\frac{kwh}{day}\right)$ is the total electricity used per day during school hours.

$\widehat{Electricity}\left(\frac{kwh}{day}\right)_{month}$ is the average electricity used per day during school hours over a defined period.

n_{days} is the number of days analyzed in the month.

Maximum 15-Minute-Averge Power

Daily and monthly peak power draw was defined to be the maximum of the 15-minute-average system power (Equation H-2).

Equation H-2: Peak power draw

$$Peak\ Power\ (kw) = \max_{7:00 \le t \le 15:44}\left(\frac{1}{15} * \sum_{t}^{t+15min} P_t\ (kw)\right)$$

$$Monthly\ Peak\ Power\ (kw) = \max_{1 \le d \le n_{days}}\left(Peak\ Power\ (kw)_d\right)$$

Where:

$Peak\ Power\ (kw)$ is the peak average 15-minute power per day during school hours.

$Monthly\ Peak\ Power\ (kw)$ is the peak 15-minute power over the month reported.

Daily Natural Gas Use

For the Sacramento region school only, the daily natural gas use during school hours and the average daily natural gas use per month during school hours was calculated from the sum of the heating runtime of the HVAC unit multiplied by the manufacturers reported furnace input in btu/hr and converted to therms using a typical heating value of 100,000 btu per therm of natural gas (Equation H-3).

Equation H-3: Electricity use during school hours from minute average power measurements

$$Natural\ \ Gas\left(\frac{therms}{day}\right) = \sum_{t=07:00}^{t=15:59} Heating\ (hr) * \ Input\left(\frac{btu}{hr}\right) * 1e^{-05}\frac{btu}{therm}$$

$$\widehat{Natural\ Gas}\left(\frac{therms}{day}\right)_{month} = \frac{1}{n_{days}}\sum_{d=1}^{n_{days}} Natural\ Gas\ \left(\frac{therms}{day}\right)_d$$

Where:

$Heating$ is the measured number of hours that the HVAC system was heating in a single day during school hours

$Natural\ Gas\ \left(\frac{therms}{day}\right)$ is the total therms used per day during school hours.

$Input\left(\frac{btu}{hr}\right)$ is the input btu/hr rating reported by the manufacturer (**Error! Reference source not found.**).

$\widehat{Natural\ Gas}\left(\frac{therms}{day}\right)_{month}$ is the average electricity used per day during school hours over a defined period.

n_{days} is the number of days analyzed in the month.

Indoor Air Conditions

The daily average temperature, absolute humidity, carbon dioxide, and particulate matter during school hours were used to analyze the indoor conditions provided by each HVAC unit (Equation H-4).

Equation H-4: Hour average and daily hour average for indoor air conditions

$$\hat{X}_{hour} = \frac{1}{60} * \sum_{m=0}^{m=59} v_m$$

$$\hat{X}_{month} = \frac{1}{n} * \sum_{H=0}^{n_{hours}} \hat{X}_{hour,\ H}$$

Where:

v_m is the value of the selected indoor air condition at the given minute.

$\hat{X}_{hour}$ is the average result for a school hour for one day.

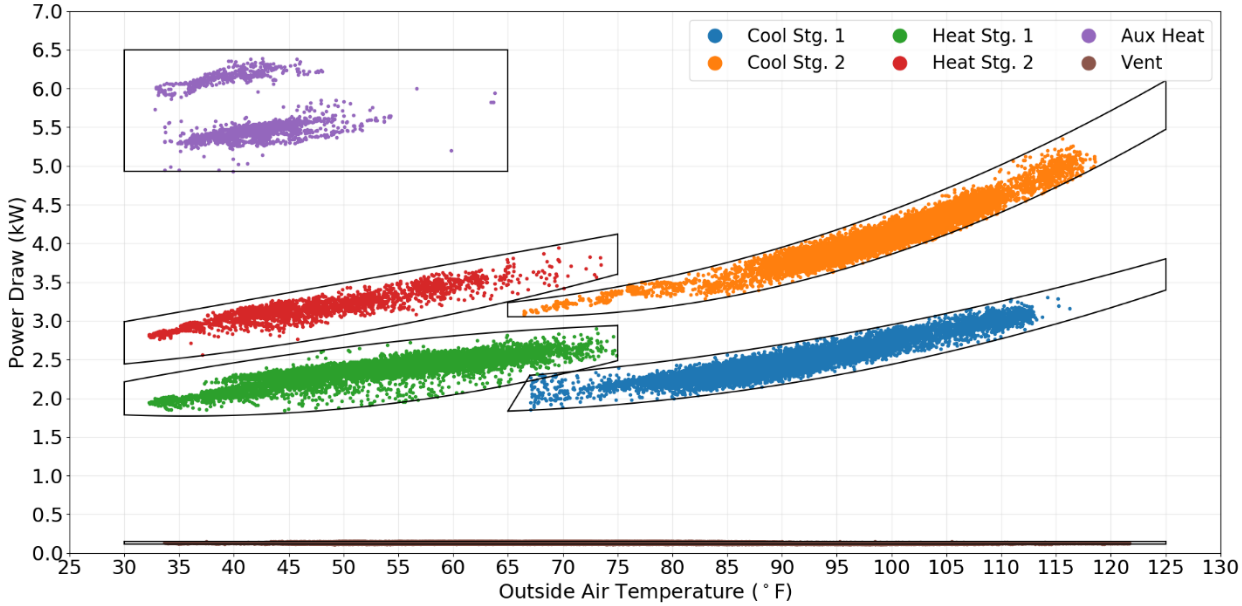
$\hat{X}_{month}$ is the average result for all school hours in one month.

n_{hours} is the number of hours in the month being analyzed.

Mode Determination

The HVAC system mode was determined at each minute from power data, as well as outdoor, supply, and return-air temperature data. First, the power data were analyzed versus outdoor air temperature and classified by mode using visual inspection. A bounding polynomial was defined to classify the power data into one of the following six modes: ventilation, cooling stage 1, cooling stage 2, heating stage 1, heating stage 2, or auxiliary heat. An example for one classroom with a heat pump is shown to illustrate the procedure (Figure H-1).

Figure H-1: Example of using power versus outdoor air temperature data to bin HVAC operation into one of six modes.



The data in each cooling and heating bin was then evaluated to compare supply and return air enthalpies. For cooling data, data points were discarded if the enthalpy of the return air minus the supply air was less than 1.0 Btu/lb. For heating data, data points were discarded if the enthalpy of the return air minus the supply air was greater than -1.0 Btu/lb.

Fan Power

The average total system power during ventilation mode, which represents the power of the indoor fan and any standby power of the HVAC unit, was used to understand the relationship between indoor fan power, filter type, and filter loading. The average total system power was analyzed over each week at the Bakersfield region school from 7:30-8:30 AM and at the Sacramento region school from 7:00-8:00 AM when the system was in ventilation mode. For the classrooms with ERVs, the ERV power was subtracted from the total power if the ERV was operating. The early morning hour was chosen so that the indoor coil would be dry since condensate is generated when cooling is used later in the day which would change the resistance of the system and thus impact fan power.

The weekly average fan power during this time period was calculated and the fan power versus week was plotted from the time a new filter was inserted until the time the filter was replaced. A best-fit linear relationship (least squares method) was used to describe the relationship between fan power and time since filter replacement (in weeks).

APPENDIX I: Long-Term Air Quality Monitoring Adjustments

Overview

The following appendix describes the methodology used to calculate adjustment factors for the long-term monitoring of CO_2 and PM2.5 during Phase 2 of the project.

Adjustment Factors for Long-Term Monitoring of CO_2

CO_2 measured from the three sampling visits were used to determine the adjustment factors for the long-term monitoring data. Adjustment is needed for the long-term monitoring of CO_2 because the sensors used for long-term monitoring can drift overtime. Linear fit between the CO_2 measured from the three sampling visits and the long-term monitoring data show that the two sets of measurements were highly correlated. R^2 from least squares regression was mostly >0.99 (Table I-1 through Table I-6). However, the Vaisala used for long-term monitoring tends to read higher values when compared to the concentrations measured during the three sampling visits. This is indicated by negative values of the intercept estimated by the least squares linear regression.

Table I-1: Parameters for linear equation to correct long-term CO_2 measurements at Bakersfield region elementary school based on data measured December 2017

Classroom	Linear Regression Slope (a')	Linear Regression Intercept (b')	Linear Regression R2
27-TS-CRV-MERV8	105.1	1.05	0.979
24-TS-CRV-MERV13	104.3	1.05	0.985
26-TS-ERV-MERV8	111.2	1.05	0.989
29-TS-ERV-MERV13	-56.5	1.03	0.991
28-TS-ECON-DCV-MERV8	--	--	--
23-TS-ECON-DCV-MERV13	-99.1	1.05	0.994

Table I-2: Parameters for linear equation to correct long-term CO2 measurements at Bakersfield region elementary school based on data measured May 2018

Classroom	Linear Regression Slope (a′)	Linear Regression Intercept (b′)	Linear Regression R^2
27-TS-CRV-MERV8	-86.7	1.02	0.985
24-TS-CRV-MERV13	156.1	1.12	0.995
26-TS-ERV-MERV8	-54.3	0.97	0.995
29-TS-ERV-MERV13	101.8	1.04	0.997
28-TS-ECON-DCV-MERV8	108.6	1.05	0.995
23-TS-ECON-DCV-MERV13	102.1	1.06	0.997

Table I-3: Parameters for linear equation to correct long-term CO2 measurements at Bakersfield region elementary school based on data measured October 2018

Classroom	Linear Regression Slope (a′)	Linear Regression Intercept (b′)	Linear Regression R^2
27-TS-CRV-MERV8	-63.4	0.98	0.973
24-TS-CRV-MERV13	159.8	1.08	0.991
26-TS-ERV-MERV8	-61.5	0.98	0.988
29-TS-ERV-MERV13	-69.9	1.02	0.995
28-TS-ECON-DCV-MERV8	-81.3	1.01	0.991
23-TS-ECON-DCV-MERV13	113.8	1.09	0.993

Table I-4: Parameters for linear equation to correct long-term CO_2 measurements at Sacramento region high school based on data measured February 2018

Classroom	Linear Regression Slope (a')	Linear Regression Intercept (b')	Linear Regression R^2
02-WG-CRV-MERV8	-59.6	1.03	0.998
03-WGS-CRV-MERV8	-85.6	1.03	0.997
12-WGS-CRV-MERV13	109.3	1.08	0.999
01-WGS-ERV-MERV8	-69.2	1.03	0.962
10-WGS-ERV-MERV13	-78.6	1.04	0.998
04-WGS-ECON-DCV-MERV8	-59.4	1.05	0.989
11-WGS-ECON-DCV-MERV13	-95.3	1.07	0.999

Table I-5: Parameters for linear equation to correct long-term CO2 measurements at Sacramento region high school based on data measured May 2018

Classroom	Linear Regression Slope (a')	Linear Regression Intercept (b')	Linear Regression R^2
02-WG-CRV-MERV8	120.3	1.08	0.997
03-WGS-CRV-MERV8	--	--	--
12-WGS-CRV-MERV13	111.0	1.08	1.000
01-WGS-ERV-MERV8	-84.9	1.06	0.995
10-WGS-ERV-MERV13	-99.6	1.05	1.000
04-WGS-ECON-DCV-MERV8	-79.4	1.05	0.999
11-WGS-ECON-DCV-MERV13	130.1	1.09	0.995

Table I-6: Parameters for linear equation to correct long-term CO2 measurements at Sacramento region high school based on data measured October/November 2018

Classroom	Linear Regression Slope (a’)	Linear Regression Intercept (b’)	Linear Regression R^2
02-WG-CRV-MERV8	-91.8	1.08	0.998
03-WGS-CRV-MERV8	--	--	--
12-WGS-CRV-MERV13	--	--	--
01-WGS-ERV-MERV8	--	--	--
10-WGS-ERV-MERV13	--	--	--
04-WGS-ECON-DCV-MERV8	--	--	--
11-WGS-ECON-DCV-MERV13	-96.5	1.04	0.996

Using the slopes and intercepts from Table I-1 through Table I-6, the corrections at a reference concentration of 1000 ppm were calculated. Next, the mean concentration correction was calculated for each classroom, as shown in Table I-7 through Table I-10. Finally, a slope and intercept are determined to adjust the long-term monitoring of CO2 that would result in the corresponding mean concentration correction (Equation I-1).

Equation I-1: Carbon dioxide linear correction

$$C_{CO2\_Adjusted} = a' + b' * C_{CO2\_Measured}$$

Where:

a' is the average value of intercepts determined from the three sampling visits (Table I-1 through Table I-6), b' is calculated by $1+(C_{Mean} - a')/1000$ ppm, where C_{Mean} is mean concentration correction in Table I-8 and Table I-10. $C_{CO2\_Measured}$ is the CO_2 concentration recorded by the long-term monitoring.

Table I-7: Concentration correction at 1000 ppm for long-term monitoring of CO2 at Bakersfield region elementary school

Classroom	December 2017 (ppm)	May 2018 (ppm)	October 2018 (ppm)
27-TS-CRV-MERV8	-57	-64	-87
24-TS-CRV-MERV13	-57	-35	-80
26-TS-ERV-MERV8	-61	-85	-81
29-TS-ERV-MERV13	-29	-66	-50
28-TS-ECON-DCV-MERV8	--	-58	-71
23-TS-ECON-DCV-MERV13	-53	-37	-24

Table I-8: Adjust factors for long-term monitoring of CO2 at Bakersfield region elementary school

Classroom	Mean (C_{Mean})	Intercept (a)	Slope (b)
27-TS-CRV-MERV8	-69	-85.1	1.02
24-TS-CRV-MERV13	-57	-140.1	1.08
26-TS-ERV-MERV8	-76	-75.7	1.00
29-TS-ERV-MERV13	-48	-76.1	1.03
28-TS-ECON-DCV-MERV8	-65	-95.0	1.03
23-TS-ECON-DCV-MERV13	-38	-105.0	1.07

Table I-9: Concentration correction at 1000 ppm for long-term monitoring of CO2 at Sacramento region elementary school

Classroom	February 2018 (ppm)	May 2018 (ppm)	Oct/Nov 2018 (ppm)
02-WG-CRV-MERV8	-30	-45	-11
03-WGS-CRV-MERV8	-53	--	--
12-WGS-CRV-MERV13	-30	-35	--
01-WGS-ERV-MERV8	-35	-27	--
10-WGS-ERV-MERV13	-43	-53	--
04-WGS-ECON-DCV-MERV8	-11	-31	--
11-WGS-ECON-DCV-MERV13	-27	-41	-52

Table I-10: Adjust factors for long-term monitoring of CO2 at Sacramento region elementary school

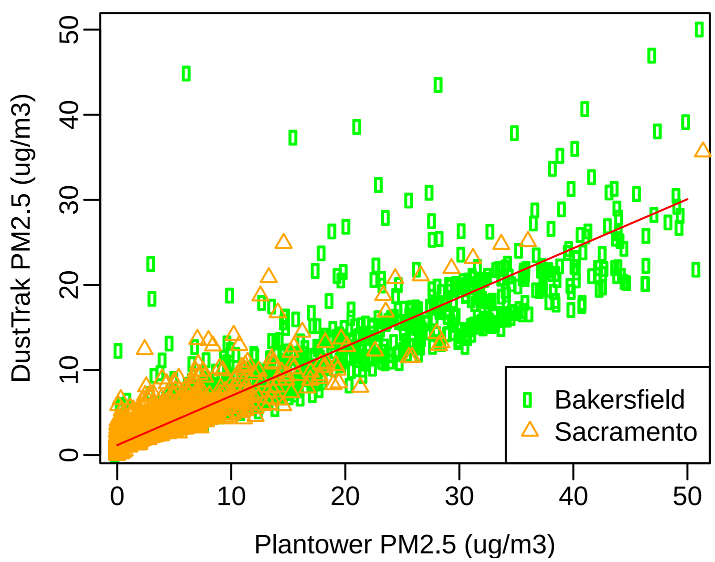
Classroom	Mean (C_{Mean})	Intercept (a)	Slope (b)
02-WG-CRV-MERV8	-29	-90.6	1.06
03-WGS-CRV-MERV8	-53	-85.6	1.03
12-WGS-CRV-MERV13	-32	-110.2	1.08
01-WGS-ERV-MERV8	-31	-77.1	1.05
10-WGS-ERV-MERV13	-48	-89.1	1.04
04-WGS-ECON-DCV-MERV8	-21	-69.4	1.05
11-WGS-ECON-DCV-MERV13	-40	-107.3	1.07

Adjustment Factors for Long-Term Monitoring of PM2.5

All Plantower sensors were compared in a room alongside with a high-precision research-grade instrument (Mini Wide Range Aerosol Spectrometer MiniWRAS 1371, Grimm Aerosol Technik) to confirm that their readings agreed with one another. The MiniWRAS measured particle size ranging from 10 nm to 35 μm and estimated the corresponding PM2.5 mass concentrations. Over the course of several days when indoor PM2.5 inside the room were kept low and Grimm read stable concentrations that varied between 1 and 2 ug/m^3, Plantower offset was determined by comparing their readings with the Grimm as a reference. The offset of Plantower sensors varied between 1.13 and 1.19 ug/m^3 (mean = 1.16 ug/m^3). Responses of the Plantower sensors were also checked by two challenge tests: pan-frying food and burning incense. Responses from the Plantower sensors differed by approximately 5% (coefficient of variation = standard deviation/mean) from one another.

Correction factors for long-term PM2.5 data measured using Plantower sensors were computed assuming that the offset of 1.16 ug/m^3 determined from lab testing applied to all field data. Next, least square regression was used to determine the slope relating the Plantower sensor readings and the adjusted DustTrak data. **Error! Reference source not found.** show results of the linear fit using all available PM2.5 data from the two schools. While there may be some differences between classrooms, the available data for making concentration correction is too limited to support computing a correction factor specific for each classroom. Instead, concentration corrections were calculated by pooling from all available data (Figure I-1).

Figure I-1: Comparison of hourly averaged indoor PM2.5 measured using DustTrak and Plantower sensors



Red line shows the best-fit linear regression with an assumed offset = 1.16 ug/m^3 as determined from lab testing of Plantower sensors. R^2 = 0.88.

Equation I-2 shows the corrections applied to the Plantower sensor data. Similar to the DustTrak, it is expected that Plantower sensors tend to overestimate PM2.5 concentrations based on work by SCAQMD[20].

Equation I-2: Plantower correction

$$C_{Plantower\_Ajusted} = 1.16 + 0.58 * C_{Plantower\_Measured}$$

Plantower sensors were installed at both schools to measure PM2.5 concentrations in the outdoor air. However, instrumentation problem resulted in data loss at the Bakersfield region elementary school. For subsequent analyses that require outdoor PM2.5 data (e.g., calculation of PM2.5 removal efficiency by air filters), outdoor PM2.5 hourly data (Air Quality and Meteorological Information System) were obtained from the closest ambient monitoring station approximately seven miles away from the Bakersfield school. Even though it is reasonable to assume that the ambient air quality station is a good approximation of the outdoor PM2.5 measured at the school, this assumption is a source of uncertainty in our estimates.

[20] Plantower is the sensor used in PurpuleAir. See http://www.aqmd.gov/aq-spec/sensordetail/purpleair-pa-ii for sensor performance evaluation by the South Coast Air Quality Management District.

APPENDIX J: Classroom CO_2 Concentration Analysis

This appendix describes the analysis of the CO_2 concentration in each classroom for Phase 2 of the project.

CO_2 Concentration Analysis by Hour and by Month

Outdoor CO_2 concentrations during school hours averaged 462 ppm at the Sacramento region school and 477 ppm at the Bakersfield region school (Figure J-1 and Figure J-2). Analysis of the hourly data shows the outdoor concentration did not vary significantly between occupied and unoccupied hours (Figure J-3 and Figure J-4). Generally, indoor CO2 levels were higher at the Sacramento-region high school due to the larger class size and older students as compared to the Bakersfield-region elementary school.

At the Sacramento-region school, the ERV rooms had the highest average CO2 concentrations, which was expected because the ventilation rates in those classrooms were lower compared to CRV and DCV rooms even though the ERV had the supply fans set to the highest available setting. Room ERV-13's lower ventilation rate resulted in average monthly CO2 concentrations that were close to, or exceeded, 1000ppm. The lower ventilation rate was enough for ERV-8 because it had the lowest occupancy of all classrooms (over the course of the day) with only four class periods (Table B-2). CO2 levels were similar for CRV classrooms and DCV classrooms, both on a monthly and hourly average basis (Figure J-1 and Figure J-3).

Review of the hourly data for the DCV classrooms shows that the CO_2 levels were not tightly controlled. Upon further investigation, the research team determined that the damper response time of the Jade controller was too slow to respond quickly to the large range of damper movement required for the equipment to respond to the normal occupancy changes that occur in school settings (e.g. class changing periods, lunch). The damper response characteristics are part of the Jade controller's firmware and could not be adjusted by the research team. Further discussion with Honeywell after the field study was completed determined that the damper speed can be adjusted using a supplementary PC tool. UC Davis is following up with Honeywell and Bard to advocate for ensuring that HVAC equipment ships with the controller configured with a damper response speed appropriate to the range of damper movement required.

The damper response characteristics are part of the Jade controller's firmware and could not be adjusted by the research team. Further discussion with Honeywell revealed that the damper speed can be adjusted using a supplementary PC tool. UC Davis is following up with Honeywell and Bard to determine

At the Bakersfield-region school, class sizes were smaller and the CRV systems, which were commissioned for a typical occupancy of 30 people, over-ventilated. CRV-8 had the lowest CO_2 levels, however there were only 20 first-grade students in the classroom, which was the lowest among the classrooms in the study (Table B-3). CRV-13 had 23 second-grade students, which resulted in CO_2 levels more closely aligned with the ERV and DCV ventilation system rooms in Bakersfield. Room ERV-13 had slightly lower CO_2 levels compared to room ERV-8, most likely due to the increased ventilation in room ERV-13 due to the increased setting on the ERV exhaust fans. The DCV systems responded to classroom CO2 concentrations, however, review of the hourly data shows that the CO_2 levels were not tightly controlled. Upon further investigation, the research team determined that the damper response of the Pelican Wireless controller did not respond accurately to abrupt occupancy changes that are typical in schools (e.g. class passing periods, lunch). The damper response characteristics are part of Pelican's cloud-based software and could not be adjusted by the research team.

Figure J-1: Average daily CO_2 concentration during school hours versus time for Sacramento-region school.

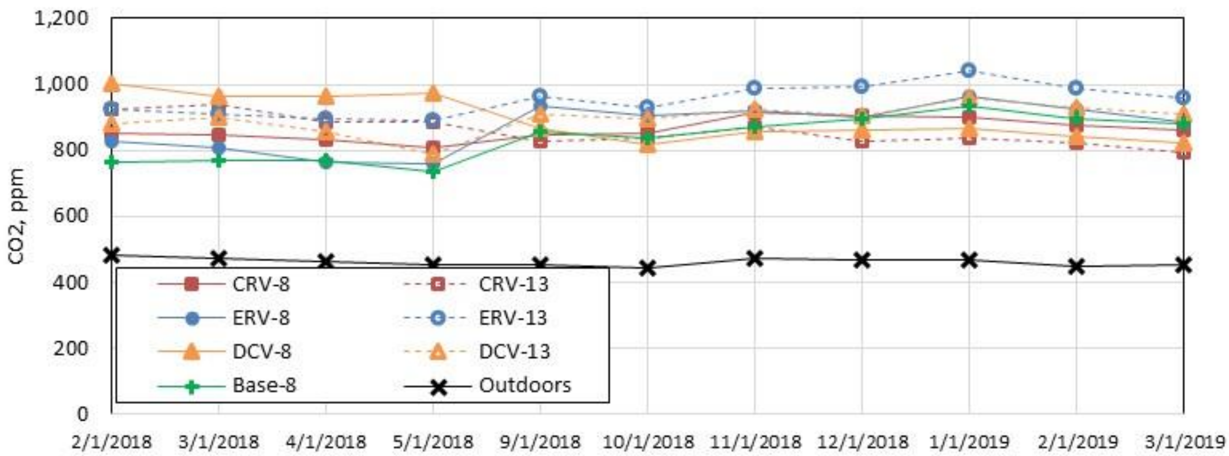


Figure J-2: Average daily CO_2 concentration during school hours versus time for Bakersfield region school.

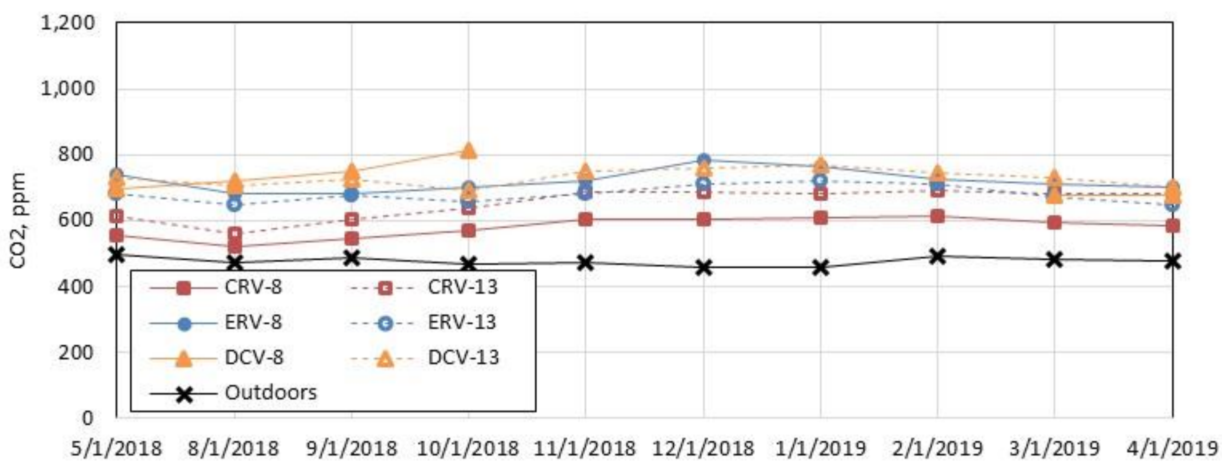


Figure J-3: Hour average indoor carbon dioxide concentration profile for Sacramento region school for different ventilation equipment and filter types.

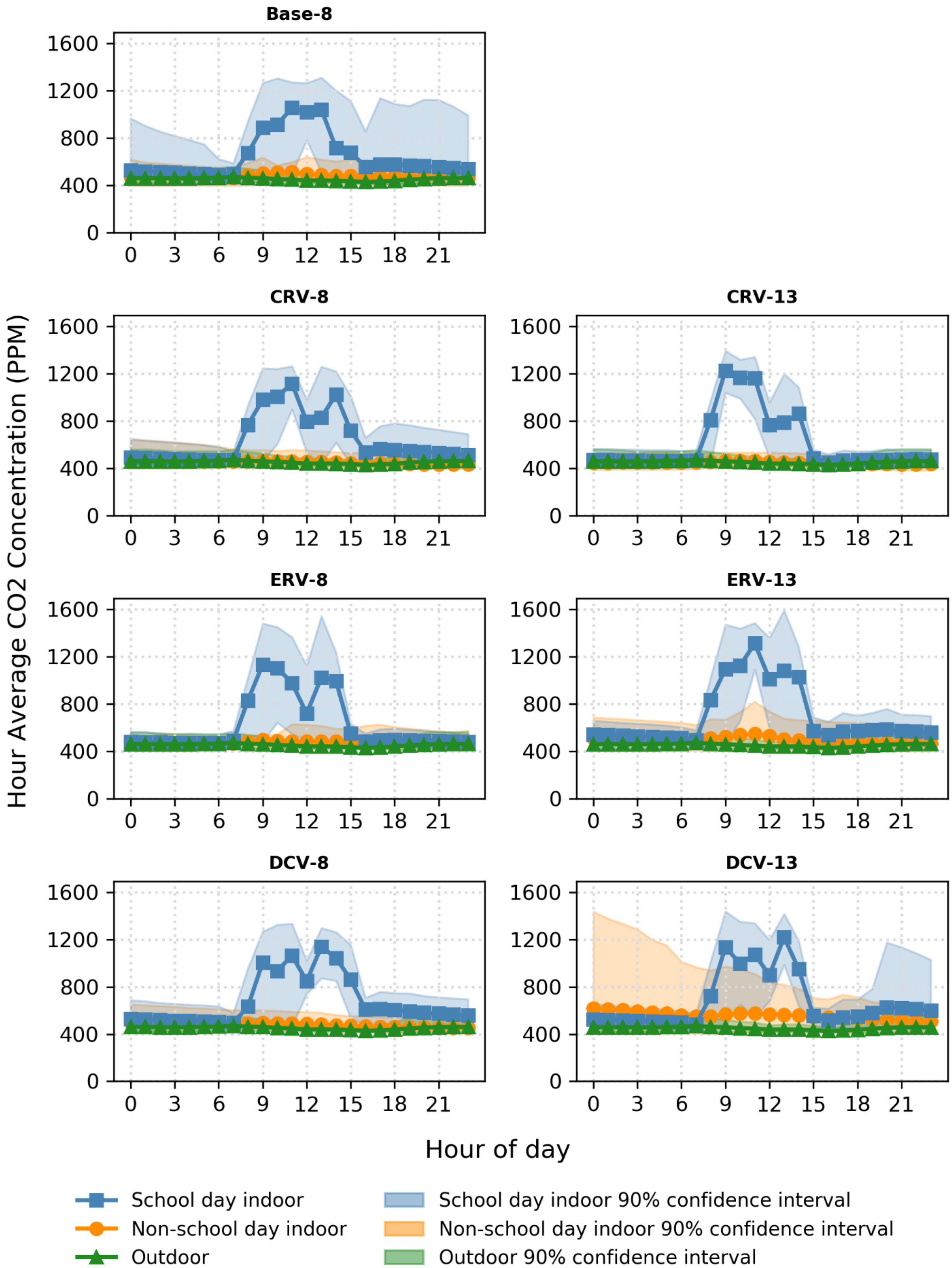


Figure J-4: Hour average indoor carbon dioxide concentration profile for Bakersfield region school for different ventilation equipment and filter types.