Title

Small and Medium Building Efficiency Toolkit and Community Demonstration Program

Authors
Kloss, M
Piette, M
Hong, T
et al.

Publication Date
2024-01-20

Peer reviewed

http://doi.org//10.7941/S93P70 LBNL-2001054

Lawrence Berkeley National Laboratory

Small and Medium Building Efficiency Toolkit and Community Demonstration Program

Mary Ann Piette, Tianzhen Hong, William J. Fisk, Norman Bourassa, Wanyu R. Chan, Yixing Chen, Iris H. Y. Cheung, Toshifumi Hotchi, Margarita Kloss, Sang Hoon Lee, Phillip N. Price, Oren Schetrit, Kaiyu Sun, Sarah Taylor-Lange and Rongpeng Zhang

Lawrence Berkeley National Laboratory

Energy Technologies Area

March 2017

Energy Research and Development Division
FINAL PROJECT REPORT

SMALL AND MEDIUM BUILDING EFFICIENCY TOOLKIT AND COMMUNITY DEMONSTRATION PROGRAM

Prepared for: California Energy Commission
Prepared by: Lawrence Berkeley National Laboratory

MARCH 2017
CEC-500-YYYY-XXX

PREPARED BY:

Primary Author(s):
Mary Ann Piette
Tianzhen Hong
William J. Fisk
Norman Bourassa
Wanyu R. Chan
Yixing Chen
Iris H. Y. Cheung
Toshifumi Hotchi
Margarita Kloss
Sang Hoon Lee
Phillip N. Price
Oren Schetrit
Kaiyu Sun
Sarah Taylor-Lange
Rongpeng Zhang

Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94720
http://www.lbl.gov

Contract Number: PIR-12-031

Prepared for:

California Energy Commission

Felix Villanueva
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

LEGAL NOTICE

ACKNOWLEDGEMENTS

This work was supported by the California Energy Commission, Public Interest Energy Research Program, under Agreement No. PIR-12-031.

The project team at Lawrence Berkeley National Laboratory would like to thank the sponsor, the Public Interest Energy Research Program of the California Energy Commission, Laurie ten Hope, Virginia Lew, and especially the Commission Project Managers, Matthew Fung and Felix Villanueva.

Thanks to our collaborators and our city partners - Bay Area Climate Collaborative, C3 Energy, City of Berkeley, City of Fremont, City and County of San Francisco, City of San Jose, City of Santa Clara, and City of Oakland for their enthusiastic participation in this research.

The project team would like to thank Pacific Gas & Electric for supporting the development of the load shape benchmarks.

Thanks to the following individuals who contributed to this work:

- Rafael Reyes, Diana Chou, Rajiv Mathur, Alison Erlenbach of the Bay Area Climate Collaborative
- Billi Romain, Alice La Pierre, and Katie Van Dyke, City of Berkeley
- Rachel DiFranco and Dan Schoenholtz, City of Fremont
- Scott Wentworth and Pete Fong, City of Oakland
- Barry Hooper, Claudia Espino, Lindsey Hirsch, and Nicholas Young, City and County of San Francisco
- Shayna Hirshfield, Osvaldo Cordero, and Michael Foster, City of San Jose
- Mary Medeiros McEnroe, City of Santa Clara
- Mangesh Basarkar, Jeff Beresini, Katie Grote, and others from PG&E

Note that institutional affiliations above reflect the time of participation.

Thanks to the many industry professionals who shared their ideas and feedback for this project. They came from utilities, energy companies, nonprofits, consultants, other national laboratories, Energy Watch, BayREN, Prospect Silicon Valley, the California Air Resources Board, Bonneville Power Administration, the US Department of Energy, and the California Energy Commission.

Thanks to the many individuals who contributed to this work including Lawrence Berkeley National Laboratory (LBNL) staff, especially Paula Ashley, Ellen Thomas, and Erin Beardsley.

Thanks, also, to our reviewers for their generosity and time improving this report.

This work was supported by the California Energy Commission's Public Interest Energy Research program and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DEAC02-05CH11231.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Small and Medium Building Efficiency Toolkit and Community Demonstration Program is the final report for the Small and Medium Building Efficiency Toolkit and Community Demonstration Program project (grant agreement number PIR-12-031) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency program area.

When the source of a table, figure or photo is not otherwise credited, it is the work of the author of the report.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Small commercial buildings in the United States consume 47 percent of all primary energy consumed in the building sector. Retrofitting small and medium commercial buildings may pose a steep challenge for owners, as many lack the expertise and resources to identify and evaluate cost-effective energy retrofit strategies. To address this problem, this project developed the Commercial Building Energy Saver (CBES), an energy retrofit analysis toolkit that calculates the energy use of a building, identifies and evaluates retrofit measures based on energy savings, energy cost savings, and payback. The CBES Toolkit includes a web app for end users and the CBES Application Programming Interface for integrating CBES with other energy software tools. The toolkit provides a rich feature set, including the following:

1. Energy Benchmarking providing an Energy Star score
2. Load Shape Analysis to identify potential building operation improvements
3. Preliminary Retrofit Analysis which uses a custom developed pre-simulated database
4. Detailed Retrofit Analysis which utilizes real time EnergyPlus simulations

In a parallel effort the project team developed technologies to measure outdoor airflow rate; commercialization and use would avoid both excess energy use from over ventilation and poor indoor air quality resulting from under ventilation.

If CBES is adopted by California's statewide small office and retail buildings, by 2030 the state can anticipate 1,587 gigawatt hours of electricity savings, 356 megawatts of non-coincident peak demand savings, 30.2 megatherms of natural gas savings, $227 million of energy-related cost savings, and reduction of emissions by 757,866 metric tons of carbon dioxide equivalent. In addition, consultant costs will be reduced in the retrofit analysis process.

CBES contributes to the energy savings retrofit field by enabling a straightforward and uncomplicated decision-making process for small and medium business owners and leveraging different levels of assessment to match user background, preference, and data availability.

Keywords: retrofit, energy efficiency, energy savings, commercial buildings, CBES, energy modeling, indoor air quality, indoor environmental quality, ventilation rate, outdoor airflow intake rate, outdoor air measurement technology

Please use the following citation for this report:

Piette, Mary Ann, Tianzhen Hong, William J. Fisk, Norman Bourassa, Wanyu R. Chan, Yixing Chen, Iris H. Y. Cheung, Toshifumi Hotchi, Margarita Kloss, Sang Hoon Lee, Phillip N. Price, Oren Schetrit, Kaiyu Sun, Sarah Taylor-Lange, Rongpeng Zhang. (Lawrence Berkeley National Laboratory), 2017. *Small and Medium Building Efficiency Toolkit and Community Demonstration Program.* California Energy Commission. Publication Number: CEC-XXX-XXXX-XXX.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Small businesses are vital to California's economy. They provide essential goods and services, employ millions of people, and generate half of the non-agricultural gross domestic product (GDP). Many small businesses and some large businesses reside in small and medium buildings (SMBs). Despite California's aggressive portfolio of efficiency programs, small businesses have been hard to reach because they lack the monetary, personnel, and technological resources of large organizations. Small business owners and energy professionals do not have easy and low-cost access to tools that can be used to identify cost-effective energy efficient retrofits. Small business owners may not have access to detailed energy use information; instead utility bills may be paid by landlords or real estate management firms. Transaction costs are also a barrier in small buildings, even when owned by large businesses.

California has been a leader in building energy efficiency standards and utility programs since the inception of the Title 24 Building Energy Efficiency Standards in 1978. Title 24 focuses on new buildings, additions, and equipment replacement, while utility programs focus on single measures. California has implemented policies addressing all aspects of state energy needs. Significant milestones include the 2003 Energy Action Plan and Assembly Bill (AB) 32, the 2006 Global Warming Solutions Act. With the recent passage of AB 758, the Comprehensive Energy Efficiency Program for Existing Buildings, there is an increased focus on existing buildings. AB 758 aims to reduce greenhouse gas (GHG) emissions to 1990 levels by 2020, the statewide target established in AB 32.

Project Purpose and Process

Through this project, researchers at Lawrence Berkeley National Laboratory (LBNL) developed tools to help SMB businesses evaluate energy savings opportunities. These tools target the underserved SMB market, which faces challenges including lack of information on the costs and benefits of energy retrofits and lack of low-cost/no-cost opportunities to reduce energy use. The goals of this project were to:

- Develop an energy retrofit analysis toolkit for SMB businesses that analyzes the energy performance of a building and identifies and evaluates retrofit measures to meet energy savings, energy cost savings, payback, and other criteria, thereby enabling and accelerating SMB retrofits.
- Demonstrate new advanced systems, methods, and tools with local cities and deployment partners, directly supporting AB 758 energy programs.
- Collaborate with local cities and communities to demonstrate innovative and verifiable approaches to energy-efficient community-scale planning that result in more efficient buildings to help California meet zero net energy and retrofit goals.

With these goals in mind, researchers developed the Commercial Building Energy Saver (CBES) Toolkit as a streamlined data collection and performance measurement system that maximizes existing data and approaches used in this sector. We sought to include the following features in the toolkit to enable use as an effective SMB retrofit assessment method:

- A rapid, web-based retrofit assessment tool for office and retail SMBs, offering benchmarking against peer buldings, load shapes, a pre-simulated database of retrofit measure energy savings results, real time EnergyPlus models, and supplying indoor environmental quality (IEQ) information
- A web services application programming interfaces (APIs) that will deliver SMB retrofit energy savings calculations for a wide range of web-based applications
- A freely-available prototype for a web-based CBES retrofit analysis tool, using the developed APIs to evaluate both individual and collective retrofit measures

In addition, project team members developed a prototype outdoor air ventilation measurement system for rooftop heating, ventilation, and air-conditioning (HVAC) to ensure that ventilation rates are adequate but not excessive

Researchers partnered with California businesses, cities, and investor-owned utilities (IOUs) to validate the toolkit's effectiveness as a robust and practical SMB retrofit assessment method. The project team also engaged in a complementary outreach plan targeting industry professionals in local government, utilities, energy companies, nonprofits, consultants, and other national laboratories. The two CBES workshops enrolled 95 participants, and 11 companies participated in the developers' webinars. The team's close collaboration with city partners and other stakeholders is evidenced by the regular input into the direction and development of the toolkit, and demonstrated by the CBES case studies using city buildings.

Project Results

The CBES retrofit software analyzes the energy performance of a user's building pre- and post-retrofit in conjunction with the user's input data to recommend retrofit measures and energy savings, as well as provide economic analysis for the selected measures. The software provides the energy benchmarking , which entails the use of external software APIs including ENERGYIQ and Energy Star Portfolio Manager. The software also provides three levels of retrofit analysis depending on the degree of the input data provided:

- Energy Benchmarking - Use of external software APIs including EnergyIQ and Energy Star Portfolio Manager.
- Level 1 - No- or low-cost improvement analysis: Base load shape analysis based on statistical models
- Level 2 - Preliminary retrofit analysis: Retrofit analysis from a database that compiles the pre-simulated energy performance using prototype buildings with retrofit measures, and associated cost data for measures
- Level 3 - Detailed retrofit analysis: Retrofit analysis from a real time simulation that calculates the energy performance of the building with user-configurable retrofit measure(s)

CBES embeds 23 IEQ recommendations for 48 retrofit measures. In addition, research staff designed, fabricated, and tested four prototypes for measuring outdoor air intake rates into Rooftop Air Handling Units (RTUs). All prototypes met the +/- 20 percent accuracy target at low wind speed and were accurate within +/- 10 percent after calibration.

Benefits to California

California's goal is to retrofit 50 percent of existing commercial building stock to reach zero net energy by 2030 (CPUC, 2011). The CBES Toolkit has proven to be a user-friendly platform to enable and accelerate SMB retrofits throughout California, thereby directly supporting AB 758 energy programs. The toolkit is free and easy-to-use, and will enable stakeholders to identify and evaluate retrofit measures based on various energy performance and economic metrics. Furthermore, CBES can be adopted by a wide range of users — from building owners to local governments to consultants — to support their energy efficiency projects.

Indoor Environmental Quality (IEQ)

Besides energy savings, the desire to ensure or improve thermal quality and indoor air quality is an important motivator for building retrofits. Research has shown that IEQ can impact occupant comfort, health, and productivity, often with significant financial implications because the costs of salaries and health benefits far exceed energy, maintenance, and annualized construction costs or rent. Information on the effects of energy retrofits on IEQ can inform the retrofit measure selection process. By providing information on potential IEQ benefits as a result of the retrofit, CBES enables users to not only consider energy cost savings, but also consider the effects of energy retrofits on comfort, health, and productivity.

Outdoor Air Intake Measurement Technologies

Commercialization and use of these or similar outdoor air measurement technologies (OAMTs) would benefit California ratepayers by enabling minimum ventilation rates (MVRs) to be maintained at the targeted ventilation rates. Excess energy use from over ventilation, which is common in offices and retail buildings, would be avoided. Instances of poor indoor air quality resulting from insufficient ventilation would be reduced. Advanced ventilation control strategies and demand response strategies could be implemented using these technologies. Further analyses are needed to quantify the energy savings potential. Modeling of the effects of different ventilation rates on HVAC energy use provides an indication of the magnitude of potential energy savings:

- For California offices with economizers, 50 percent and 100 percent increases in Title 24-prescribed MVRs increased HVAC modeled energy use by 7.6 percent and 21.6 percent, with greater effects for small offices. Office buildings without economizers realized a few percent energy savings in many climate zones by increasing ventilation rates (VRs) up to 150 percent of the current Title-24-required MVR, because cooling energy savings exceeded heating energy increases (Dutton and Fisk, 2014).
- In the medium-size retail building, projected gas heating energy and total HVAC energy increased markedly with ventilation rates, similar to the projected effects in small offices. For example, increasing the MVR from the Title 24 requirement to 150 percent of

the Title 24 requirement increased HVAC energy by 22 percent and increased total building energy consumption by approximately 7 percent (Dutton and Fisk, 2015).

CBES Toolkit

The implementation and use of the CBES Toolkit to determine cost effective retrofits for small and medium office and retail buildings and for spaces occupied by small businesses is expected to increase the percent of energy retrofits implemented in these target sectors. The tool will be used by engineers, energy consultants, facility, property managers and building and business owners to systematically determine and rank energy retrofit opportunities. It is anticipated that the level of predicted energy savings identified will fall into two categories:

1. Operations and maintenance savings. We anticipate that 15 percent of all target building owners, managers, and energy consultants will use the load shape benchmarking tool, and savings are expected to average 10 percent.
2. Savings related to use of the simulation portion of the tool. These savings scale directly with the complexity of the simulation applied to a specific building, and range from 5 to 10 percent for level 1 (no simulation), 10 to 20 percent for level 2 (presimulation), to 20 to 40 percent for level 3 (detailed simulation).

With the adoption of CBES Toolkit, assuming a conservative average whole building or premises energy savings potential of 10 percent savings by using the load shape benchmarking tool in 15 percent of the statewide small office and retail building population by 2030 and 30 percent savings by using the simulation portions of the tool in 10 percent of the same population by 2030, it is anticipated that the use of the tool will help facilitate 464 gigawatt hours (GWh) of electricity savings, 133.5 megawatts (MW) of non-coincident peak demand savings, 2.5 megatherms (Mtherms) of natural gas savings, $62 million of energy-related cost savings, and reduce emissions by 188,198 metric tons of carbon dioxide equivalent (MTCO2e). Furthermore, assuming an average three-year payback for implemented energy retrofits, the toolkit could lead to employment of 558 people during the retrofit implementation period and the creation of 3,165 direct, indirect, and induced jobs each year for the life of the investment.

If the CBES Toolkit is used for all small and medium size buildings in California by 2030, the resulting retrofits could lead to 1,587 GWh of electricity savings, 356 MW of non-coincident peak demand savings, 30.2 Mtherms of natural gas savings, $227 million of energy-related cost savings, reduce emissions by 757,866 MTCO2e, create 2,041 jobs during the retrofit implementation period and create 11,569 direct, indirect, and induced jobs each year for the life of the investment.

CHAPTER 1: Introduction and Background

1.1 Introduction

Small businesses are vital for California's economy. They provide essential goods and services, employ millions of people, and generate half of the non-agricultural gross domestic product (GDP). Many small businesses and some large businesses reside in small and medium buildings (SMBs). While California has had an aggressive portfolio of efficiency programs, small businesses have been hard to reach because they lack the monetary, personnel, and technological resources of large organizations. There is an information gap regarding opportunities for improved energy efficiency; and small business owners and energy professionals do not have easy and low-cost access to tools to consider cost-effective energy efficient retrofits. Small business owners may not have access to detailed energy use information; instead utility bills may be paid by landlords or real estate management firms. Transaction costs are also a barrier in small buildings, even when owned by large businesses.

California has long been a leader in building energy efficiency standards and utility programs since the inception of the Building Energy Efficiency Standards (Title 24) in 1978. Title 24 focuses on new buildings, additions, and equipment replacement, while utility programs focus on single measures. California has implemented policies addressing all aspects of state energy needs. Significant milestones include the 2003 Energy Action Plan and Assembly Bill (AB) 32), the 2006 Global Warming Solutions Act. With the recent passage of the Comprehensive Energy Efficiency Program for Existing Buildings (AB 758), there is an increased focus on existing buildings. AB 758 aims to reduce GHG emissions to 1990 levels by 2020, the statewide target established in AB 32.

The Small and Medium Building Efficiency Toolkit and Community Demonstration Program developed the CBES toolkit to enable and accelerate SMB retrofits. This project will: 1) identify no-cost/low-cost operational improvements; 2) maintaining indoor environmental quality during retrofits; 3) web-based retrofit toolkit; and 4) demonstration of toolkit with local partners.

In a parallel effort, this project will explore the problem of poor control of outdoor airflow ventilation that is particularly acute in buildings with rooftop HVAC units. Often, ventilation rates far exceed code requirements, leading to excess energy consumption; conversely, insufficient ventilation can affect people's health, comfort, and productivity. The goal is to develop and test an outdoor air measurement technology that will be capable of continuous measurement of outdoor air intake flow rates.

1.2 Objectives

The project objectives are to:

- Partner with California businesses, local governments, and investor-owned utilities (IOUs) to develop, test, and demonstrate the CBES Toolkit, and validate a robust, practical, and effective SMB retrofit assessment method that includes:
  - A rapid, web-based retrofit assessment tool based on load shapes, benchmarking, and a pre-simulated database of retrofit measure energy savings results for office and retail SMBs.
  - Indoor environmental quality (IEQ) information in retrofit analysis.
  - Commercial Building Energy Saver (CBES) web services application programming interfaces (APIs) based on the identified functional requirements. The APIs will deliver SMB retrofit energy savings calculations for a wide range of web-based applications.
  - Freely available web-based CBES retrofit analysis tool, using the developed APIs to evaluate both individual and collective retrofit measures.
- Develop a prototype outdoor airflow rate measurement system for rooftop heating, ventilation, and air-conditioning (HVAC), to ensure that ventilation rates are adequate but not excessive.

1.3 The Commercial Building Energy Saver (CBES) Toolkit

The CBES retrofit software analyzes the energy performance of user's building for pre- and post-retrofit. Once the user inputs building and energy data, CBES identifies recommended retrofit measures, estimates energy savings, and returns economic and environmental results for the selected measures, and ranked by user preferences. The software provides the energy benchmarking and three levels of retrofit analysis depending on the degree of the input data provided.

- Energy Benchmarking: Use of external energy benchmarking software APIs including EnergyIQ and Energy Star Portfolio Manager. In addition, a building's electric load shape can be benchmarked against those of its peer buildings (of same type and size).
- Level 1 - Load Shape Analysis: No- or low-cost improvement analysis based on statistical models.
- Level 2 - Preliminary Retrofit Analysis: Retrofit analysis from a database that compiles the pre-simulated energy performance using prototype buildings with retrofit measures, and associated cost data for measures.
- Level 3 - Detailed Retrofit Analysis: Retrofit analysis from a real time simulation that calculates the energy performance of the building with user-configurable retrofit measure(s).

1.4 IEQ Effects and Outdoor Air Measurement Technologies

The project team conducted a review of IEQ effects related to energy retrofits and we identified key opportunities to improve IEQ. We summarized qualitative IEQ information and mitigation suggestions for categories of retrofit measures in CBES, e.g., HVAC, building shell, and lighting. For some retrofit measures, we reviewed quantitative response functions for their suitability to be included in CBES, e.g., the effects of outdoor air ventilation rates on sick building syndrome (SBS) symptoms and productivity of office workers.

In a parallel effort, the project team developed prototype systems to measure outdoor air intake rates for: 1) use during commissioning to facilitate the initial setting of dampers in outdoor air, supply air, and recirculation airstreams; and 2) throughout building operation to maintain OA intake rates at targets, thereby preventing excessive ventilation rates (VR) or insufficient ventilation to meet standards.

Chapters 2 through 6 follow:

- Chapter 2: Efficiency Measure and Smart-Meter Data Compilation
- Chapter 3: Maintaining Indoor Environmental Quality during Retrofits
- Chapter 4: Web-based Retrofit Analysis and Investment Action Plans
- Chapter 5: Stakeholder Engagement and Technology Transfer Activities
- Chapter 6: Conclusions and Next Steps

The Glossary of abbreviations follows the main body of the report. References can be found at end of the document.

CHAPTER 2:
Efficiency Measure and Smart-Meter Data Compilation

The project team developed and compiled energy performance and implementation cost data for operational improvements and retrofits targeting office and retail buildings, which were then used as inputs for CBES. This chapter documents the literature review and methodology used to develop the list of electricity and natural gas efficiency measures used in the Efficiency Measure Cost and Performance Database. We also describe the overall structure of the database, and the components and assumptions that form the technical and cost basis for the selected energy conservation measures (ECMs). The city partners supplied smart meter data for the buildings used to demonstrate CBES Toolkit. This data was collected and compiled in a database.

2.1 Literature Review

LBNL conducted a comprehensive literature review to identify and prioritize retrofit measures applicable to the SMB market segment, for inclusion into the web-based tool. This task consisted of two parts: 1) to understand best practices for efficiency improvements in small and medium commercial buildings, and 2) to develop a taxonomy and data schema which can be expanded to deliver machine-readable data for use by modeling tools and a recommendation engine. The team made concerted efforts to review materials that would contribute to development of additional measures beyond those found in the Database for Energy Efficiency Resources (DEER), published by the California Public Utilities Commission (CPUC).

Researchers developed the initial list of measures using the following resources, which enumerated the best practices in energy efficient retrofits and operational improvements. LBNL then refined this list by considering the scope of the energy model and applying the combined technical expertise of the project team.

Table 1: Sources for Retrofit Measures

Title	Description
Advanced Energy Retrofit Guide, Practical Ways to Improve Energy Performance, Office Buildings (Liu et al., 2011a and 2011b)	Presented general project planning and execution guidance for the assessment and implementation of energy efficiency measures for different types buildings that represent the overall US stock. The guide included measures that span both standard replacement/retrofit recommendations, as well as commissioning, operations, and maintenance measures that could be undertaken at low or no additional cost.

Title	Description
Database for Energy Efficiency Resources (CEC and CPUC, 2011)	CEC- and CPUC-sponsored database provided detailed component-level efficiency measures, as well as estimates of energy savings values and effective useful life. For the purposes of this task, the database was used to populate detailed retrofit measures under each major category: HVAC, Lighting, Building Envelope, Plug Loads, Misc.
2010-2012 WO017 Ex Ante Measure Cost Study Draft Report	Presented the results and findings from Work Order 17 – the Ex Ante Measure Cost Study. The primary objective of the study was to provide the California Public Utilities Commission (CPUC) and the Investor Owned Utilities (IOUs) with improved ex ante measure cost estimates to support fulfillment of CPUC policy requirements. The study included all deemed measures contained in the Database for Energy Efficient Resources (DEER), as well as non-DEER deemed measures.
Small HVAC System Design Guide (CEC, 2003)	Provided design guidance on how to improve the installed performance of small packaged rooftop HVAC systems in commercial buildings. In addition to integrated design guidance, this document included information on unit size and selection, ventilation, thermostats and controls, commissioning, and operations and maintenance.
Advanced Energy Design Guide, Small Commercial Buildings (ASHRAE 2011)	Provided best practice recommendations on ways to achieve 50% site energy savings in small to medium commercial buildings (less than 100,000 ft2). The guide provided climate-specific recommendations for the design of building systems including: envelope, lighting systems, HVAC, outdoor air requirements, service hot water heating, and plug and process loads. The guide focused primarily on new construction, but provided valuable insights in situations where a building may be undergoing a comprehensive renovation.
Integrated Office Lighting Systems: Making It Personal (CEC, 2007)	Technical brief offered design guidance, applicable codes, and efficiency improvements for design strategies which incorporated lower levels of ambient overhead lighting, with task lighting at the individual work surface.
Commercial Buildings Breathe Right with Demand-Controlled Ventilation (CEC, 2005)	Technical design guide published by the CEC offered design suggestions and benefits of using a CO2-based ventilation strategy, as opposed to prescriptive measures of CFM (cubic feet per minute) per square foot. The findings suggested that greatest savings were achieved in buildings with unpredictable occupancy patterns.
Home Energy Saver Measures Database	Home Energy Saver (HES), developed by LBNL, recommended residential energy-saving upgrades that are appropriate to the home and are relevant for the home's climate and local energy prices. HES used a measures list compiled by the LBNL research team, and although the measures list was developed for residential applications, it serves as a foundational model for the data schema that was used for CBES.

Once the initial literature review and summary was completed (see Table 1), the team filtered efficiency measures and selected a high priority set for inclusion in CBES based on the following considerations:

- Installation complexity and the corresponding impacts on costs.
- Suitability and likelihood of adoption in the SMB environment.
- Ability of the modeling platform to accurately model the energy performance of a given measure.
- Effects on indoor environmental quality

Selection of retrofit measures also considered user experience and simplicity. The team populated the measures list with detailed data, including performance characteristics, installation cost, and energy performance compared to baseline (further discussed below). The team also included some retrofit measures that are potentially beneficial to IEQ in addition to saving energy, such as avoid overcooling in summer, add a functioning economizer to HVAC, and use high-efficiency/low-pressure drop air filters.

2.2 Energy Efficiency Measures

Measures were generally divided into two categories - retrofits and no/low cost operational improvements. Retrofits typically required higher capital expenditures, sometimes calling for the replacement of equipment or building parts to improve performance. Examples include install new windows, replace boiler with high-efficiency unit, etc. Conversely, no/low cost measures typically involved minimal cost for materials and labor, but rather generated energy savings by implementing more efficient practices and operation. Examples include adjusting temperature set points to minimize mechanical heating and cooling, and equipment maintenance/tuning to optimize run conditions.

Table 2: Efficiency Measure Types

Measure Types
Building Shell
HVAC
HVAC – cooling
HVAC – heating
Indoor Lighting
Outdoor Lighting
Plug Loads
Service Hot Water

The measures were grouped into eight categories, listed in Table 2. “Building shell” refers to measures that improve the performance of the building envelope, such as wall insulation, window replacement, and adding window shades to reduce building solar heat gains. Because of the high number of available HVAC related measures, we separated them into three categories: “HVAC-cooling,” “HVAC-heating,” and “HVAC" (HVAC groups together all HVAC measures that do not fit entirely into either the heating or cooling categories). In addition, we separated lighting measures into "indoor" and "outdoor" sub-categories. “Plug loads” refer to building loads that do not belong to the other major end-uses listed, and draw power from an AC plug. Finally, the “Service Hot Water” category captures measures that can be realized in the building hot water system, such as water tank insulation and water heater upgrade.

In the Retrofit Measure Database, each measure is further delineated under “Measure Type,” with the addition of the Component and Description columns (see Table 3 for examples). Component refers to the specific part of the building or the equipment type comprising the measure, while “Description” provides details on the retrofit or improvement.

Table 3: HVAC Efficiency Measure Examples

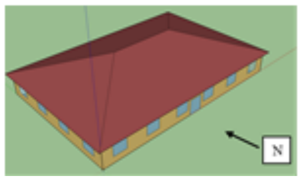
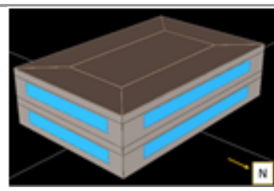
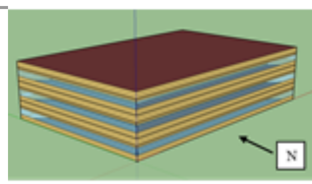
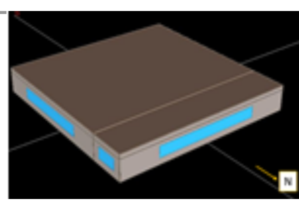
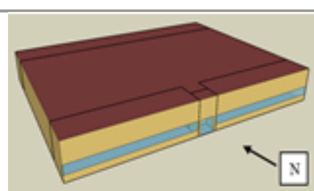
Measure Types	Component	Description
HVAC	Economizer	Install economizer on existing HVAC system
HVAC - cooling	RTU Upgrade	Replace RTU with higher-efficiency unit, SEER 14 [single zone - 3 ton cooling]
HVAC - heating	Boiler Upgrade	Replace gas boiler with higher-efficiency unit, AFUE 96 [capacity 245 MBH]

2.3 Technical Parameters and Technology Types

The project team aimed to develop a taxonomy and structure that allowed for seamless integration within the SQL database used by the simulation engine. A number of factors can significantly affect costs. The project team grouped these into technical parameters and technology types. Technical parameters include performance characteristics, equipment capacity, etc. Technology types offer different technical solutions, such as blown-in insulation vs. fiberglass insulation blankets, etc.

All efficiency measures were specified with technical parameters, which were then automatically entered in the energy model along with cost information, in order to calculate energy savings and financial returns in the form of payback period. We researched performance characteristics from the literature review sources if available, and checked to ensure that they met or exceeded the values listed in Title 24 (2013), for the respective building types, vintages, and also climate zones. Table 3 lists example performance characteristics for selected efficiency measures. Another set of technical parameters is equipment capacity; because of the different building types considered in the toolkit (Table 4), a given efficiency measure may be duplicated to include different equipment capacity options. For example, in the Rooftop Air Handling Units (RTUs) efficiency upgrade measure, three line items define the three capacities used across building types: single zone units each providing ton of cooling; 50-ton multi-zone units; and 90-ton single zone units.

Table 4: Descriptions of Prototype Buildings

Building type		Forms	Gross floor area (m^2/ ft^2)	Aspect ratio	Glazing fraction	Floor-floor height (m/ft)
Office	Small 1-story		511 / 5,500	1.5	0.21	3.05/10
	Medium 2-stories		929 / 10,000	1.5	0.33	3.66 / 12
	Medium 3-stories		4,982 / 53,628	1.5	0.33	3.66 / 12
Retail	Small		743 / 8,000	0.8	0.25	3.66 / 12
	Medium		2294 / 24,962	1.3	0.07	6.1/20
Mixed-use	retail at the 1^{st} floor, office at the 2^{nd} and 3^{rd} floors					

Technology types were also considered for the target efficiency measures. Prior knowledge of existing equipment configuration, occupant schedule, energy loads, and other details is needed to determine which technology type was best suited for a particular building. As a result, we included a diverse set of technology types in the toolkit to optimize energy performance and cost payback. Table 5 lists example technology types for selected efficiency measures.

Table 5: Efficiency Measure - Example Technology Types

Measure Types	Retrofits	Example Technology Types
Building Shell	Ceiling Insulation	Fiberglass insulation blanket
Building Shell	Wall Insulation	Blown-in insulation
Building Shell	Roof Insulation	Foam insulation
HVAC - cooling	Efficiency Upgrade	Electric cooling, Heat pump
HVAC - heating	Efficiency Upgrade	Gas Furnace, Boiler
Lighting - all	Efficiency Upgrade	Fluorescent T5 and T8, LED
Service Hot Water	Efficiency Upgrade	Electric instantaneous and storage, Gas instantaneous and storage, Hybrid (with heat pump)

2.4 Costs

As discussed previously in this chapter, a given retrofit may sometimes be duplicated in multiple measures to accommodate the different building types, vintages, and performance characteristics considered in the model. For example, there may be multiple measures for wall insulation, which describe the different insulation levels applied to the range of building vintages considered. Space layout and existing equipment configurations (and capacities) assumed for the different building types also necessitate multiple measures for a given retrofit strategy.

The implementation cost of each measure varied, and was input into the model simulation. We employed the simple payback method to analyze cost investment versus energy savings for each measure. The payback period for a given efficiency measure was computed based on three factors: 1) retrofit or operational improvement cost, 2) energy savings calculated by the CBES Toolkit for a given measure, and 3) the price of electricity or natural gas projected for the simulation period. The sources for this information are discussed below. Figure 1 demonstrates the payback periods for a range of efficiency measures simulated in a sample run.

2.4.1 Sources and Cost Estimate Methodology

The "References" section lists the information sources we used to estimate installed costs for both retrofit and no- and low-cost operational measures. Estimated installation cost typically included material, labor, and contractor overhead and profit. The Building Component Cost Community (BC3) database (PNNL 2014) and Itron Mobile Collections System (MCS) report (Itron 2014) were specifically developed for building retrofit work in California; these served as

Figure 1: Sample Model Output - Payback Period

	Measure ID(s)	Energy Cost Savings ($)	Energy Savings (kWh)	Electricity Cost Savings ($)	Electricity Savings (kWh)	Natural Gas Cost Savings ($)	Natural Gas Savings (therm)	Investment Cost ($)	Paybac (Year)
1	ECM 1	2,081	8,750	2,143	10,569	-62	-62	3,750	1.8
2	ECM 12	2,115	10,235	2,116	10,250	-1	-1	2,476	1.2
3	ECM 15	2,178	9,212	2,239	11,004	-61	-61	6,000	2.8

primary sources for the cost estimate. We used RSMeans 2014 data to develop other cost estimates and to estimate installation costs. To estimate materials and labor costs for window replacements, we used cost information listed in RSMeans 2014 to augment cost data found in COMFEN version 4.1 (LBNL 2012), which is a software tool for evaluating alternative fenestration systems for commercial building applications.

For no-cost/low-cost operational measures, cost estimation can be more challenging, and typically requires building-specific judgment calls and assumptions when estimating the number of labor hours required for a given maintenance activity.

The literature sources usually provided unit costs as "equipment replacement cost per unit," or "wall insulation per square foot of wall area," and similar. In some cases, the unit costs may not be ideal input to the simulation model. For example, in lighting efficiency upgrades, retrofit cost may be available as a per-fixture cost, but the model input takes the form of cost per floor area. In these cases we converted between unit costs based on technical information found in the literature and used assumptions as required. These methods are documented in the measures database where applicable.

2.4.2 Cost Year and Location

Each cost should include the year and location in which the estimated equipment and labor costs were based. Most installed costs found in the BC3 database were based on the year 2012 in California; Itron MCS reported 2013 average California costs.

When the cost estimate was assembled in April 2014, we used the latest RSMeans cost booklet that was based on construction cost estimates for 2014; however the online subscription edition of RSMeans reported the most current cost quarter (e.g. 2014 Quarter 2). RSMeans segments California into eight major metropolitan areas. Since the measure costs will likely be adjusted to match user-input zip code in the toolkit, we recorded the national average RSMeans costs, rather than major California metro area costs, to simplify the cost conversion process. All COMFEN costs were based on 2013 national averages.

2.4.3 Contractor Markup Costs (Overhead and Profit)

Contractor markups were included in the cost items in order to better reflect true installation costs. The Itron MCS costs already had contractor markups included in the materials and labor cost components. RSMeans explicitly lists bare labor, bare material, and total cost with contractor overhead and profits. The BC3 database and COMFEN tool, however, did not include markup costs, and we assumed a 10% markup for the costs developed using these two sources.

2.4.4 Additional Measure Information

We documented the information sources and any technical and cost assumptions for each efficiency measure in the database. This also ensures that the measure list can be revised with minimal effort in the future, to reflect changes in performance characteristics and installed costs.

The database of 75 energy conservation measures has performance and detailed cost data for each measure. The database is used in the CBES Toolkit to allow users to choose and customize retrofit measures.

Chapter 3: Maintaining Indoor Environmental Quality during Retrofits

The IEQ element of the project had two main goals: 1) to develop and incorporate information about the IEQ impacts of retrofits in CBES, and 2) to design, construct, and test a prototype system for measuring rates of outdoor air intake into HVAC systems.

3.1 IEQ Introduction and Background

Many energy efficiency retrofits applicable to small and medium commercial buildings will affect indoor environmental quality positively, negatively, or both positively *and* negatively. In particular, thermal comfort conditions and levels of pollutants in the indoor air will be modified by many retrofits. Most of the available related data are from studies in homes (Crump et al. 2009, Davies and Oresczczyn 2012, Noris et al. 2013a, Sharpe et al. 2015, Shrubsole et al 2014); however, these same effects are expected in commercial buildings. Many retrofits will change outdoor air ventilation rates and there is compelling evidence that ventilation rates affect health and performance, at least in offices and schools (e.g., Fisk et al. 2009, Haverinen-Shaughnessy et al. 2011, Mendell et al. 2013, Sundell et al. 2007). Ideally, the process of selecting retrofits should consider the potential effects of retrofits on IEQ, comfort, and health, as well as the retrofit cost and potential energy savings. In a prior project (Noris et al. 2013b), a point-based system was developed for selecting retrofits in multifamily buildings, with points assigned to account for expected energy savings, changes in comfort conditions, and changes in indoor air quality. The total point score normalized by retrofit cost was used to rank retrofits. Instead, the CBES toolkit provides information about the potential effects of retrofits on IEQ so that users of the toolkit can make more informed selections of retrofits.

Many of the retrofits that influence IEQ do so by modifying ventilation rates; improving control of ventilation rates is one of the retrofit options included in CBES. The small and medium-size commercial buildings addressed in this project often use packaged rooftop air handling units (RTUs). Available data indicate that minimum ventilation rates (MVRs) are poorly controlled in small and medium size offices and stores, as well as in larger commercial buildings and in schools (Bennett et al. 2012, Chan et al. 2014, Mendell et al. 2014, Persily and Gorfain 2008, Siefel et al. 2012). MVRs are the ventilation rates present at all times during occupancy in buildings without economizers and the ventilation rates that occur when the economizer systems supply minimum outdoor air in buildings. Several factors are likely to contribute to the poor control of MVRs. These factors include uncontrolled air leakage through building envelopes, differences between design and actual occupancy (with actual occupancy often lower), and failure to continuously operate heating, ventilating, and air conditioning (HVAC) systems during occupancy. However in almost all commercial buildings, poor control of MVRs is also a consequence of the absence real time measurement system and feedback control, and of minimum outdoor air (OA) intake rates in HVAC systems. Accordingly, manufacturers have begun to market technologies for real time measurement of OA intake rates. In a prior study, three of these technologies were evaluated and none proved consistently adequate for HVAC systems with economizers (Fisk et al 2005a, Fisk et al. 2005b), which are very common, particularly in California's mild climates. The causes of poor measurement accuracy included low, hard-to-measure air speeds when minimum outdoor air ventilation is provided, as well as complex airflow patterns (sometimes with recirculating eddies) in the outdoor air intake sections of air handlers (Fisk et al 2005 c).

Parallel to the CBES Toolkit development, this project element will help overcome the problem of poorly controlled MVRs. The project team has designed and tested prototype measurement systems (see section 3.3) for OA intake rates in RTUs, called outdoor air measurement technologies (OAMTs). The project focused on OAMTs for RTUs, because RTUS are very common and also because the project is a component of a larger effort to develop an energy retrofit toolkit for small and medium-size commercial buildings which often employ RTUs.

3.2 IEQ Content in the Toolkit

We conducted a review of IEQ effects related to energy retrofits and we identified key opportunities to improve IEQ. We summarized qualitative IEQ information and mitigation suggestions for categories of retrofit measures in CBES, e.g., HVAC, building shell, and lighting. For some retrofit measures, we reviewed quantitative response functions for their suitability to be included in CBES, e.g., the effects of outdoor air ventilation rates on sick building syndrome (SBS) symptoms and productivity of office workers. We summarized this information in a report which served as the background and framework for incorporating IEQ content in CBES.

3.2.1 IEQ Approach

IEQ content was implemented in CBES in three ways:

1. We mapped California 2013 PM2.5 (particulate matter less than 2.5 um in diameter) air monitoring data to identify areas that exceed the State's ambient air quality standards. We used an inverse distance-weighted method to determine if a zip code was located in an area with high outdoor PM2.5, based on its proximity to nearby air monitors. In CBES, the use of high efficiency air filters is recommended to buildings that are located in high outdoor PM2.5 areas.

2. For retrofit measures that can potentially affect building ventilation rate (e.g., add air economizer), quantitative relationships can be used to predict the effects on office occupants. Health care costs of SBS symptoms were obtained from the U.S. EPA Cost of Illness Handbook, and symptom prevalence was obtained from the U.S. EPA BASE Study of 100 randomly selected office buildings. The overall cost savings per worker annually from increased outdoor air ventilation rate can be calculated using outputs from EnergyPlus. In addition, work performance benefits can also be calculated using the average annual wages plus compensation for California office workers. This information is provided to CBES users in online documentation.

3. CBES IEQ recommendations include the following retrofit measure categories: envelope, HVAC, lighting, plug loads, and service hot water. We developed messages based on

the review of IEQ effects and energy retrofits. IEQ recommendations included not just benefits to occupants, but also cautions that there may be health hazards associated with retrofit work, and some measures may have adverse impacts on occupant health.

3.2.2 IEQ Results and Conclusions

Energy retrofits of HVAC systems and controls, building shell, and to a limited extent indoor lighting, are recognized as the categories with the most direct impact on IEQ that have been measured. Some of the key problems commonly found in commercial buildings also presented opportunities for retrofit measures to save energy and at the same time improve IEQ.

- Avoid overcooling in summer and overheating in winter
- Ensure outdoor air intake in all buildings
- Add functioning air economizer
- Use nighttime precooling
- Improve access to daylight in offices and retail buildings
- Use high efficiency air filters

Researchers identified a few energy retrofit software packages that take IEQ effects into consideration. However, the highly quantitative and data-driven approaches taken by these packages were not suitable for potential CBES users, who span a wide range of skill levels and may have limited access to occupant data on satisfaction, complaints, and so on. For example, TOBUS is a decision-making tool for selecting retrofit measures in office buildings (Caccavelli and Gugerli 2002). It requires an inventory of occupant complaints and questionnaire responses to give retrofit measure recommendations based on identified IEQ problems, as well as other considerations: energy consumption, functional obsolescence, and equipment deterioration.

Instead of designing a numerical system to rank or rate IEQ effects, IEQ content was implemented in CBES to be consistent with the level of detail of the available information. The recommendation to use high efficiency particle air filters was given at a zip code level, since outdoor PM2.5 concentrations vary spatially. Of the 2,602 zip codes in California, about half of the zip codes were classified as high outdoor PM2.5, largely located in air districts that are classified as PM2.5 nonattainment area in 2013 by the Air Resource Board. The areas were predominantly located in the south coast (South Coast and San Diego County) and the central valley (San Joaquin Valley) areas. About 17% of the zip codes were located too far from an air monitor for the method used to classify the outdoor PM2.5 level. These zip codes tended to be located in sparsely populated areas of California.

For office buildings that currently do not have an air economizer, HVAC upgrade measures that involve adding an economizer would greatly increase the outdoor air ventilation rate when outdoor air conditions favor free cooling. The cost savings from SBS symptoms prevalence reduction and work performance improvements were calculated for the average California office worker. The baseline condition was assumed to be 15 ft3/min per person, which is the ventilation rate required by the California Building Code Title 24. Tables 6 and 7 show the estimated monetary values if a California office building were to add an air economizer and increase the ventilation rate. The economic gains from providing more outside air ventilation are large relative to energy savings. These monetary estimates are provided to CBES users in online documentation, which is useful information to consider when including an economizer as the retrofit measure.

Table 6: Estimated cost savings from reduction in sick building syndrome (SBS) symptoms as ventilation rate increase from adding air economizer in a California office building

Ventilation Rate (ft^3/min-person)	SBS symptoms prevalence reduction	Cost savings (annual, per worker)
15 (Title 24)	--	--
17–19	5%	$8
20–22	10%	$15
23–26	15%	$23
27–30	20%	$30
31–35	25%	$38
36–43	30%	$45
44–56	35%	$53
≥57	40%	$60

Table 7: Estimated benefits from work performance improvement as ventilation rate increase from adding air economizer in a California office building

Ventilation Rate (ft^3/min-person)	Work performance improvement	Benefits to employer (annual, per worker)
15 (Title 24)	--	--
17–21	0.5%	$480
22–27	1.0%	$960
28–34	1.5%	$1,400
35–45	2.0%	$1,900
46–59	2.5%	$2,400

Ventilation Rate (ft^3/min-person)	Work performance improvement	Benefits to employer (annual, per worker)
60–84	3.0%	$2,900
≥85	3.5%	$3,400

More general recommendations on IEQ benefits and cautionary messages are displayed to CBES users for a number of retrofit measures. Some of these IEQ recommendations are the same for multiple retrofit measures with similar outcomes. For example, adding ceiling insulation and adding wall insulation can both improve thermal comfort. In addition, users are also warned that adding insulation can disturb existing building materials that may contain asbestos. CBES suggested that users contact a trained and accredited asbestos professional to determine if this is a concern. For users who want to learn more, CBES included a more detailed explanation of the health hazards of asbestos exposure, and simple measures that are likely required (e.g., controlling access to the work area) during the installation. Other building envelope retrofit measures such as air sealing can also improve thermal comfort and reduce cold draft. It is important to make sure that the building has sufficient ventilation after air sealing, otherwise indoor air quality may deteriorate.

In total, 23 IEQ recommendations were incorporated in CBES for 48 retrofit measures. Their descriptions are documented in the online user manual. The remaining retrofit measures are expected to have no obvious impact on IEQ, e.g. exterior lighting, photocell calibration, heat pump upgrade, water tank insulation, etc. Other retrofit measures may affect user experience, but not IEQ, e.g., use plug load controller, computer power management, etc.

3.2.3 IEQ Anticipated Benefits for California

The desire to ensure or improve thermal comfort and indoor air quality are important motivators for building retrofits, in addition to energy savings. A recent analysis of the Center for the Built Environment (CBE) Occupant IEQ Satisfaction Survey found that many occupants are unsatisfied with temperature and air quality (Meier et al. 2014). Among the 101 buildings surveyed in California and including only buildings with at least 35% response rate, analysis found 34% of occupants dissatisfied with temperature, and 22% dissatisfied with indoor air quality.

Research has shown that IEQ can impact occupant comfort, health, and productivity, often with significant financial implications because the costs of salaries and health benefits far exceed energy, maintenance, and annualized construction costs or rent. Information on the effects of energy retrofits on IEQ can inform the retrofit measure selection process. By providing information on potential IEQ benefits or decrements as a result of the retrofit, CBES enables users to not only consider energy cost savings, but to also consider the effects of energy retrofits on people's comfort, health, and productivity.

3.3 Measurement of Outdoor Air Intake Rates in RTUs

As detailed in section 3.1, it is important to have outdoor air intake rates that will provide adequate ventilation to meet standards and enable good indoor environmental quality, as well as to avoid excessive ventilation rates and the associated energy costs.

3.3.1 OAMT Approach

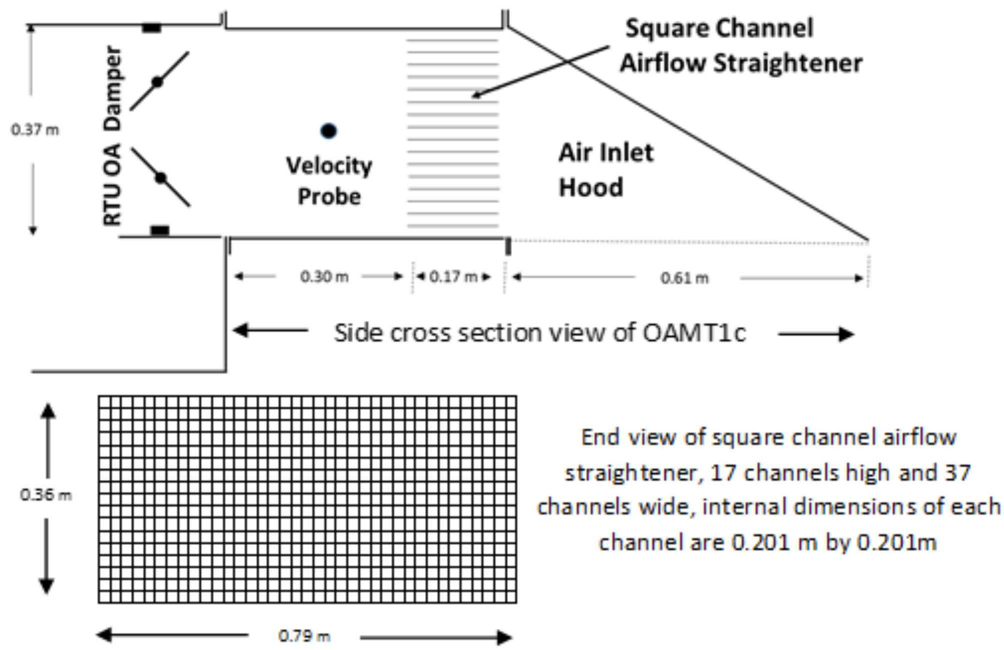
In order to accurately measure outdoor air intake rates in RTUs, researchers developed the following methodology:

1. We created a set of design targets for OAMTs, including a 20% measurement accuracy at MVR conditions, a maximum airflow resistance of 35 Pa, a simple bolt-on retrofit, and a cost less than 20% of the cost of a RTU retrofit.
2. We developed design concepts to reflect prior research findings that indicated the importance of the following:
    a. Conditioning of the airflow, so that the direction of airflow at the location of air velocity sensors is uniform and known, and
    b. Use of air velocity sensors that are accurate at the airspeeds encountered when MVRs are provided.
3. We considered and evaluated various configurations and hardware systems for OAMTs using standard engineering methods to predict air velocities, airstream pressure drops, and measurement accuracy. We also roughly estimated costs. To support these analyses, we collected data on the specifications, accuracy, and cost of electronic air velocity sensors, pressure-based velocity probes, pressure transducers, and hardware potentially suitable for this application.
4. We fabricated and evaluated four Prototype OAMTs (OAMT1a. OAMT1b, OAMT1c, OAMT2) using a unique test facility located on a building rooftop where the OAMT systems encounter variable wind speeds and wind directions, which may affect accuracy. Researchers assessed accuracy at various OA intake rates, with different probe locations, with different degrees of opening of the downstream damper, and with variable wind speed and direction.

3.3.2 OAMT Results and Conclusions

OAMT1a, OAMT1b, and OAMT1c, had similar designs, all relying on velocity probes containing electronic velocity sensors, installed downstream of airflow straighteners. OAMT1a and OAMT1c contained a single probe with four sensors, while OAMT1b contained two probes, each with two sensors. OAMT1a and OAMT1b incorporated a special air intake hood with turning vanes, while OAMT1c used an air intake hood typical of existing RTUs. OAMT2 relied on three low-cost pressure-based velocity probes downstream of three independent airflow straighteners, located in parallel with a damper that closed when the economizer was deactivated and the minimum rate of OA supply was provided. The pressure signal was measured using a pressure transducer marketed for HVAC applications. Closing of the damper increased the air velocity at the probes, resulting in a pressure signal of sufficient magnitude for accurate measurement of the OA intake rate. As examples, Figure 2 schematically shows the design of OAMT1c and Figure 3 schematically shows the design of OAMT2.

Figure 2: Schematic of OAMT1c



The project did not have the resources to determine mass production costs. The retail cost of the parts and materials used to fabricate prototypes ranged from $1200 to $1700. The fabrication cost of prototypes was as high as $4300. The cost of parts was lowest for OAMT2 because it used a pressure-based velocity measurement system, which cost less than the electronic velocity probes of other OAMT designs. The mass production costs of parts, materials, and fabrications would likely be far less than the corresponding costs of the prototypes.

With low wind speeds, all OAMT prototypes were able to provide a measure of OA intake rate accurate to within approximately ± 10% after application of calibration equations, thus all met the accuracy target of ± 20% when wind speeds were low. With some wind directions, the accuracy of OAMT1a and OAMT1b diminished substantially with elevated wind speed, reducing the utility of these systems. However, wind had no discernable effect on the accuracy of OAMT1c and OAMT2. OAMT2 was accurate within ± 10% even before calibration, except with a very low OA intake rate, where error increased to 13%

Figure 3: Schematic of OAMT2. The pressure transducer and tubing connecting the transducer to velocity probes are not shown

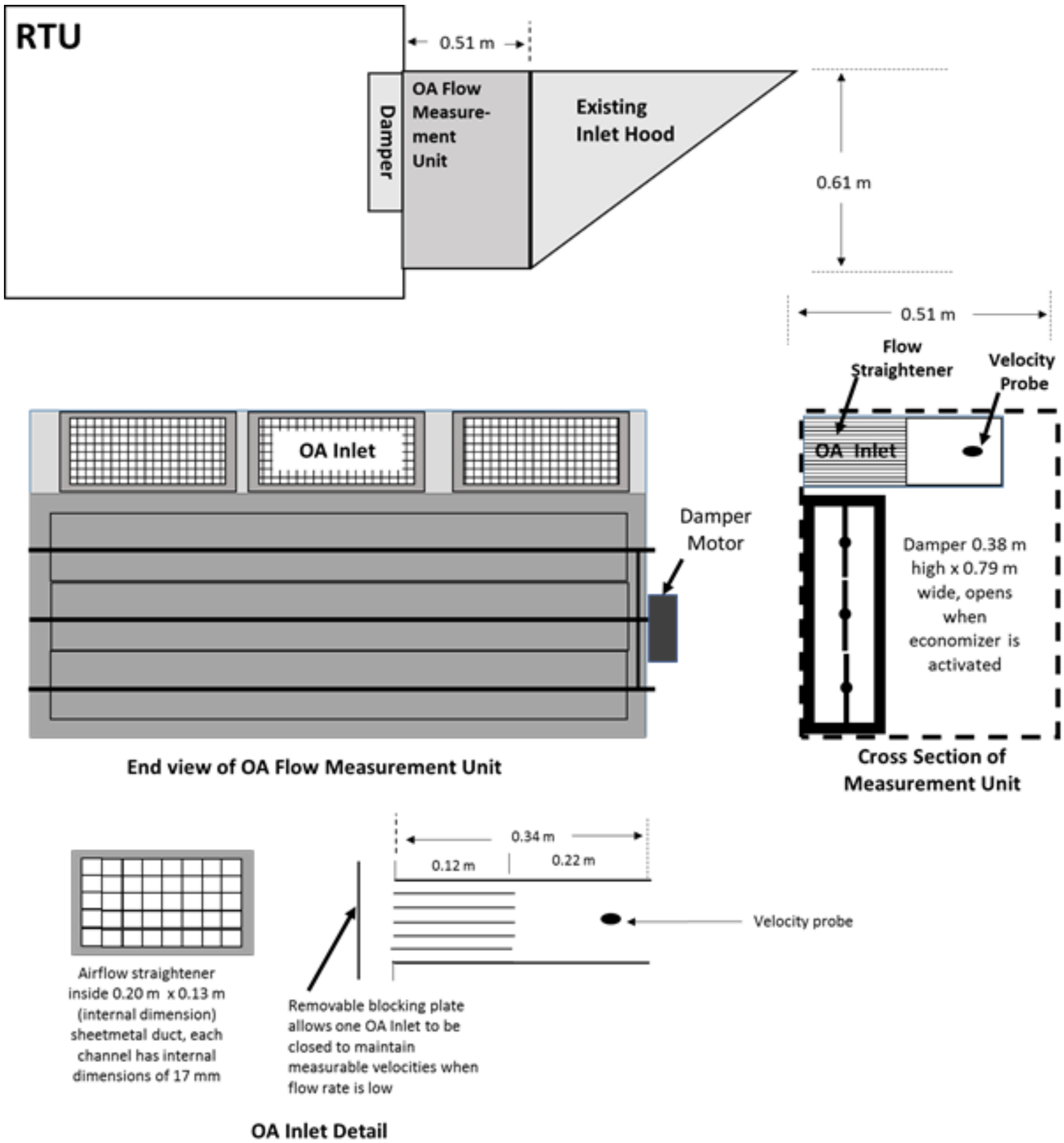


Figure 4 shows that OAMTc substantially overpredicted the true (reference) OA intake rate prior to application of a calibration equation. Limited data suggest that the electronic velocity probe provided a velocity exceeding the true air velocity. However, Figure 5 shows that OAMT1c was accurate within ± 10% after developing a calibration equation.

Figure 4: Results of tests of OAMT1c when wind speeds are low

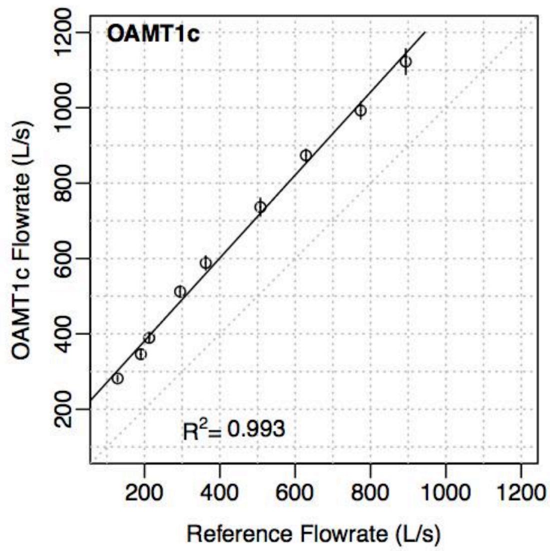


Figure 5: Errors in determination of outdoor air intake flow rates with OAMT1c after applying calibration equation 14

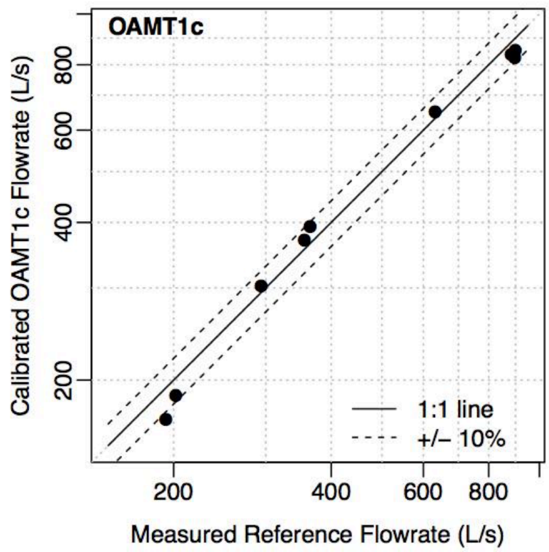
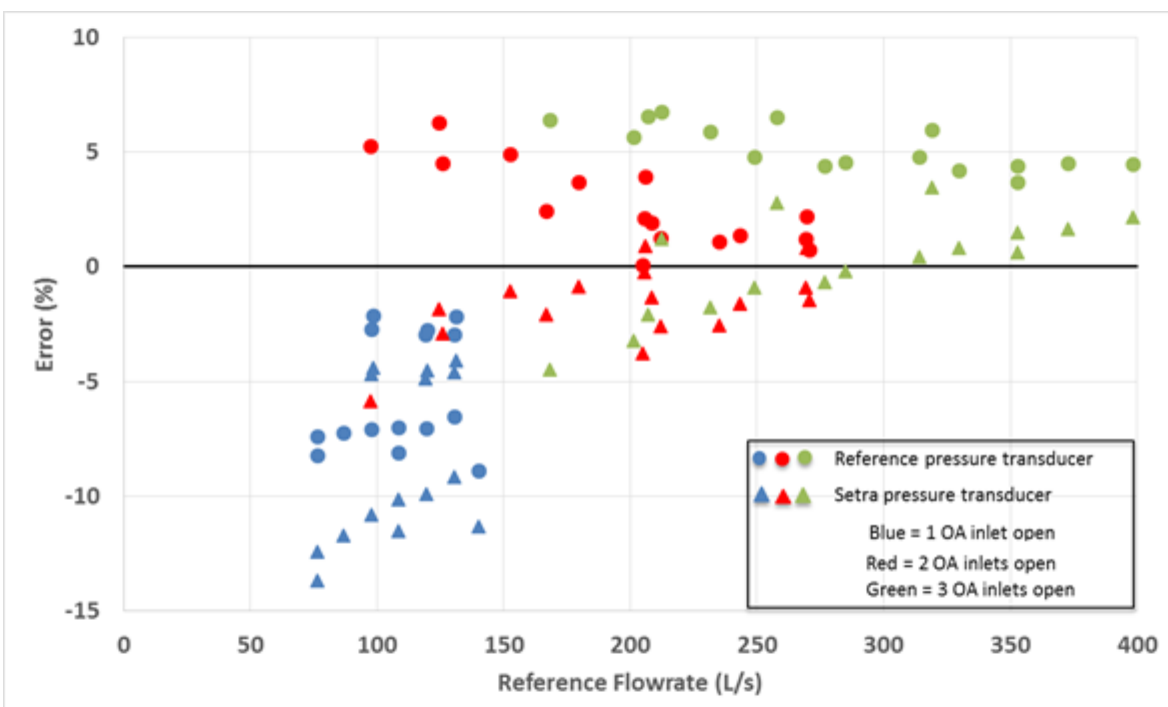


Figure 6 shows the accuracy data for OAMT2 before application of any calibrations, with errors generally less than 10%.

Figure 6: Errors in measurement of OA intake rates with OAMT2, with no application of calibration factors



The airflow resistance of all prototypes met the target of less than 35 Pa at maximum airflow rate.

In summary, the project designed, fabricated, and tested four prototypes of systems for measuring rates of outdoor air intake into RTUs. All prototypes met the ±20% accuracy target at low wind speeds, with all prototypes accurate within approximately ±10% after application of calibration equations. One prototype (OAMT2) met the accuracy target without a calibration. With two of four prototype measurement systems, there was no evidence that wind speed or direction affected accuracy; however, winds speeds were generally below 3.5 m s^{-1} (12.6 km h^{-1}), and further testing is desirable. The airflow resistance of the prototypes was generally less than 35 Pa at maximum RTU airflow rates. A pressure drop of this magnitude will increase fan energy consumption by approximately 4%. The project did not have the resources necessary to estimate costs of mass produced systems.

3.3.3 OAMT Anticipated Benefits for California

The test data indicate that the basic designs developed in this project, particularly the designs of OAMT1c and OAMT2, have considerable merit. In practice, systems for measurement of outdoor air intake rates would be used during commissioning to facilitate the initial setting of dampers in outdoor air, supply air, and recirculation airstreams, and then throughout building operation to maintain OA intake rates at targets, thereby preventing excessive VRs or insufficient ventilation to meet standards. Some examples of applications of OAMTs follow:

- As supply airflow rates in variable air volume heating, ventilating, and air conditioning (HVAC) systems are modulated, OA intake rates will often deviate from the target rates; however, OA intake measurement systems would enable dampers to be automatically adjusted to maintain the targeted MVR.
- The need for ventilation varies with occupancy. MVRs could be adjusted over time as occupancy varies. Advances in occupancy counting systems will facilitate dynamic adjustments.
- The energy costs of ventilation vary as the weather varies and during each day as temperatures and humidity vary. MVRs could be adjusted in response to outdoor temperature and humidity variations, to save energy.
- OAMT systems for measuring MVRs will facilitate peak demand response by enabling a controlled temporary reduction in MVRs to a known value; this will reduce peak energy demands and associated high energy costs.
- OAMT systems that measure OA intake rates when the economizer is activated could detect faults in economizer systems. For example, the measurement system would detect when the economizer fails and does not increase the VR during mild weather.

Commercialization and use of these or similar OAMTs would benefit California ratepayers by enabling MVRs to be maintained at the targeted ventilation rates. Excess energy use from over ventilation, which is common in offices and retail buildings, would be avoided. Instances of poor indoor air quality resulting from insufficient ventilation would be reduced. Advanced ventilation control strategies and demand response strategies could be implemented using these technologies. Further analyses are needed to quantify the energy savings potential. Modeling of the effects of different ventilation rates on HVAC energy use provides an indication of the magnitude of potential energy savings. The dependence of HVAC energy consumption on different MVRs, ranging from no mechanical ventilation to mechanical ventilation at twice the requirement of Title 24, was modeled by Dutton and Fisk (2014) for offices in California and by Dutton and Fisk (2015) for a medium size retail building in California. For California offices with economizers, 50% and 100% increases in Title 24 prescribed MVRs increased HVAC modeled energy use by 7.6% and 21.6%, with larger effects for small offices. Office buildings without economizers realized a few percent energy savings in many climate zones by increasing VRs up to 150% of the current Title-24-required MVR, because cooling energy savings exceeded heating energy increases. In the medium-size retail building, projected gas heating energy and total HVAC energy increased markedly with VR, similar to the projected effects in small offices. For example, increasing the MVR from the Title 24 requirement to 150% of the Title 24 requirement increased HVAC energy by 22% and increased total building energy consumption by approximately 7%.

Chapter 4: Web-based Retrofit Analysis and Investment Action Plans

The CBES Toolkit provides a rich feature set, and this chapter describes an overview of the software architecture, related databases, levels of analysis, licensing options, and benefits to California.

4.1 Overview of the CBES Toolkit

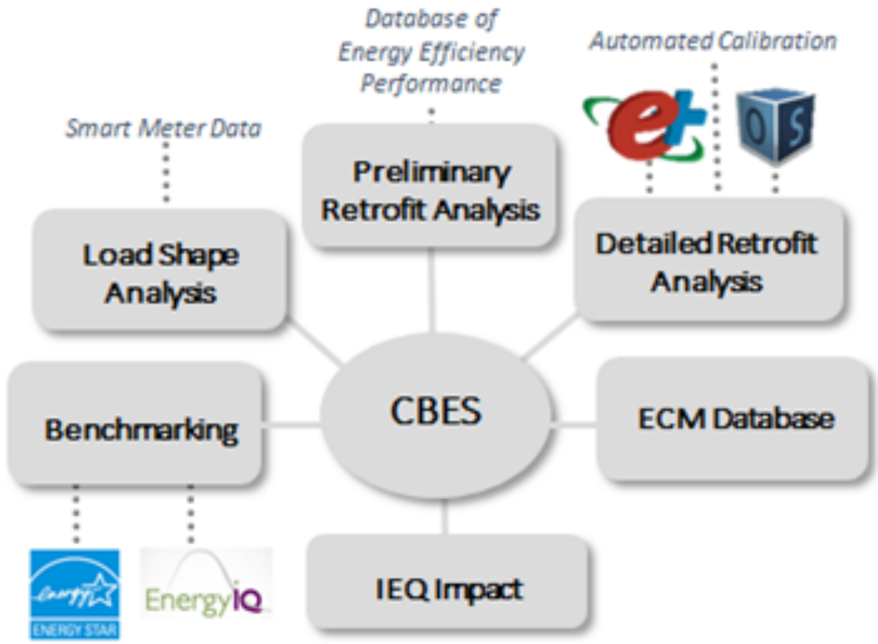
Figure 7 shows the key components of the CBES Toolkit. CBES provides the energy benchmarking and three levels of retrofit analysis depending on the input data:

- Benchmarking is provided using the EnergyIQ and Energy Star Portfolio Manager score, so that building owners and managers can see how the building performs compared to its peers;
- Level 1: Load Shape Analysis identifies unexpected changes in energy use patterns and potential building operation improvements using statistical analysis of the building's 15-minute interval electric load data. Level 1 usually recommends no- or low-cost operation improvements;
- Level 2: Preliminary Retrofit Analysis provides a quick, pre-simulated assessment of retrofit measures and their energy and cost benefits. Level 2 uses a lookup table developed from CBES' energy efficiency performance database, which is compiled from results of about 10 million EnergyPlus simulations covering seven prototype buildings, 16 California climate zones, 75 ECMs and their associated cost data; and
- Level 3: Detailed Retrofit Analysis performs on-demand energy simulation using EnergyPlus to calculate the energy performance of the building with user-configurable ECMs and detailed description of the building and its operation characteristics. Notably, as described in the previous chapter, the CBES Toolkit considers the impacts of ECMs on IEQ during the retrofit of a building.

In Level 2 and Level 3, users can specify investment criteria to rank retrofit measures by priority: maximizing energy cost savings, maximizing energy savings, minimizing CO2 emissions, minimizing investment cost, and minimizing payback year. If the last two options are selected, additional inputs are needed -- maximum budget and maximum payback year are required.

The CBES Toolkit has two main components, the CBES App and the CBES API. The CBES API guides the application programming interface (API) to command the full features of the CBES retrofit analysis. The CBES App is a web-based prototype app aimed at demonstrating the main features and provides a sample user interface that calls the CBES API.

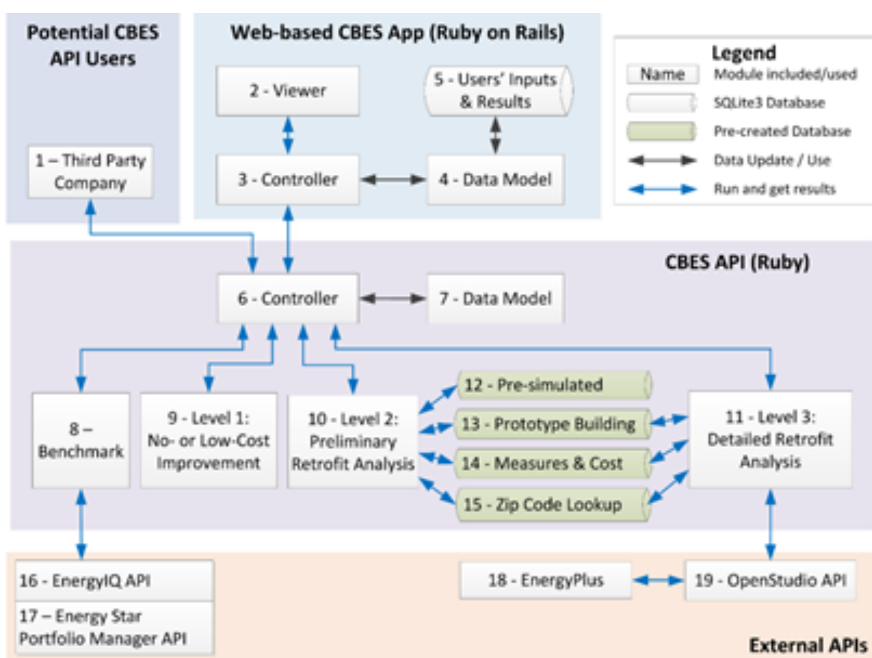
Figure 7: Key components of CBES Toolkit



4.2 Software Architecture

Figure 8 shows the schematic diagram of the CBES Toolkit software architecture. The CBES API is the core of the toolkit. CBES utilizes three external APIs and four databases, including the pre-simulated Database of Energy Efficiency Performance, the prototype buildings database, the ECMs and cost database, and the zip code database. Researchers developed a publicly accessible web-based CBES application (CBES App) to demonstrate the functionality of the CBES API. The software architecture has three layers: (1) the CBES API, the core; (2) the External APIs, the bottom layer, and (3) the top application layer with third party applications/graphical user

Figure 8: The software architecture of the CBES Toolkit

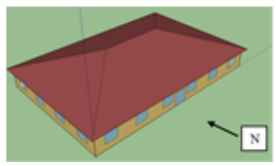
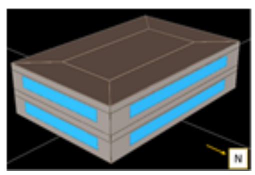
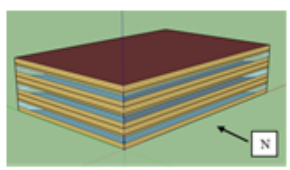
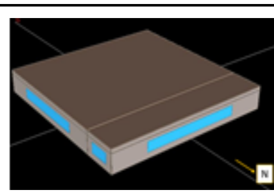
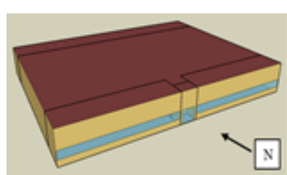


interfaces (GUIs) and CBES Web App. The object-oriented software architecture of CBES enables future expansion to cover more building types, more climates, and more retrofit measures and emerging building technologies.

4.3 Prototype Buildings

The CBES Toolkit uses prototype building models for the Level 2 and the Level 3 Retrofit

Table 8: The prototype buildings in the CBES Toolkit Analyses

Building types		Gross floor area (m^2 / ft^2)	Forms	Climate zones	Vintages
Office	Small 1-story	511 / 5,500		CZ 1: Arcata CZ 2: Santa Rosa CZ 3: Oakland CZ 4: Sunnyvale CZ 5: Santa Maria CZ 6: Los Angeles CZ 7: San Diego CZ 8: El Toro CZ 9: Pasadena CZ10: Riverside CZ11: Red Bluff CZ12: Sacramento CZ13: Fresno CZ14: China Lake CZ15: El Centro CZ16: Mount Shasta	Before 1978 1978-1992 1993-2001 2002-2005 2006-2008 2009-2013
	Medium 2-stories	929 / 10,000			
	Medium 3-stories	4,982 / 53,628			
Retail	Small	743 / 8,000			
	Medium	2,294 / 24,962			
Mixed -use	Retail at the 1st floor, office at the 2nd Floor (929 / 9,996)				
	Retail at the 1st floor, office at the 2nd and 3rd Floors (1,394 / 14,494)				

Analyses. The prototype buildings were developed based on DEER (CEC 2011), the DOE reference buildings (Deru et al. 2011), and California Title 24 building energy standards (CEC 2013). The prototype building models represent seven small and medium-sized office and retail building types in all 16 climate zones in California at six vintages (year built) (Table 8). The six vintages are: Before 1978, 1978-1992, 1993-2001, 2002-2005, 2006-2008, 2009-2013, each representing a specific version of Title 24. The prototype models contain detailed characteristics of the building and systems, internal loads, and operation schedules.

4.4 Energy Conservation Measures

As discussed in Chapter 2, the CBES Toolkit includes a rich set of ECMs to be considered as potential retrofit measures. The ECMs database has detailed descriptions of the technical specifications, modeling methods, and investment cost for each ECM. The measures data are compiled from various sources and cover typical and emerging building technologies of the building envelope, HVAC, indoor lighting, plug loads, service water heating, outdoor lighting, and building operation and maintenance. A sample list of ECMs is shown in Table 9.

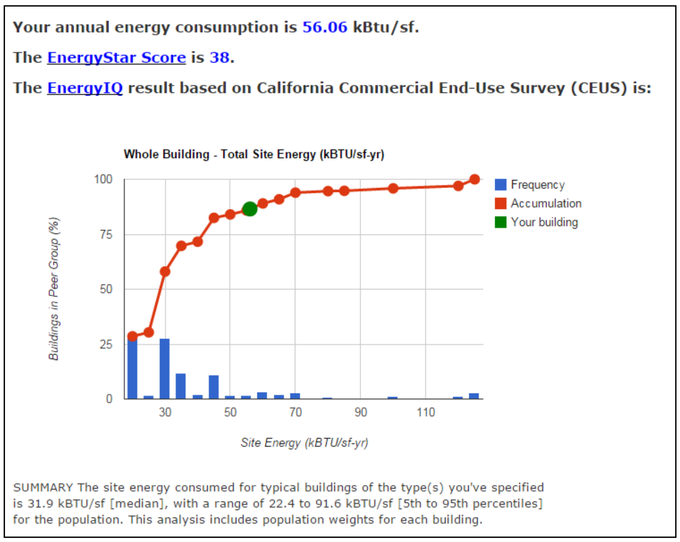
Table 9: A sample list of energy conservation measures in the CBES Toolkit

Category	Component	Name	Description
Lighting	Interior Lighting Equipment Retrofit	Replace existing lighting with LED upgrade (0.6W/sf)	Replace existing lighting to LEDs with 6.5 W/m2 [2.38 Btu/h/ft2]. LEDs consume less power and last longer than fluorescent lamps. A retrofit kit is recommended for converting ballasts. Replacement may improve lighting quality.
Plug Loads	Equipment Control	Use Plug Load Controller (30% efficient from Baseline)	Connect plug loads to a smart plug strip with some or all of the following functions: Occupancy sensing, load sensing, timers, remote control.
Envelope - Exterior Wall	Exterior Wall	Apply Wall Insulation (R21)	Apply blown-fiberglass insulation (R21) to wall cavity will help maintain the thermal comfort. Insulation provides resistance to heat flow, taking less energy to heat/cool the space.
Envelope - Roof	Roof	Reroof and Roof with Insulation	Demolish existing roof, install insulation (R24.83) and reroof to reduced unwanted heat gain/loss. This measure is most applicable to older roofs.
Envelope - Window	Window	Replace fixed-window to U-factor (0.25) and SHGC (0.18)	Replace existing window glass and frame with high performance windows by changing the U-factor and SHGC of the window material. The U-factor is a measure of thermal transmittance and SHGC stands for Solar Heat Gain Coefficient, values taken as 0.25 Btu/(h·ft2·°F), SHGC: 0.18. The SHGC and U-factor are 30% below Title 24 values.
Service Hot Water	Storage Tank	Efficiency Upgrade of the Gas Storage Water Heater	Replace the existing service hot water heater with more efficient gas storage unit, with better insulation, heat traps and more efficient burners to increase overall efficiency of (0.93).
HVAC - Cooling	Cooling System	Packaged Rooftop VAV Unit Efficiency Upgrade (SEER 14)	Replace RTU with higher-efficiency unit with reheat, SEER 14. Cooling only; include standard controls, curb, and economizer.
HVAC - Economizer	Ventilation	Add Economizer	Install economizer for existing HVAC system (includes temperature sensors, damper motors, motor controls, and dampers). Typically an economizer is a heat exchanger used for preheating.
Envelope - Infiltration	Infiltration	Add Air Sealing to Seal Leaks	Air sealing can reduce cold drafts and help improve thermal comfort in buildings. Air sealing is a weatherization strategy which will change the air exchange rate and IAQ.

4.5 Energy Benchmarking

For energy benchmarking, the CBES Toolkit provides a platform to integrate existing benchmarking tools, including EnergyIQ and Energy Star; CBES can be extended in future to include other benchmarking tools, e.g. the Building Performance Database (bpd.lbl.gov). Figure 9 shows an example of benchmarking results from CBES. In this case, the building has an Energy Star score of 38 (a score of 75 or higher qualifies a building for Energy Star certification) and consumes more energy than 80% of peer group buildings. In other words, the building exhibits poor energy performance and therefore represents a significant energy savings potential for retrofitting. The data needed for benchmarking are: (1) building information: type/use, vintage, location and floor area, and (2) Twelve months of energy usage data.

Figure 9: Example benchmarking results from the CBES Toolkit

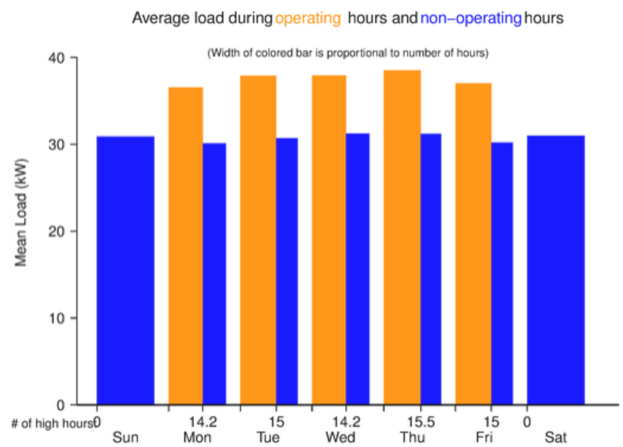


4.6 Load Shape Analysis – Level 1

The CBES Toolkit provides load shape analysis to identify low- or no- cost improvement opportunities based on statistical analysis of the smart meter data of a building. Figure 10 shows an example of the analysis results from CBES, which calculates the operational and non-operational hours, as well as the average load during those hours. The results indicate that the building has quite high energy consumption during the non-operational hours, which may be caused by leaving the lights and/or equipment on. The results can also include the sensitivity of building energy use vs. outdoor air temperature, which indicates a building's overall envelope insulation performance or amount of outdoor air for ventilation or cooling. The data needed for the load shape analysis are: (1) smart meter data, 15-minute interval electricity use, (2) building floor area, and (3) outdoor air temperature (optional).

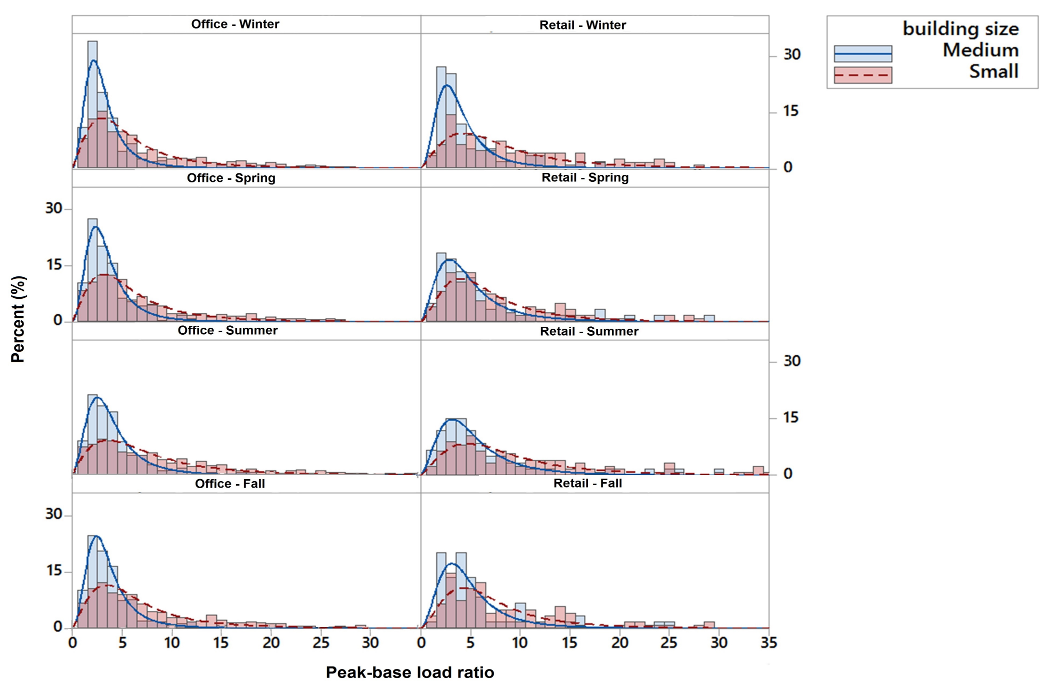
Load shape benchmarking (Luo et al. 2017) was based on smart meter data at 15-minute intervals. Researchers assessed the energy use time series for several thousand buildings, and

Figure 10: The example load shape analysis results from the CBES Toolkit



analyzed load shape in tandem with building characteristics such as building size and building type. Buildings were grouped into four categories - small office buildings, small retail buildings, medium office buildings, and medium retail buildings. Researchers then determined statistical distributions of the load shape parameters (Figure 11) and the clustered representative load patterns for each category of buildings (Figure 12).

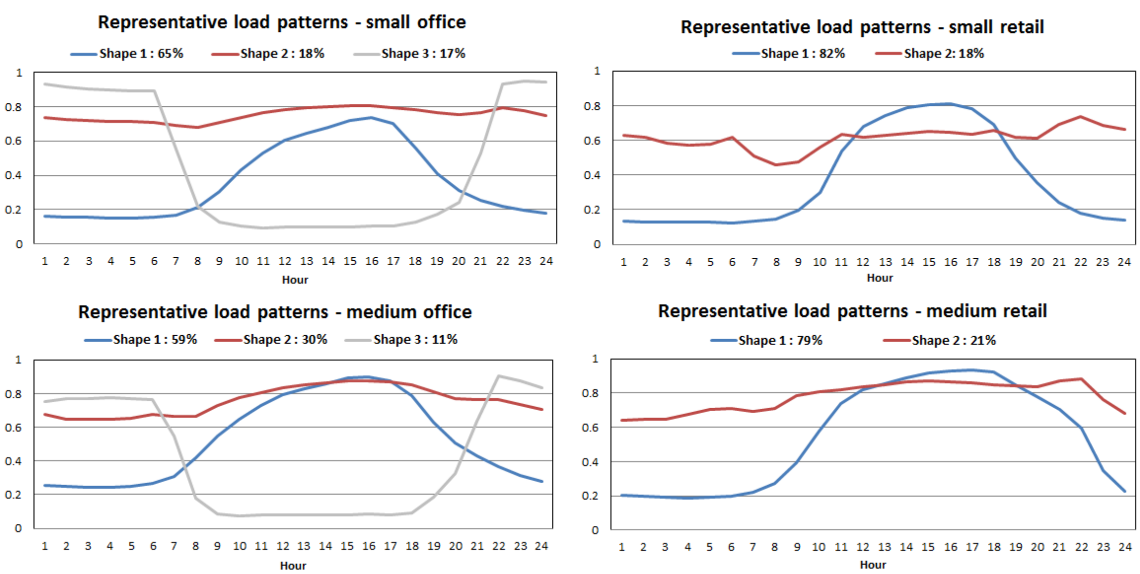
Figure 11: Histogram of peak-base load ratio for each building category



Using this methodology, researchers developed a number of benchmarking metrics measuring different aspects of the building operation performance, such as the peak-base load ratio, the number of hours a building is "on" (on-hour duration), and the workday/non-workday load ratio. Specifically, the statistical load shape parameters indicate whether the building is fully shut down during non-operation hours and non-working days, while the normalized load curve reveals the detailed load shape features during working hours, such as the load rise time and fall time.

Utility customers can benchmark their building's operational performance by comparing the load shape against peer buildings in the database. This comparison could highlight opportunities for operational improvements and energy retrofits, some of which may be low- or no-cost.

Figure 12: Clustered representative load patterns for each building category in summer



4.7 Preliminary Retrofit Analysis - Level 2

The Preliminary Retrofit Analysis feature aims to provide a quick assessment and screening of potential ECMs at the early stage of a retrofit project. DEEP is an SQL-based database with energy performance of 75 ECMs for various building types and climates. Researchers created DEEP from pre-simulated results of about 10 million EnergyPlus simulation runs on clusters in the DOE's NERSC supercomputer center. *Running EnergyPlus simulations at this scale would take about 40 years on current desktop computers*! The minimum input data needed for the preliminary retrofit analysis include: (1) building information: type/use, floor area, vintage, and location, and (2) investment criteria, e.g. maximizing energy savings, cost savings, CO_2 reduction, or economic payback. The measures identified from the Level 2 preliminary retrofit analysis can feed in to the Level 3 detailed analysis; additional building data will allow the user to customize the prototype building to better match the user's building.

4.8 Detailed Retrofit Analysis - Level 3

Detailed building energy models can help identify and quantify the energy savings and cost of most retrofit measures. The detailed retrofit analysis provides a streamlined process to create and run detailed EnergyPlus models based on the user's customized building information. This module enables building owners and managers to make retrofit decisions by providing the quantified energy and cost performance of the retrofit measures. Based on the zip code, building type, and the year built, CBES aggregates default values for all the parameters required to create a detailed energy model. Default values are extracted from different versions of energy standards such as California Title 24 and ASHRAE 90.1. Researchers developed an automatic model calibration procedure for CBES to bring the predicted energy consumption close to the utility bills of the baseline building before evaluating the ECMs. Based on the detailed calibrated baseline energy model, single retrofit measures as well as user-defined packages of measures can then be evaluated to look at their energy savings and economic metrics. The detailed level of analysis enables energy professionals to enter specific building data to customize the prototype buildings to better match their actual buildings. Knowledge of building systems and energy modeling are required to use this level of analysis effectively and correctly.

4.9 CBES App

The publicly available web-based application (CBES App) for the small and medium office and retail buildings in California provides an easy platform for retrofit analysis. CBES analyzes the energy performance of a user's building for pre- and post-retrofit, in conjunction with user's input data, to identify recommended retrofit measures, energy savings, and economic analysis for the selected measures. The App allows for streamlined data collection and performance measurement systems that maximize the existing data and approaches used in this section, and displays the results using the App platform. The goals of the App are as follows:

- Enable and accelerate SMB retrofits by providing a user-friendly platform.
- Demonstrate new advanced systems, methods, and tools with local cities and deployment partners, directly supporting AB 758 energy programs.
- Collaborate with local cities and communities to demonstrate innovative and verifiable approaches to energy-efficient community-scale planning that result in more efficient buildings to help California meet zero net energy and retrofit goals.

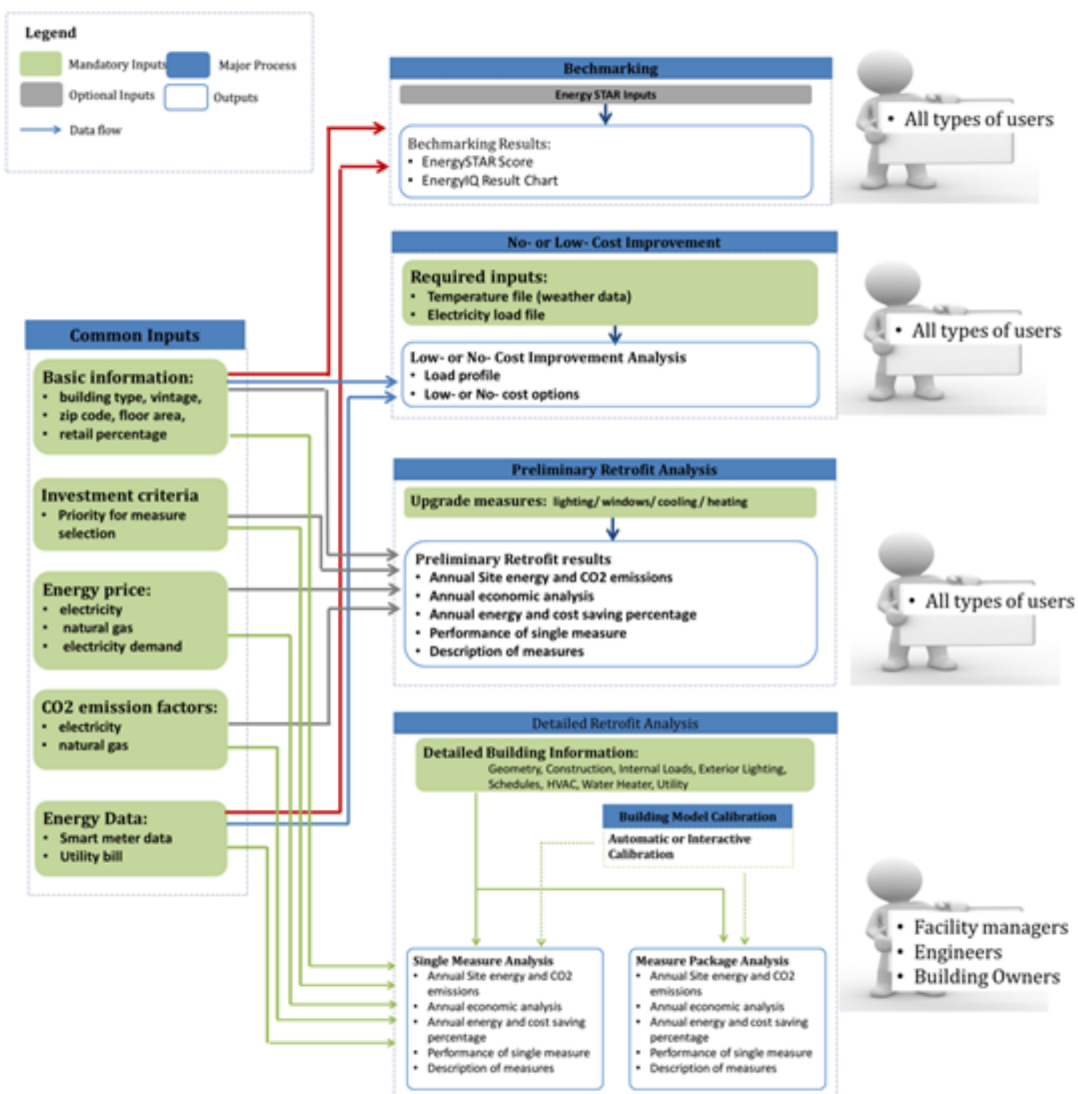
During the course of development, LBNL partnered with California businesses, local governments, and investor-owned utilities (IOUs) to develop, test, and demonstrate the CBES Toolkit. CBES has proven to be a robust, practical, and effective tool to assess retrofits.

4.9.1 App Description

The app consists of a series of tabs including: 1) introduction, 2) common inputs, 3) benchmarking, 4) no- or low-cost improvements, 5) preliminary retrofit analysis and, 6) detailed retrofit analysis and 7) contacts. CBES allows the user to jump to any level of evaluation, after the common inputs have been entered.

In the common inputs page, a new analysis will open a new or existing session, and assign a session number if needed. As a first step, hte user will enter a minimum amount of information in the common inputs page. These inputs include the basic building information (i.e. year built, California zip code, gross floor area, retail floor area), the investment criteria (maximum budget, maximum payback year), the priority for measure selection (i.e. maximize energy cost savings, maximize energy savings, minimize CO2 emissions, minimize investment cost, minimize payback period), the energy price, the CO2 emission factors and the energy data input. Upon successfully uploading the common information, users can simply click the benchmark button to launch the building benchmark analysis using both Energy Star and EnergyIQ.

Figure 13: Overview of the CBES App features



To identify potential no- or low-cost improvements, users can upload a local outdoor temperature file and electricity use file. The user can choose the source of the weather data, which can come from a nearby airport or be user-specified data. For the preliminary retrofit analysis, more details about the building are required, and the user will need to specify the upgrades of the building that have been completed to date. CBES provides options in lighting-interior, windows, cooling system and heating system for selection by the user. Following the completion of the analysis, CBES displays the results, including selected specific retrofit measures that match the input criteria, the calculated annual site energy, the CO2 emissions, an annual economic analysis, and an annual energy and cost saving percentage. If the user desires additional refinement, then the detailed retrofit analysis can be completed.

For the detailed retrofit analysis, on-demand energy simulations using OpenStudio and EnergyPlus calculate the energy performance of the building with user-configurable ECMs. In addition to the basic building information provided in the Common Inputs page, detailed building information needs to be inputted in this page for the Detailed Retrofit Analysis. These inputs are generally categorized as: 1) geometry, 2) construction, 3) internal loads, 4) exterior lighting, 5) schedules, 6) HVAC, 7) water heater, 8) utility rates. Once this information has been input, CBES optionally conducts a building model calibration. The calibration tunes the user inputs to the detailed building information, using the monthly energy data provided in the Common Inputs section. The aim of the calibration is to create an improved building model that more closely reflects the real building conditions. The calibration, an optional feature, has two options: automatic mode or customized mode. Following the calibration, selected measure analysis can be conducted, where specific measures are added to the measure list, by providing either a measure name or measure ID. At the completion of this step, a single measure analysis is performed. From the existing measure list (from the single measure analysis), users can pick measures and form a measure package to be applied and evaluated. Users can make up to four packages for a parallel comparison. The Measure package analysis result gives the performance of all created packages. A final tab, Miscellaneous, allows for the user to download all IDF files, including the baseline model, retrofit models with single measure, and retrofit models with measure package. An overview of the CBES App features is shown in Figure 13.

4.10 Anticipated Benefits for California

California has the goal to retrofit 50% of existing commercial building stock to reach zero net energy by 2030 (CPUC, 2011). To meet this goal, it is critical to enable stakeholders to identify and evaluate retrofit measures. CBES is a free and easy-to-use tool that ranks retrofit solutions based on various energy performance and economic metrics. Project partners have demonstrated that CBES can be adopted by cities and consultants to support their energy efficiency projects.

The implementation and use of the CBES Toolkit to determine cost effective retrofits for small and medium office and retail buildings and for spaces occupied by small businesses is expected to increase the percent of energy retrofits undertaken in these target sectors. The tool will be used by architects, engineers, energy consultants, facility and property managers, and building and business owners to systematically identify and rank energy retrofit opportunities. We anticipate that the level of predicted energy savings will fall into two categories:

- Operations and maintenance savings - assumes that 15% of all target building owners, managers, and energy consultants use the load shape benchmarking tool and obtain energy savings averaging 10%.
- Retrofit simulation - assumes that the savings scale directly with the complexity of the simulation applied to a specific building, with savings ranging from 5-10% for level 1 (no simulation), 10-20% for level 2 (pre-simulation), to 20-40% for level 3 (detailed simulation).

We developed the following assumptions to estimate a conservative average whole building or premises energy savings potential:

- 10% savings by using the load shape benchmarking tool in 15% of the statewide small office and retail building population by 2030, and
- 30% savings by using the simulation portions of the tool in 10% of the same population by 2030.

Using the above assumptions, estimates yield 464 GWh of electricity savings, 133.5 MW of non-coincident peak demand savings, 2.5 Mtherms of natural gas savings, $62 Million of energy-related cost savings, and emissions will be reduced by a projected 188,198 MTCO2e by 2030. Further, assuming an average three year payback for implemented energy retrofits, 558 people could be employed during the retrofit implementation period, and 3,165 direct, indirect, and induced jobs could be created each year for the life of the investment.

Expansion to all small and medium size buildings in California by 2030 could result in 1,587 GWh of electricity savings, 356 MW of non-coincident peak demand savings, 30.2 Mtherms of natural gas savings, $227 Million of energy-related cost savings, reduce emissions by 757,866 MTCO2e. In addition, 2,041 jobs could be created during the retrofit implementation period, and 11,569 direct, indirect, and induced jobs could be created each year for the life of the investment.

Chapter 5: Stakeholder Engagement and Technology Transfer Activities

CBES targets a broad audience, and the LBNL project team reached out to potential users and third-party developers of the CBES Toolkit via public workshops, seminars, webinars, technical papers, conferences, and presentations. The catalogue in Figure 14 below provides a list of project team activities.

5.1 CBES Workshops and Webinars

The CBES project enlisted stakeholder and partner engagement through open workshops at both the launch and wrap up of the project. A summary of each gathering is provided below.

5.1.1 Stakeholder and Partner Workshop

On December 5, 2013, LBNL held the Stakeholder and Partner Workshop to launch project activities and serve as a forum for stakeholders, collaborators, and partners. Workshop attendance numbered 37 onsite attendees, and 13 remote participants, spanning utilities, energy companies, nonprofits, consultants, other national laboratories, UC Davis, BayREN, Prospect Silicon Valley, DOE, and the Energy Commission.

Workshop content focused on the elements of the SMB Toolkit - web-based retrofit analysis, energy conservation measures and smart meter data, low-cost/no-cost operational improvements, and maintaining indoor environmental quality during retrofits. The workshop concluded with a planning session for the workshop city partners on the toolkit demonstrations.

Workshop Conclusions and Summary

Workshop participants in concert with project team members concluded the following:

- One of the strengths of CBES is that it considers whole-building, interactive effects. This capability is lacking in many of the existing tools.
- There are existing tools for asset rating, benchmarking, and also for other energy efficiency purposes. It is important that the design of the toolkit be as flexible as possible to allow integration with other tools.
- It is important to evaluate accuracy of the toolkit and enable its performance be tracked. Eventually, comparison with measured data should be incorporated to improve the toolkit.
- Building owners, building managers, and tenants can result in split incentives -- a serious challenge. Retrofit measures need to be actionable not just by one sector of the users, but some options must be available to other users.
- Getting access to interval data continues to be a challenge, due to privacy concerns.

- IEQ considerations are an important driver in addition to energy efficiency. Providing IEQ information to users of the toolkit is a good way to educate them on the potential benefits from retrofit measures beyond energy savings. In some cases IEQ effects may be critical to the user.
- Development of this toolkit needs to stay current with other initiatives that are closely related to this work, e.g. DOE Asset Rating Tool, and EPA Energy Star.
- A useful next step of the toolkit is to allow the consideration of renewable energy.

5.1.2 CBES Open Workshop

LBNL held the CBES Open Workshops on March 19, 2015. The day was broken into two sessions -- the morning focused on our city partners and collaborators (20 onsite and four virtual participants), and the afternoon session was directed toward potential users of CBES (23 onsite and 22 virtual participants).

Workshop participants spanned a range of sectors, representing our partner cities, utilities, Energy Watch, energy companies, nonprofits, consultants, other national laboratories, our collaborators, large companies, the California Air Resources Board, Bonneville Power Administration, DOE, and the Energy Commission.

Workshop Description

In the morning session, LBNL team members gave an overview and demo of CBES, discussed the city partners' experience using the toolkit, presented strategies for fine-tuning CBES, and described the availability of the software. In the concluding element the project team requested feedback, and opened discussion and Q&A for city partners.

The afternoon session was an open workshop, consisting of a CBES overview and demo, as well as feedback, discussion, and Q&A. The audience asked questions about the capabilities and features of CBES, licensing plan and options, access to the software, backend scalability, updating provisions, and recommendations for future releases.

5.1.3 CBES Developers' Webinars

The first Developer's Webinar was conducted on March 31, 2015, and the second was held April 8, 2015. A total of ten developers participated in the two webinars, and their response to CBES was enthusiastic.

5.2 Technology Transfer

In addition to the workshops and webinars, a number of outreach activities were performed throughout this project.

1. LBNL Seminar (July 2, 2015)
2. IBPSA-USA Seminar (February 17, 2015)
3. Workshop as part of the Laney College National Science Foundation (NSF) project (January 13, 2017).

Comprehensive documentation was developed in parallel with the CBES Toolkit, including:

1. CBES Software Functional Specification
2. CBES Software Testing Plan
3. CBES User Manual
4. CBES Tutorial
5. Software Developers' Guide to the CBES API

A number of other materials were developed over the course of the project that highlighted the features and capabilities of the CBES toolkit:

1. CBES Workshop White Paper
2. Demonstration Sourcebook
2. CBES Flier
3. DEEP Flier

The catalogue in Figure 14 below provides a list of project team activities, including papers and presentations resulting from this work.

5.3 Licensing Overview

The LBNL project team reached out to potential users and third-party developers of the CBES Toolkit via public workshops, seminars, webinars, and presentations. Two licensing options were developed: (1) a no-fee license for non-profit use, and (2) a one-time fee-based non-exclusive commercial license. End users will have access to the free CBES web app hosted at LBNL. These license agreements have been in place since July 2015. The software team will continue talking with interested parties about adopting and integrating CBES with their software tools and platforms.

Figure 14: Catalogue of Outreach Activities

Catalogue of Stakeholder Engagement and Technology Transfer Activities

- Outreach activities
- Presentation or briefing
- Paper or poster
- News releases, electronic or digital publications, etc.
- Other (licensing, etc.)

Date	Category	Description	Lead
9/20/13	Presentation or briefing	C3 Energy - SMB Toolkit Presentation and Kick	MAP, TH
12/5/13	Presentation or briefing	Stakeholder and Partner Kick-off Workshop	All
3/27/14	Presentation or briefing	City Partners Update on SMB Toolkit - Webinar	All
9/19/14	Presentation or briefing	City Partners Update on SMB Toolkit - Webinar	All
11/12/14	News releases, electronic or digital publications, etc.	LBNL Report: *"Review of Existing Energy Retrofit Tools."* 6774E.	TH et al.
11/12/2014	Paper or poster	Lee SH, Hong T, Piette MA. *"Review of Existing Energy Retrofit Tools."* Department of Building Technology and Urban Systems, Ernest Orlando Lawrence Berkeley National Laboratory Report, LBNL-6774E, 2014.	SHL, TH, MAP
12/10/14	Presentation or briefing	Transactive Energy Conference, Portland, OR	MAP, PP
12/10/14	Paper or poster	*"Automated Measurement and Verification of Transactive Energy Systems, Load Shape Analysis, and Consumer Engagement"*	MAP, PP
12/12/14	Presentation or briefing	C3 Energy - SMB Toolkit Demo	All
12/17/14	Presentation or briefing	Met PG&E to showcase and discuss CBES use to support PG&E's EE programs. Requested smart meter data for commercial building benchmarking.	MAP
1/25/15	Presentation or briefing	Presentation of DEEP (also a conference paper) at the ASHRAE winter conference	SHL
1/25/15	Paper or poster	Lee SH, Hong T, Sawaya G, Chen Y, Piette MA. *"DEEP: A Database of Energy Efficiency Performance to Accelerate Energy Retrofitting of Commercial Buildings."* ASHRAE Winter Conference, Chicago, 2015.	SHL, TH, GS, YC, MAP
2/15/15	News releases, electronic or digital publications, etc.	CBES flyer	
2/15/15	News releases, electronic or digital publications, etc.	DEEP flyer	
2/17/15	Presentation or briefing	Presented the CBES Toolkit to IBPSA-SF chapter members. Got their feedback to improve the CBES.	MAP, TH
3/13/15	Other (licensing, etc.)	A call with Nexant to discuss their adoption of CBES Toolkit.	TH
3/19/15	Presentation or briefing	Partner Workshop - CBES Demo	All
3/19/15	Outreach activities	Open Workshop - CBES Demo	All
3/20/15	Paper or poster	*Journal article submitted to Energy: "Energy Retrofit Analysis Toolkits for Commercial Buildings: A Review"*	SHL, TH, MAP
3/31/15	Outreach activities	First Developers' Webinar to introduce CBES APIs and discuss CBES availability.	YXC, MK
4/8/15	Outreach activities	Second Developers' Webinar to introduce CBES APIs and discuss CBES availability	YXC, MK, PP
4/10/15	Other (licensing, etc.)	A follow-up discussion with Nexant about their adoption of CBES and CBES licensing.	TH
4/15/15	Presentation or briefing	Discussed with Cody and Amir about alignment of CBES and Asset Score Tool	MAP, TH
4/22/15	Other (licensing, etc.)	A call with Autodesk to demonstrate the CBES Toolkit and explored collaboration between CBES and Autodesk's tools	MAP, TH
4/27/15	Paper or poster	Journal article submitted to Enterprise Information Systems: *"Accelerating the energy retrofit of commercial buildings using a database of energy efficiency performance"*	SHL, TH, MAP
5/6/15	Presentation or briefing	Discussed with Cynthia Regnier and Lawrence Lau about licensing the use of CBES for Architecture 2030's 2030 Districts	TH, YXC
5/21/15	Paper or poster	Journal article submitted to Applied Energy: *"Commercial Building Energy Saver: An Energy Retrofit Analysis Toolkit"*	TH, MAP, et al
7/2/2015	Presentation or briefing	Presented CBES Toolkit to ETA/LBNL staff	MAP, TH et al
2015	Paper or poster	Lee SH, Hong T, Piette MA, Sawaya G, Chen Y, Taylor-Lange SC. *"Accelerating the energy retrofit of commercial buildings using a database of energy efficiency performance."* Energy, 2015.	SHL, TH, MAP, GS, YC, SCTL
2015	Paper or poster	Lee SH, Hong T, Piette MA, Taylor-Lange SC. *"Energy Retrofit Analysis Toolkits for Commercial Buildings: A Review."* Energy, 2015.	SHL, TH, MAP, SCTL
2015	Paper or poster	Hong T, Chen Y, Lee SH, Zhang R, Sun K, Taylor-Lange SC, Piette MA, Kloss M, Bourassa N, Cheung I, Schetrit O. *"Commercial Building Energy Saver: An Energy Retrofit Analysis Toolkit,"* The 9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd International Conference on Building Energy and Environment (COBEE) July 12-15, Tianjin, China.	TH, YC, SHL, RZ, KS, SCTL, MAP, MK, NB, IC, OS
2015	Paper or poster	Hong T, Piette MA, Chen Y, Lee SH, Taylor-Lange SC, Zhang R, Sun K, Price P. *"Commercial Building Energy Saver: An Energy Retrofit Analysis Toolkit,"* Applied Energy, 2015.	TH, MAP, YC, SHL, SCTL, RZ, KS, PP
8/2016	Other (licensing, etc.)	LBNL's Technology Transfer Department communicated the OAMT designs developed in this project with industry and decided not to file a patent application.	WF
2016	Paper or poster	Sun K, Hong T, Taylor-Lange SC, Piette MA. *"A Pattern-based Automated Approach to Building Energy Model Calibration,"* Applied Energy, 2016.	KS, TH, SCTL, MAP
1/2017	Other (licensing, etc.)	Laney College Workshop on using CBES; part of NSF project	KS, TH, MAP

Chapter 6: Conclusions and Next Steps

In conclusion, the Commercial Building Energy Saver (CBES), intended for use in small and medium office and retail buildings in California, provides energy benchmarking and three levels of retrofit analysis considering the retrofit goal, data availability, and user experience. CBES offers prototype building models for seven building types, six vintages, in 16 California climate zones and 75 energy conservation measures (ECMs) for lighting, envelope, equipment, HVAC, and service hot water retrofit upgrades. CBES targets a diverse audience, including building owners, business owners, facility managers, energy managers, building operators, energy auditors, designers, architects and engineers, contractors/builders, and consultants.

CBES Load Shape Analysis identifies low- and no-cost improvements based on statistical analysis of the smart meter data, building floor area, and outdoor air temperature.

CBES Preliminary Retrofit Analysis utilizes the DEEP database, a data bank for screening and evaluating retrofit measures for commercial buildings generated from 10 million building energy simulations conducted using EnergyPlus at the U.S. National Energy Research Scientific Computing (NERSC) center.

CBES Detailed Retrofit Analysis employs advanced automated calibration algorithms to attune inputs prior to simulating energy savings of ECMs. For the detailed retrofit analysis, on-demand energy simulations use OpenStudio and EnergyPlus to calculate the energy performance of the building with user configurable ECMs. Once the common inputs have been entered, CBES flexibility allows the user to jump to any level of evaluation.

For those who wish to use the tool beyond California, a national version can be found at the Architecture 2030 whole building retrofit toolkit portal.

IEQ content was implemented in CBES to be consistent with the level of detail of the available information -- 23 IEQ recommendations were incorporated for 48 retrofit measures. For an additional number of retrofit measures, general recommendations on IEQ benefits and cautionary messages are displayed to CBES users.

The project team designed, fabricated, and tested four prototypes of systems for measuring rates of outdoor air intake into RTUs. All prototypes met the ±20% accuracy target at low wind speeds, with all prototypes accurate within approximately ±10% after application of calibration equations. One prototype met the accuracy target without a calibration. With two of four prototype measurement systems, there was no evidence that wind speed or direction affected accuracy; however, winds speeds were generally below 3.5 m s^{-1} (12.6 km h^{-1}), and further testing is desirable. The airflow resistance of the prototypes was generally less than 35 Pa at maximum RTU airflow rates. A pressure drop of this magnitude will increase fan energy consumption by approximately 4%.

The testing results indicate that some of the designs developed in this project have considerable merit. OAMTs could be used during building commissioning to set the dampers in outdoor air, supply air, and recirculation airstreams, and then throughout ongoing building tuning operations to maintain OA intake rates at targets, thereby preventing excessive VRs or insufficient ventilation to meet standards.

6.1 Next Steps

The CBES Toolkit will provide new capabilities to support California's energy efficiency programs for existing buildings, AB 758. The CBES Toolkit analytical techniques are flexible and easily expansible. Based on the feedback from partners and participants of recent Energy Commission-funded workshops, future rollouts could focus on a number of topics and features. These improvements will provide new capabilities to California and utility energy efficiency programs for existing buildings.

1. Cover more building types, e.g. restaurants, hotels, hospitals, large office buildings, schools
2. Add more ECMs
3. Expand the climate zones
4. Export to utilities — throughout California, and beyond.
5. Include incentives and rebates
6. Add renewable energy systems
7. Consider demand response measures
8. Include behavioral measures
9. Develop interoperability with DOE Commercial Buildings Asset Scoring Tool
10. Develop interoperability with EPA Energy Star Portfolio Manager
11. Enable further customization of building systems characteristics

The quantitative benefit estimates from sick building syndrome (SBS) symptoms reduction and work performance improvement can be extended to include the expected health benefits from PM2.5 exposure reduction by using high efficiency air filters. Indoor exposure to PM2.5 is the leading driver of chronic health risks in commercial buildings (Chan et al., 2015). The health benefits are expected to be much higher than the incremental material and energy costs of using high efficiency air filters. Future development of CBES can incorporate the monetary estimates of benefits to occupants from IEQ improvements as part of the decision making logic, in addition to other criteria such as maximizing energy cost savings and minimizing payback period.

The designs and test results for the OAMT systems will be communicated to the HVAC manufacturing community after a review of the potential to apply for patents. Further design refinement, testing (including extended deployments in buildings), and cost analysis would be necessary to fully assess commercial potential.

A city and district scale building energy modeling platform, City Building Energy Saver (CityBES), is under development by LBNL. CityBES builds on top of the functionality of the CBES API. CityBES can be used to visualize building performance data, e.g., the building dataset published by cities' public building energy benchmarking ordinances. CityBES enables users to identify and evaluate technologies and scenarios to retrofit a small or large group of buildings to reach certain energy savings target, with or without incentive and rebate programs. CityBES can be accessed at CityBES.lbl.gov.

GLOSSARY

AB	Assembly Bill
AFUE	Annual Fuel Utilization Efficiency
API	Application Programming Interface
APP	Web Application
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBE	Center for the Built Environment
CBES	Commercial Building Energy Saver
CFM	Cubic Feet Per Minute
CO2	Carbon Dioxide
CPUC	California Public Utilities Commission
DEER	Database for Energy Efficiency Resources
DOE	U.S. Department of Energy
ECM	Energy Conservation Measure
Energy Commission	California Energy Commission
EPA	Environmental Protection Agency
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GUI	Graphical User Interface
GWh	Gigawatt Hours
HES	Home Energy Saver
HVAC	Heating, Ventilation, and Air Conditioning
IBPSA	International Building Performance Simulation Association
IEQ	Indoor Environmental Quality
IOU	Investor-Owned Utilities
LBNL	Lawrence Berkeley National Laboratory

MTCO2e	Metric Tons of Carbon Dioxide Equivalent
Mtherms	Megatherms
MVR	Minimum Ventilation Rate
MW	Megawatts
NERSC	U.S. National Energy Research Scientific Computing
NSF	National Science Foundation
OA	Outdoor Air
OAMT	Outdoor Air Measurement Technology
Pa	Pascal
PM	Particle Matter
RTU	Rooftop Air Handling Unit
SBS	Sick Building Syndrome
SMB	Small and Medium Buildings
VR	Ventilation Rate

REFERENCES

ASHRAE. *Advanced Energy Design Guide for Small to Medium Office Buildings.* American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2011.

Bennett, D. H., W. Fisk, M. G. Apte, X. M. Wu, A. Trout, D. Faulkner and D. Sulivan. "Ventilation, Temperature, and HVAC Characteristics in Small and Medium Commercial Buildings (SMCBs) in California." Indoor Air **22**(4): 309-320. 2012.

CEC. *Small HVAC System Design Guide.* Sacramento, CA. California Energy Commission. Publication No.: 500-03-082-A12. 2003. Available at: http://www.energy.ca.gov/2003publications/CEC-500-2003-082/CEC-500-2003-082-A-12.PDF. 2003. (accessed July 17, 2017)

CEC. *Commercial Buildings Breathe Right with Demand-Controlled Ventilation.* California Energy Commission, Public Interest Energy Research – Buildings Program. Publication No.: CEC-500-2005-126. 2005. Available at: http://www.energy.ca.gov/2005publications/CEC-500-2005-126/CEC-500-2005-126-FS.PDF. (accessed July 17, 2017)

CEC. Integrated Office Lighting Systems: Making it Personal. California Energy Commission, Public Interest Energy Research – Buildings Program. Publication No.: CEC-500-2007-108-FS. 2007. Available at: http://www.energy.ca.gov/2007publications/CEC-500-2007-108/CEC-500-2007-108-FS.pdf. (accessed July 17, 2017)

CEC. California Energy Commission. Database for Energy Efficient Resources (DEER). Retrieved from http://www.deeresources.com/ (accessed July 20, 2017)

CEC. California Energy Code. Title 24. Building Energy Efficiency Standards, California Energy Commission. 2013.

CEC and CPUC. *Database for Energy Efficient Resources (DEER); DEER2011 for 13-14.* California Energy Commission and California Public Utilities Commission. 2011. Available at: http://www.deeresources.com/ (accessed July 20, 2017)

Chan, W. R., S. Cohen, M. Sidheswaran, D. Sullivan and W. J. Fisk. "Contaminant levels, source strengths, and ventilation rates in California retail stores." Indoor Air DOI: 10.1111/ina.12152. 2015.

CPUC. California Long Term Energy Efficiency Strategic Plan, California Public Utilities Commission. 2008.

Crump, C., Macmillan, A. and Swainson, M. Indoor air quality in energy efficient homes - a review, United Kingdom, IHS BRE Press. 2009.

Davies, M. and Oreszczyn, T. The unintended consequences of decarbonising the built environment: A UK case study, Energy and Buildings, 46, 80-85. 2012.

Deru M, Field K, Studer D, Benne K, Griffith B, Torcellini P, Liu B, Halverson M, Winiarski D, Rosenberg M, Yazdanian M, Huang J, Crawley D. U.S. Department of Energy Commercial Reference Building Models of the National Building Stock, National Renewable Energy Laboratory, Technical Report NREL/TP-5500-46861, 2011.

Dutton, S.M. and Fisk , W.J. Energy and indoor air quality implications of alternative minimum ventilation rates in California offices. Building and Environment, 82, 121-127. 2014.

Dutton, S.M. and Fisk , W.J. Energy and IAQ implications of alternative minimum ventilation rates in California retail and school buildings, Berkeley, CA, Lawrence Berkeley National Laboratory.(LBNL number pending) 2015.

Fisk, W. J., D. Faulkner and D. P. Sullivan. "An evaluation of three commercially available technologies for real time measurement of rates of outdoor airflow into HVAC systems." ASHRAE Transactions **111**(2): 443-455. 2005a.

Fisk, W. J., D. Faulkner and D. P. Sullivan. Real time measurement of rates of outdoor airflow into HVAC systems: a field study of three technologies. LBNL 58856. Berkeley, CA, Lawrence Berkeley National Laboratory. 2005b.

Fisk, W. J., D. Faulkner and D. P. Sullivan. "Technologies for measuring flow rates of outdoor air into HVAC systems: some causes and suggested cures for measurement errors." ASHRAE Transactions **111**(2): 456-463. 2005c.

Fisk, W.J., Mirer, A.G. and Mendell, M.J. Quantitative relationship of sick building syndrome symptoms with ventilation rates, Indoor Air, 19, 159-165. 2009.

Haverinen-Shaughnessy, U., Moschandreas, D.J. and Shaughnessy, R.J. Association between substandard classroom ventilation rates and students' academic achievement, Indoor Air, 21, 121-131. 2011.

Liu G, B Liu, W Wang, J Zhang, RA Athalye, D Moser, E Crowe, N Bengtson, M Effinger, L Webster, and M Hatten. Advanced Energy Retrofit Guide Office Buildings. PNNL-20761, Pacific Northwest National Laboratory, Richland, WA. 2011a.

Liu G, B Liu, J Zhang, W Wang, RA Athalye, D Moser, E Crowe, N Bengtson, M Effinger, L Webster, and M Hatten. 2011b. Advanced Energy Retrofit Guide Retail Buildings. PNNL-20814, Pacific Northwest National Laboratory, Richland, WA. 2011.

Luo X, Hong T, Chen Y, Piette MA. Small- and Medium-Sized Commercial Building Natural Gas and Electric Load Shape Benchmarks, LBNL Technical Report for PG&E. 2017.

Itron. “2010-2012 WO017 Ex Ante Measure Cost Study (MCS) Draft Report” for the California Public Utilities Commission. February 28, 2014. Available at: http://www.energydataweb.com/cpucFiles/pdaDocs/1039/2010-2012 WO017 Ex Ante Measure Cost Study - Draft Report.pdf. 2014. (accessed July 17, 2017)

LBNL. "COMFEN 4.1" Fenestration Evaluation Tool. Lawrence Berkeley National Lab. Available at: http://windows.lbl.gov/software/comfen/comfen.html. 2012. (accessed July 17, 2017)

Meier, A, M Moezzi, C Hammer, and J Goins. "Behavioral strategies to reduce the gap between potential and actual savings in commercial buildings" Contract Number: 09-327. Sacramento: California Air Resources Board. 2014.

Mendell, M.J., Eliseeva, E.A., Davies, M.M., Spears, M., Lobscheid, A., Fisk, W.J. and Apte, M.G. Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools, Indoor Air, 23, 515-528. 2013.

Noris, F., Adamkiewicz, G., Delp, W.W., Hotchi, T., Russell, M., Singer, B.C., Spears, M., Vermeer, K. and Fisk , W.J. Indoor environmental quality benefits of apartment energy retrofits, Building and Environment, 68, 170-178. 2013a.

Noris, F., Delp, W.W., Vermeer, K., Adamkiewicz, G., Singer, B.C. and Fisk , W.J. Protocol for maximizing energy savings and indoor environmental quality improvements when retrofitting apartments, Energy and Buildings, 61, 378-386, LBNL-6147E. 2013b.

Persily, A. K. and J. Gorfain. Analysis of ventilation data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study, NISTIR-7145-Revised. Bethesda. MD, National Institute for Standards and Technology. 2008.

PNNL. "Building Component Cost Community (BC3) Database" Pacific Northwest National Lab. Available at: http://bc3.pnnl.gov/. 2014.

RSMeans. "RSMeans Green Building Cost Data 2014" Reed Construction Data. 2013.

Sharpe, R.A., Thornton, C.R., Nikolaou, V. and Osborne, N.J. Higher energy efficient homes are associated with increased risk of doctor diagnosed asthma in a UK subpopulation, Environment international, 75, 234-244. 2015.

Shrubsole, C., Macmillan, A., Davies, M. and May, N. 100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock, Indoor and Built Environment, 23, 340-352. 2014.

Siegel, J. A., J. Srebric, N. Crain, E. Nirlo, M. Zaatari, A. Hoisington, J. Urquidi, S. Shu, Y. S. Kim and D. Jareemit. Ventilation and indoor air quality in retail stores. ASHRAE research project 1596-RP. Atlanta, GA, American Society of Heating, Refrigerating, and Air Conditioning Engineers. 2012.

Sundell, J., Levin, H., Nazaroff, W.W., Cain, W.S., Fisk, W.J., Grimsrud, D.T., Gyntelberg, F., Li, Y., Persily, A.K., Pickering, A.C., Samet, J.M., Spengler, J.D., Taylor, S.T. and Weschler, C.J. Ventilation rates and health: multidisciplinary review of the scientific literature, Indoor Air, 21, 191-204. 2011.