Title
CEC EPIC, zero net energy small commercial retrofits

Permalink
https://escholarship.org/uc/item/0r21m2v5

Authors
Regnier, C
Bruschi, J

Publication Date
2019

Building Technologies & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

Integrated Whole-Building Zero Net Energy Retrofits for Small Commercial Offices

Cindy Regnier, P.E. , Luis Fernandes, Kaiyu Sun, Pia Engel-Moss, Tom Abram, Luke McGuire, P.E., Ruju Rathod

Energy Technologies Area
March, 2023

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Webpage Abstract

Small commercial offices experience a number of unique barriers to achieving substantial energy reductions including: 1) a lack of awareness of and access to cost-evaluative information about how to achieve energy targets, and 2) affordable access to services such as engineering and audits. Existing tools and services currently involve higher costs when applied to small commercial buildings due to the lower amount of energy cost savings realizable on a per-square-foot basis. Small commercial buildings are consequently disadvantaged in accessing the same detailed retrofit information that larger buildings can gain cost effectively.

This project developed cost-effective retrofit packages to achieve zero net energy and/or zero carbon performance for California multi-story small commercial offices (<50,000 sf). The packages target 50 percent energy savings, with costs within 10 percent of conventional construction costs, and internal rates of return of 5 percent or more within 10 years. The developed retrofit packages have been validated for energy performance, visual and thermal comfort, under controlled laboratory test conditions and demonstrated in a small commercial building (City of Berkeley Mental Health Services facility). Energy measures were also built into an online public tool, the Commercial Building Energy Saver (https://cbes.lbl.gov/), to enable small commercial facilities to conduct zero net energy retrofit assessments, providing cost-evaluative metrics.

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

FINAL PROJECT REPORT

Integrated Whole-Building Zero Net Energy Retrofits for Small Commercial Offices

Agreement Number: EPC-16-004

Author(s):
Cindy Regnier, P.E.
Luis Fernandes
Kaiyu Sun

Building Technology and Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory (LBNL)
1 Cyclotron Road
Berkeley, CA 94720
510-486-4000
www.lbl.gov

Pia Engel-Moss
Tom Abram
Luke McGuire, P.E.
Ruju Rathod

Integral Group
427 13th Street
Oakland, CA 94612
510-663-2070
Integral Group

California Energy Commission Project Manager: Dustin Davis
Energy Research and Development Division

March 2023 | CEC-500-XXXX-XXX

DISCLAIMER

Table of Contents

Agreement Number: EPC-16-004 1

Table of Contents 2

Executive Summary 1

Background 1

Project Purpose and Approach 1

Key Results 2

Knowledge Transfer and Next Steps 3

Target Stakeholders .... **Error! Bookmark not defined.**

Outreach Activities .... **Error! Bookmark not defined.**

CBES Use and Industry Engagement .... **Error! Bookmark not defined.**

Recommendations and Next Steps .... **Error! Bookmark not defined.**

Introduction 5

Background 5

ZNE Status in Commercial Buildings in California 6

Status of ZNE Analysis Tools and Methods for Small Commercial Buildings in California 6

Project Approach 8

ZNE Package Development 10

Common Cost Effective Package Measures 11

Envelope Focused Retrofit Package Measures 11

Lighting Focused Retrofit Package Measures 11

HVAC System Focused Retrofit Package Measures 11

Plug Load Focused Retrofit Measures 12

Energy Generation/Photovoltaic System Focused Retrofit Package Measures 12

FLEXLAB Testing 12

ZNE Packages 12

ZNE package configuration 12

Baseline configuration 13

Tubular Daylight Devices (TDDs) .... **Error! Bookmark not defined.**

Field Demonstration 14

ZNE Retrofit Analysis 14

Occupant Engagement 15

Measurement and Verification 15
Commercial Building Energy Savings 15
Implementation of New Features and EEMs 15
Demonstration of Path to ZNE using CBES 16
Validation of Simulation Accuracy 16
Results 18
ZNE Package Development 18
Baseline Building Model Development and Calibration 18
Common Measures 19
ZNE Package Analysis 20
Energy Consumption 20
Energy Costs 24
ZNE Package and Measure Validation ..... **Error! Bookmark not defined.**
FLEXLAB Testing ..... **Error! Bookmark not defined.**
ZNE Packages 26
Tubular Daylight Devices 27
Field Demonstration 27
ZNE Retrofit 28
Measurement and Verification 33
Occupant Engagement 35
Commercial Building Energy Saver 36
Implementation of New Features and EEMs 36
Demonstration of Path to ZNE using CBES 37
Validation of CBES Simulation Accuracy 37
Conclusion 39
ZNE Package Development 39
FLEXLAB Testing 39
ZNE Packages 39
Tubular Daylight Devices 39
Field Demonstration 39
Occupant Experience and Engagement 40
Commercial Building Energy Saver 40
General Conclusions 40

Scaling in Small Commercial Market ... 40
Acknowledgments ... 42
GLOSSARY AND LIST OF ACRONYMS ... 43
References ... 44
Project Deliverables ... 45
Appendix A: ZNE Packages ... 1
Common Measures ... 3
Package 1: Envelope focused ... 3
Package 2: Lighting-daylighting focused ... 4
Package 3: HVAC system focused ... 4
Package 1+2: Envelope and Lighting-daylighting focused ... 4
Package 2+3: Lighting-daylighting and HVAC focused ... 5
Package 1+2+3: Envelope, Lighting-daylighting, and HVAC focused ... 5
Appendix B: Field Demonstration ... 1
Existing Conditions ... 1
Description & Inputs ... 1
ZNE Packages ... 2
Package 1a: DOAS + VRF (Dedicated Outside Air System + Variable Refrigerant Flow), No Window Replacement ... 2
Package 1b: DOAS + VRF, Window Replacement ... 3
Package 2a: Heat Pump ... 3
Package 2b: Heat Pump with ERV (Energy Recovery Ventilator) ... 3
Package 100% DD: Heat Pump with ERV (Energy Recovery Ventilator) ... 4
Package Construction Phase Updates: Heat Pump with ERV (Energy Recovery Ventilator) ... 4
Appendix C: Commercial Building Energy Saver ... 1
Appendix D: Measurement and Verification Energy Analysis Tool ... 1

Executive Summary

Background

California's aggressive energy policies, enacted through legislation such as AB32, target reducing greenhouse gas (GHG) emissions to 1990 levels by 2020, and Assembly Bill (AB)758 (Skinner, N, Bass, K, et al., Chapter 233, Statutes of 2021), which aims to increase energy savings in existing nonresidential buildings. Further, AB1279 (Muratsuchi, A., Garcia, C., et al., Chapter 337, Statutes of 2022) requires California to reduce statewide GHG emissions by 85 percent compared to 1990 levels by 2045. The small commercial building market sector accounts for a significant amount of the state's energy consumption. Efforts to achieve the state's goals for GHG emission reductions must address the barriers to transitioning 50 percent of California's commercial building stock to zero net energy (ZNE) use by 2030.

In 2012, small commercial offices in California represented 650 million square feet (sf) of real estate and consumed more than 3,500 GWh of electricity. At that time, there were only 50,000 sf of small office space considered zero-net energy (ZNE).

The small commercial office market faces unique barriers to achieving substantial energy reductions. Those barriers are (1) awareness and access to centralized, comprehensive, cost-evaluative information about how to achieve energy targets and (2) affordable access to energy reduction services such as engineering and auditing services. Energy efficiency tools and services have comparatively high initial costs per square foot or per kWh saved for small commercial projects as compared with large commercial projects. Because small commercial stakeholders often cannot afford to hire expertise to provide efficiency services, maintenance contractors and product representatives are their available resources for energy reduction guidance. Neither resource may prioritize energy efficiency, however, and both generally are limited to knowledge within their area of specialization, leaving whole building integrated strategies behind. As a result, small commercial buildings typically approach efficiency upgrades through end-of-life equipment replacement or light-touch interventions such as replacing light bulbs or fixtures, often as recommended by their resources.

Project Purpose and Approach

This project aimed to reduce the barriers for small commercial ZNE retrofits by (1) developing sets of ZNE retrofit packages that meet cost-effectiveness criteria; (2) validating performance of the packages in a controlled lab setting and in an occupied demonstration site; and (3) developing a free public online tool called the Commercial Building Energy Saver or "CBES" to support small commercial ZNE retrofit analysis using the developed packages, and provide cost-evaluative information. The retrofit packages were developed for a northern and southern California climate, using readily available, but in some cases underused, commercially available technologies and controls. The ZNE package development included measures to allow for a zero carbon retrofit as well. The packages also had a goal of having an Internal Rate of Return (IRR) of 5 percent within 10 years.

Key Results

In analyzing potential energy efficiency measures, three categories of design approaches were identified focusing strongly on the envelope, lighting/daylighting, heating, and ventilation and air-conditioning (HVAC). These energy efficiency measures (EEM) were grouped into packages applied to the southern and northern California Prototype Buildings. Nearly all of the ZNE packages tested were able to achieve ZNE based on the solar PV potential of the prototype buildings.

For the Southern California Prototype Building the ZNE packages resulted in reducing energy use 56 to 73 percent (a 59 percent reduction is required to meet the ZNE threshold). Subsequently, these ZNE Packages led to an energy cost reduction from the Southern California Prototype Building of 31 to 58 percent before considering further energy cost reductions associated with PV. For the Northern California Prototype Building a 60 percent energy use reduction was required, due to slightly different solar availability, and different climate conditions resulting in different space conditioning needs. The ZNE Packages for this climate met the ZNE target at 60 to 72 percent energy savings. Subsequently, the ZNE Packages led to an energy cost reduction from the Northern California Prototype Building of 37 to 56 percent before considering the energy cost reductions associated with PV.

The lighting/daylighting and HVAC strategies met the cost payback threshold with an IRR of more than 5 percent within 10 years, and simple paybacks of 2 years or less when assessed using the incremental cost over an equivalent non-energy saving upgrade. Their simple paybacks would be 25 years or more if the retrofit was done solely for energy savings (and not for end-of-life replacement of equipment).

The envelope strategy had a much longer return period due to the higher up-front costs for those measures. As a result, it is generally recommended to focus on HVAC and daylighting/lighting strategies for some buildings to achieve ZNE, but also envelope upgrades where needed for additional reasons, such as end-of-life equipment replacement needs, water intrusion, leakage, and discomfort.

To validate the energy, thermal comfort, and visual comfort aspects of the developed ZNE packages, tests were first conducted in a controlled lab environment at LBNL's FLEXLAB® for a ZNE package applicable to southern and northern California, as well as the Berkeley Mental Health Services building demonstration site. The package included improvements in the HVAC and lighting systems, including the addition of tubular daylight devices (TDD), as well as reductions in plug load energy use. Separate tests evaluated the daylight delivery and glare performance of various TDD configurations. Tests were conducted throughout the year to cover a range of outdoor conditions. The proposed ZNE package demonstrated energy savings similar to those that were modeled (e.g., 59 to 69 percent savings during the cooling season and 22 to 25 percent savings during the heating season), without causing glare or making the space too hot or too cold. TDD-specific tests showed potential annual lighting energy savings of 27 to 69 percent, without glare. The demonstration documented the reduction in energy consumption between the historical building averages and the metered energy consumption for the building at 79% (43.9 kBtu/sf/yr to 9.0 kBtu/sf/yr), exceeding the 64 percent savings predicted in the models. The reduction in annual energy costs over the same period was 35 percent from an average of approximate $11,114/yr to $7,273/yr, a 35 percent reduction. It is expected that once the PV system is fully and correctly enabled, net zero operation will be achieved, as the normalized modeled generation of 21 kBtu/sf/yr is significantly larger than the metered energy consumption of 9 kBtu/sf/yr.

For this project, new capabilities were implemented in CBES to enable ZNE retrofit analysis and deep retrofit analysis with advanced technologies. New capabilities include four new features, specifically the rooftop PV system, electric battery, solar shading, the Time Dependent Valuation (TDV) energy metric, and 12 new EEMs, such as advanced HVAC systems, advanced lighting control, and improved envelope performance. A case study was then performed to demonstrate CBES's capability to explore ZNE pathways.

To validate the simulation accuracy of the CBES tool, the measured data from FLEXLAB experiments was used as a validation case to compare with CBES's simulation results. Overall, the simulated results match well with the measurement data on lighting energy use, HVAC energy use, and whole building Energy Use Intensity (EUI).

The Berkeley Mental Health Services retrofit was used as a demonstration site for the ZNE package approach. The team analyzed the change in energy consumption before and after implementation of the retrofit package. A full year of continuous data was collected to verify performance of the ZNE package. Note that while the PV system was installed on the building, it has not been activated due to delays with the utility approval process but based on the modeled generation of the PV system the building is expected to achieve ZNE performance once the system is active.

Knowledge Transfer and Next Steps

The key stakeholders for this project include small commercial business owners and building owners, manufacturers, product vendors and distributors, contractors, and code officials. In addition, the architecture and engineering service provider communities may be important outlets to access CBES and promote its use through their networks. The project used industry events, presentations, and diverse media outlets including the San Francisco 2030 District (members are owners), ACEEE, and the America Western Pacific Region of the Association of Energy Engineers (AEE). Codes and standards developers may also be interested in this work and were reached through industry events and organizations such as ACEEE.

This project engaged stakeholders through multiple in person events held in California, as well as some virtual events. This included selection to present at AEE West's conference, ACEEE Summer Study for Energy Efficiency in Buildings (presented in 2018 and 2020), Greenbuild (2021), the EPIC Symposium (2018, 2019), Zero-Net Energy conference (2021), and NBI's Getting to Zero Forum (2019). In addition, LBNL published and publicized the work through several press releases and newsletters (Building Technologies and Urban Systems Division newsletter and FLEXLAB newsletter). CBES was also recognized as an R&D 100 winner in 2019, which included additional press release and newsletter features.

Two websites were developed to promote the project – the first hosts the CBES online tool (https://cbes.lbl.gov/) and the second promotes the work of the project overall (https://buildings.lbl.gov/cbs/zero-net-energy-small-commercial-retrofits). Since January 2019, there have been a total of 5,564 user visits and 21,866 page views to the CBES website, according to Google Analytics (see Appendix D). Starting in August 2020, a new feature was added to the site to require registration and login to track and collect users' basic information. Within the last two years, CBES has had a total of 110 registered users.

A number of efforts have been put in place to increase the adoption of CBES in industry. For example, a training session was provided for the HVAC faculty of Laney College, who would leverage CBES as a tool in their teaching; the team provided a demo to the teachers and students at the Industrial Assessment Center (IAC) of Louisiana State University, who plan to use CBES in their process of energy audit and measure evaluation for commercial buildings.

Overall, the packages demonstrate that it is possible with current off-the-shelf technologies and controls to achieve zero net energy retrofits. Furthermore, these packages can be cost-effective compared to equivalent whole building retrofits using conventional technologies, particularly where care is paid to what systems are targeted, and thermal loads are lowered to the point where some HVAC system retrofit savings are possible due to smaller equipment sizes. However, retrofits that focus on envelope upgrades primarily are hampered by higher capital costs, and consequently longer paybacks. Research into more cost-effective wall and window upgrade methods and technologies would benefit all parts of the commercial market and likely improve thermal comfort for some occupants as well.

While the project efforts and outcomes have been of keen interest to the audiences engaged, it is noted that small commercial building owners and tenants are inherently a difficult market to engage. This may be due to a lack of industry organizations that serve this disparate group but it is also noted that these building and business owners typically are extremely busy and have other business priorities to attend to. Furthermore, whole building retrofits are extremely disruptive to a business and are not likely to occur unless there is a business need for such improvement. Small businesses also tend to lack the capital needed for whole building retrofits. Further work is recommended to develop approaches to engage, educate and offer technical and financial assistance to these stakeholders to achieve a more rapid uptake of this work.

In 2019, the CBES application program interface or "API", which is the underlying simulation engine for the CBES web app, was expanded for the needs of two projects: one funded by CEC project EPC-17-035 titled "Building Healthier and More Energy-Efficient Communities in Fresno and the Central Valley", the other funded by California Strategic Growth Council titled "CAL-THRIVES: A California Toolkit for Heat Resiliency in Vulnerable Environments". New building types (single family homes, multi-family homes) and new EEMs (e.g., duct sealing, window film, precooling, electric vehicles, radiant barriers, mini-split heat pump, etc.) were added to enable the simulation capability of residential buildings, electrification, and heat resilience.

Introduction

Background

Assembly Bill (AB) 1279 (Muratsuchi, A., Garcia, C., et al., Chapter 337, Statutes of 2022) requires California to reduce statewide greenhouse gas (GHG) emissions by 85 percent compared to 1990 levels by 2045, and AB758 (Skinner, N, Bass, K, et al., Chapter 233, Statutes of 2021), which targets greater energy savings in existing nonresidential buildings. In addition, the California Public Utilities Commission (CPUC) Energy Efficiency Strategic Plan calls for newly constructed commercial buildings to achieve zero net energy (ZNE) use by 2030. The small commercial building market sector accounts for a significant amount of the state's building area and energy consumption. In 2012, small commercial offices in California represented 650 million square feet (sf) of real estate and consumed more than 3,500 GWh of electricity.[1] Efforts to achieve the state's goals for GHG emission reductions must address the barriers to transitioning 50 percent of California's commercial building stock to ZNE use by 2030[2] in order to meet these targets, and provide equitable access to energy cost savings, and solar energy production.

In addition, California has a need to reduce peak demand in small commercial buildings and ensure their electric load shapes can help improve electric system reliability and avoid increased peak electricity loads, which can result in utility system capacity constraints and investment needs. New demand response technology has been developed and demonstrated for small commercial buildings yet remains underutilized.[3]

Achieving ZNE designs requires saving 50 percent or more in energy compared to baseline energy use, as demonstrated through a number of case studies.[4,5,6] This depth of savings requires whole-building solutions and cannot be achieved by incremental equipment upgrades alone. Although single equipment upgrade efforts can produce significant energy savings in commercial buildings, their impact is inherently limited. As an example of their limited impact, in 2013 the U.S. domestic energy service company (ESCO) industry completed $6 billion worth

---

[1] Reducing Costs for Communities and Businesses Through Integrated Demand-Side Management and Zero Net Energy Demonstrations Grant Funding Opportunity. CEC. (2015)

[2] J. B. Greenblatt. Estimating Policy-Driven Greenhouse Gas Emissions Trajectories in California: The California Greenhouse Gas Inventory Spreadsheet (GHGIS) Model. (2013) LBNL Report LBNL-6451E.

[3] J. Page, S. Kiliccote, J. Dudley, M. Piette, Al Chiu, B. Kellow, E. Koch, and P. Lipkin, Automated Demand Response Technology Demo for Small and Medium Commercial Buildings (2011). LBNL-4982E.

[4] C. Regnier, A. Harding, A. Robinson. Achieving a Net Zero Retrofit in a Hot, Humid Climate—Lessons from the University of Hawaii at Manoa. U.S. Department of Energy, Commercial Building Partnerships. (2015) LBNL Report LBNL-189802.

[5] C. Regnier, K. Settlemyre. The Business of High Performance: The USC Darla Moore School of Business. U.S. Department of Energy, Commercial Building Partnerships. (2015) LBNL Report LBNL-6904E.

[6] International Living Future Case Study, IDEAS Z2 Facility, San Jose. http://living-future.org/case-study/ideasz2

of energy upgrade projects,[7] Another study showed that a set of 421 ESCO projects conducted from 2012 to 2017 had an average savings of 25 percent, with more than 60 percent of these only focusing on the retrofit of one end use system such as lighting, or HVAC).[8]

ZNE Status in Commercial Buildings in California

As of 2020, less than 63 million sf of buildings across the U.S. had verified or emerging ZNE status, with less than 65 percent of these being small commercial[9]. According to the New Buildings Institute, there are currently 290 ZNE Buildings in California, 53 of which have been verified as ZNE, while 237 are considered "Emerging". Of these, 50 (21 percent) are office buildings less than 50,000 square feet in size. These small commercial office buildings have an equal 50/50 split between public and private ownership. While these building are located all over the state, they have been predominantly located in cooler coastal climates. It should be noted that this data is for all projects in the New Buildings Institute Getting to Zero Buildings Database, and the dataset is not differentiated between new construction and retrofits. To enable the existing small commercial market to transition to ZNE, cost effective packages of whole building technologies and grid supportive controls that achieve energy savings on the order of 50 percent must be developed, along with accessible means to replicate these strategies.

The small commercial office market faces several unique barriers to achieving substantial energy reductions. Those barriers include: 1) awareness and access to centralized, comprehensive, cost-evaluative information about how to achieve energy targets, and 2) affordable access to energy reduction services such as engineering and auditing services. Energy efficiency tools and services have comparatively high-cost entry points per square foot or per kWh saved for small commercial projects as compared with large commercial projects. Because small commercial stakeholders often cannot afford to hire expertise to provide efficiency services, maintenance contractors and product representatives are their available resources for energy reduction guidance. Neither resource may prioritize energy efficiency however, and both generally are limited to knowledge within their area of specialization, leaving whole building integrated strategies behind. As a result, small commercial buildings typically approach efficiency upgrades through end-of-life equipment replacement or light-touch interventions such as replacing light bulbs or fixtures, often as recommended by their resources.

Status of ZNE Analysis Tools and Methods for Small Commercial Buildings in California

---

[7] E. Stuart, P. Larsen, C. Goldman, D. Gilligan. Current Size and Remaining Market Potential of U.S. ESCO Industry. (2013) LBNL Report LBNL-6300E.

[8] C. Regnier, P. Mathew, A. Robinson, J. Shackelford, T. Walter. System Retrofit Trends in Commercial Buildings: Opening Up Opportunities for Deeper Savings, Lawrence Berkeley National Laboratory. (2020)

[9] New Buildings Institute. 2020 Getting to Zero Buildings List. (2020).

There are a number of existing tools that have the capability of ZNE retrofit analysis, spanning two major categories: (1) physics-based simulation engines like EnergyPlus, eQuest, and DOE2, and (2) web-based or standalone apps that are built upon these engines, such as Buildee (previously named as Simuwatt) and cove.tool. However, these tools often rely on professionals with expertise in building physics and modeling, for example, energy modeling consultants, to perform ZNE analysis using simulation engines directly. Web-based or standalone apps with well-developed easy-to-use analysis features may require less expertise but are usually not free to use. Meanwhile, small business owners do not have the resources to hire consultants or purchase commercial apps, in other words, they do not have easy and low-cost access to tools that can be used to identify cost-effective energy efficient retrofits. Therefore, existing tools can't satisfy the needs of the small commercial market and stakeholders.

Previous work sponsored by the U.S. Department of Energy and led by Lawrence Berkeley National Lab (LBNL) worked with four U.S. 2030 Districts to develop a suite of online technical tools to help the small commercial sector, such as a lighting and controls replacement calculator and HVAC and plug-loads replacement calculators. All tools were designed for ease of use by time-constrained, less specialized users applicable to this sector, and enable quick or detailed, customizable evaluations. One tool developed was the Commercial Building Energy Saver (CBES), which initially was funded by the California Energy Commission (CEC) and developed by LBNL to provide easy-to-use, accessible whole-building assessments for small commercial office and retail applications, targeting up to 20 percent whole building energy savings. The CBES tool offers a public online app, and a commercially available application program interface (API). As a platform, CBES provides many features important to the small commercial sector, however it did not include energy efficiency measures sufficient to achieve the deeper whole building energy savings needed to achieve ZNE, and did not offer any assessments of onsite solar installation power production potential.

Overall, small commercial buildings are an important market to achieve California's energy and carbon reduction goals but lack the tools and resources to identify cost-effective retrofit strategies suitable for their building.

Project Approach

This project developed packages of commercially available, and in some cases underutilized, technologies and controls and made them available through accessible means to enable whole building analysis and replication at scale. The whole-building retrofit packages developed in this project include deep, cost-effective, replicable energy saving strategies for small commercial offices. The project results are well suited for the new construction market as well. The technologies packaged and disseminated provide the means to achieve on the order of 50 percent energy savings over current use and exceed Title 24 compliance requirements.
In addition, the publicly available CBES tool (https://cbes.lbl.gov/) was expanded to include additional energy efficiency measures to enable whole retrofit analysis. The tool identifies cost effective retrofit packages and makes assessments of photovoltaic energy generation on site. Overall, this project provides accessible information to the small commercial market on how to achieve ZNE retrofits. In addition, the project approach provides additional benefits to this market through improvements in energy reliability, and lower energy costs while providing significant potential for quantitative benefits to California.

Reliability - The whole-building retrofit packages use energy only when necessary, relying on passive building approaches to lower building loads such as heating, cooling, and lighting. Because of the emphasis on thermal and daylighting design aspects, passive building designs create a built environment that has greater reliability in serving its occupants' needs through all phases of building operation, including times of power disruption. Passive design also benefits the electrical grid by lowering peak demand and reducing overall demand. The ZNE energy efficiency measures (EEMs) also potentially provide flexible load shapes for demand response programs to assist in grid management, managing electric costs, reducing risks to grid reliability, and facilitating grid-scale integration of renewable energy.

Lower Costs - By identifying cost-effective EEM approaches to achieve ZNE performance, this project advanced the understanding of and interest in successful EEMs, lowering the cost barrier to the widespread adoption of technologies that enable ZNE.

Quantitative Benefits - The quantitative benefits for this project, including ratepayer benefits of lowered operating costs, in 2012 energy consumption in California was 3,567.19 GWh for 651.91 million sf of small commercial office space (spaces <30,000 sf). If we assume that the whole-building retrofit packages resulting from this project are adopted by 5 percent of small California commercial buildings by 2030, annual savings would be 50 percent at those buildings, or 89 million kWh/year of site energy saved. A site energy reduction of 50 percent compared to baseline energy use is a reasonable assumption for achieving ZNE performance, based on review of relevant case studies.[10] Further, if on-site energy generation through renewables offsets all annual energy use, total site energy savings would be 178 million

[10] U.S. Department of Energy, Commercial Building Partnerships. “Achieving a Net Zero Retrofit in a Hot, Humid Climate—Lessons from the University of Hawaii at Manoa.” (2015) LBNL-189802. “The Business of High Performance: The USC Darla Moore School of Business.” LBNL-6904E.

kWh/year. The adoption rate of 5 percent, or 32 million sf, may be feasible over a 15-year period by targeting district scale or community lead approaches, such as the San Francisco 2030 District's 10 million sf and growing portfolio, as well as targeting utility programs, and building owners.

The 2006 California Commercial End Use Survey shows an average natural gas energy intensity for the small commercial market of 10.54 kBtu/sf-yr. Assuming natural gas is removed from building services during the retrofit, a natural gas savings of 69 million therms/year would result from the 5 percent market uptake. A carbon-neutral ZNE retrofit is a suitable assumption and goal for this project, based on the experience of the project team.[11] At a 5 percent adoption rate, combined energy savings from electricity and natural gas would be $32.58 million/year for California Investor-Owned Utility (IOU) customers based on a statewide average rate for IOUs of $0.1564/kWh for electricity and $0.95/therm for natural gas. In addition, the resulting energy savings would reduce carbon emissions by 83,238 metric tons/year.

Reducing peak electric demand can provide further benefits to the small commercial market and the local electric utility. First, peak loads will be reduced by the inherent reduction in overall energy use from the retrofit. Based on the experience of the project team, a small commercial ZNE retrofit that reduces annual energy use by about 50 percent could reduce peak energy load by 100 kW for a 30,000-sf office building. Secondly, using demand response controls can contribute an additional 10-percent reduction in peak energy use, or 9kW for a 30,000-sf building. Assuming a 5-percent adoption rate in small commercial spaces by 2030, the combined effect would be 118.5 MW of peak load reduction. Those reductions in peak load will result in greater grid resiliency, due to automated demand control of the load shapes.

Qualitative Benefits - This project provides numerous qualitative benefits, such as increased thermal comfort, improved daylighting and lighting quality, factors that support greater productivity and improved health from fresh air, daylight, and improved indoor air quality. Those benefits to wellbeing may even dwarf energy benefits given the high costs of paid sick leave and health care, often 100 times the cost of the associated energy use. In numerous pilot projects over the past seven years, the International WELL Building Institute, in partnership with the Mayo Clinic, has found that 25 percent of owners report productivity gains of greater than 3 percent, and two-thirds of owner's report gains in employee satisfaction in the months following completion of WELL retrofit projects. More than 40 percent of owner's report reductions in health care costs of 1 percent to 4 percent. The WELL Building performance requirements for improved daylighting, indoor air quality, and comfort are well aligned with ZNE building designs.

The project had these goals.

- Development and demonstration of a replicable, integrated whole-building retrofit package that enables small commercial multi-floor office spaces to achieve energy use intensities equivalent to ZNE through cost-effective pre-commercial,

[11] International Living Future Case Study. IDEAS Z2 Design Facility. http://living-future.org/case-study/ideasz2

underutilized technologies and controls. A whole-building retrofit package will be developed for both a Northern California and a Southern California climate.

- Use FLEXLAB to test the two integrated whole-building packages under various climate conditions to understand performance and validate EEM modeling results.
- Pilot-test one whole-building package at a Northern California site to study energy use, comfort and occupant engagement, providing results and best operating practices.
- Incorporate the validated EEMs into a publicly available tool to make whole-building assessments and ZNE retrofit packages accessible to stakeholders.

The objectives of this project included:

1. Development and validation of ZNE-equivalent integrated whole-building EEM retrofit packages applicable to small commercial, multi-floor office spaces in Northern California and a Southern California climate, using commercial and/or underutilized technologies and controls.
2. Demonstrate a whole-building retrofit package in Berkeley, CA, collecting 12 months of monitoring and verification (M&V) data on energy performance, comfort, and occupant behavior.
3. Incorporate the validated EEM packages into the online CBES (https://cbes.lbl.gov/) whole-building retrofit tool for small commercial spaces.
4. Document best practices in implementation and operations, including as pertains to energy savings, comfort, and occupant behavior.

The following sections detail the approach used to develop the ZNE packages, incorporate ZNE retrofit analysis into CBES and conduct package validations through lab and field demonstration testing while documenting best practices in ZNE operations.

ZNE Package Development

To achieve a ZNE building, active and passive design strategies were identified in three broad categories namely envelope, lighting and daylighting and heating, ventilation and air-conditioning (HVAC). These categories also represent three main potential paths for a whole building retrofit, offering the building owner a strategy that can best fit the current upgrade needs of their building. For example, if the roofing and windows need replacement then the envelope focused package would be appropriate to follow. For buildings that were aiming to improve daylighting in their space the second package would be a good starting point. The third package focuses on an HVAC system upgrade, appropriate for buildings that require significant HVAC equipment replacement. All strategies were considered in terms of cost effectiveness, appropriateness to climate, space planning and applicability in eliminating natural gas. These strategies were developed as three packages:

- Package 1 - Envelope focused
- Package 2 - Lighting - daylighting focused
- Package 3 - HVAC System focused

The detailed list of measures incorporated in Package 1, 2 and 3 is provided in the Appendix A. An additional set of common cost-effective measures were also included in each of these packages as described in Appendix A, as well as a photovoltaic system to achieve the ZNE condition. For the purposes of enabling a comparison with a 'standard' building retrofit for cost effectiveness comparisons, two standard retrofit packages were developed to represent a typical building retrofit scope for projects without a ZNE goal. Each of these packages focused on a combination of HVAC replacement, lighting upgrades, and domestic hot water upgrades. The HVAC packages were split into two different options based on the types of HVAC systems present specifically, Package A was for buildings using single-zone systems, while Package B was for buildings whose HVAC units serve multiple zones.

Common Cost-Effective Package Measures

Before developing the ZNE retrofit packages, common cost-effective retrofit packages were investigated based on typical projects in both northern and southern California. Common to both upgrade packages were a replacement of interior bulbs with LEDs (LPD: 0.8 W/sf) along with occupancy and daylighting sensors, as well as improved domestic hot water heater efficiency (80 percent, per Title 24 minimum efficiency). In addition, a set of plug load energy reduction strategies were put in place. Further details on the common cost-effective package measures are detailed in Appendix A. These were the most common cost-effective upgrades being deployed at the time and created a foundation for the ZNE packages to be developed.

Envelope Focused Retrofit Package Measures

The envelope package consisted of passive strategies such as adding R40 insulation for the top floor ceiling and R20 wall insulation, improving thermal performance through glazing properties, increasing the solar heat gain coefficient of windows and sealing envelope leaks.

Lighting Focused Retrofit Package Measures

The lighting package included a combination of passive and active strategies that were evaluated in terms of cost-benefits. The lighting focused retrofit package included replacing exterior lighting with 50 LED bulbs at 50 W each with astronomical time-based controls, replacing interior lighting with LED upgrades with a lighting power density of 0.4 W/sf, installing wall-mounted occupancy sensors, installing daylighting sensors for interior lighting control. Tubular skylights were considered as a low-cost passive strategy for the deep floor plate – for the areas where side-lighting is incapable of reaching – along with active strategies such as reducing lighting power density and providing controls.

HVAC System Focused Retrofit Package Measures

The HVAC focused retrofit package included installing a dedicated outside air system DOAS) energy recovery ventilator (enthalpy wheel) with variable air volume (VAV) fan, installing variable refrigerant flow (VRF) rooftop heat pump with indoor refrigerant fan coils (with heat recovery), adding demand controlled ventilation (DCV) with CO_2 sensors, implementing unoccupied room temperature setbacks, widening zone temperature deadband (cooling: +2F; heating -2F) and reducing HVAC equipment runtime (shutoff when unoccupied). Widening thermostat setpoints, providing 100 percent outside air and including an enthalpy wheel are low cost measures that are appropriate for the climate of California

Plug Load Focused Retrofit Measures

Plug load controllers were also considered for inclusion in the packages. These occupancy-based controllers send power to the controlled receptacles only when there is someone in the room. This strategy reduces energy use when the building is unoccupied, and equipment is idling.

Energy Generation/Photovoltaic System Focused Retrofit Package Measures

Photovoltaic panels were included in the packages, assuming they were installed on the roof only to meet the annual energy consumption of the building. An assumption that no more than 80 percent of the roof area would be available for installation was made.

FLEXLAB Testing

In order to validate the energy, thermal comfort and visual comfort aspects of the developed packages, tests were first conducted in a controlled lab environment at LBNL's FLEXLAB[Ò](FLEXLAB.lbl.gov). Further testing later in the project also occurred in an occupied demonstration site (described later). The tests were conducted on a single ZNE package, designed to be applicable to both Southern and Northern California as well as the Berkeley demonstration site. The package consisted of modulating supply diffusers (MSDs/Thermafusers) with VAV control and ventilation-only air, LED lighting and daylight dimming, reduced plug load power, and tubular daylighting devices (TDDs). Separate tests evaluated the daylight delivery and glare performance of various TDD configurations. Package/TDD-only tests were conducted throughout the year to cover a representative range of outdoor conditions.

ZNE Packages

The ZNE package was evaluated in a FLEXLAB testbed containing two identical cells. One cell was set up to represent the ZNE package and the other a baseline configuration. Each 20 x 30 ft cell was subdivided into three areas using floor-to-ceiling partitions: an area (20 x 12 ft) adjacent to the window wall, another (14 x 10 ft) representing a small interior office, and a third area comprising the rest of the cell. The testbed rotated to allow orienting the façade towards south and west. Measurements included energy use (HVAC, lighting, plug loads) and comfort (visual, thermal).

ZNE package configuration

The ZNE package was configured as follows (Figure 1):

- HVAC: variable refrigerant flow, dedicated outdoor air system, wide deadband, setbacks/shutoff when unoccupied, MSDs.
- Façade: 0.25 window-to-wall ratio, clear single-pane window, thermally-broken aluminum frame, metal stud wall (R-19 batt cavity insulation).

- Lighting: 0.4 W/ft^2, LED, occupancy sensing, daylight harvesting.
- Plug loads: 0.539 W/ft^2 connected load, 90 percent diversity, 0.485 W/ft^2 max. operating load.

Figure 1: ZNE Package Cell in FLEXLAB Test

Interior of ZNE package cell. Shown are window-adjacent space (*left*) and interior office space (*right*).

Source: LBNL

Baseline configuration

The baseline cell was configured as follows (Figure 2):

- HVAC: packaged VAV with hydronic coils, gas furnace, static supply diffusers.
- Façade: identical to ZNE package cell.
- Lighting: 1.19 W/ft^2, T8 fluorescent troffers, no automated controls.
- Plug loads: 0.539 W/ft^2 connected load, 90 percent diversity, 0.485 W/ft^2 max. operating load.

Tubular Daylight Devices

TDDs were evaluated as a standalone measure in a single cell to verify their energy and daylighting performance in particular, as an emerging technology, for its representation in CBES and the packages. Windows were blocked and floor-to-ceiling partitions formed a 14 x 14 ft interior space. The TDD opening was at the center of that space and was the only light source. Light level and visual comfort measurements were performed for several combinations of TDD diameter, dome (clear or prismatic) and diffuser type (clear, Fresnel, diffusing), in order to evaluate impacts of these options on energy use and comfort.

Figure 2: Baseline Cell in FLEXLAB Test

Interior of baseline cell. Shown are window-adjacent space (*left*) and interior office space (*right*).

Source: LBNL

Field Demonstration

The Berkeley Mental Health Services building, located at 2640 Martin Luther King Jr Way, Berkeley, CA 94704 was selected to provide a field demonstration and validation of the ZNE package approach, including study of both technology performance and occupant comfort and acceptance of the retrofit. The building is a one-story office building of approximately 8,800 square feet. The following is a list of the EEMs included in the ZNE design package:

- (2) packaged heat pump variable air volume energy recovery ventilators (ERVs) with demand-controlled ventilation and thermafusers.
- LED lighting with occupancy and daylighting controls, (35) tubular skylights, and (5) existing skylights.
- (6) instantaneous electric water heaters.
- R-19 roof and R-19 cavity insulation added.
- Reduced plug loads to 0.49 W/sf connected load.
- Rooftop solar photovoltaic (PV) system.

A full description of the field demonstration building and all EEMs analyzed can be found in Appendix B: Field Demonstration.

ZNE Retrofit Analysis

After the Baseline model for the building was calibrated to 2015 monthly utility data, packages were developed and modeled in OpenStudio to see if ZNE could be achieved. For the Berkeley Mental Health Clinic, four ZNE packages were suggested which each included the same upgrades to the lighting, domestic hot water, and plug loads. The packages differed in the selection of the HVAC system type and whether or not the windows were replaced.

Occupant Engagement

Two strategies were implemented to educate and engage occupants in their workspace.

1. An educational signage program highlighting ZNE features in the building was developed. The signage was installed at several places in the building.
2. An occupant survey was conducted to evaluate and maintain individual comfort in terms of 9 categories namely: personal workspace, layout, visual privacy, air quality, thermal comfort, acoustics, furnishings, cleanliness and maintenance and lighting. The aim was to ensure thermal comfort and air supply were not compromised while achieving a ZNE building and to identify any potential performance issues that need to be rectified.

Measurement and Verification

A measurement and verification plan was developed to verify that the building is performing as expected and to assist in optimizing energy performance over the lifetime of the building. As part of this plan, twelve months of post-occupancy trend data has been collected and compared to the energy model per the International Performance Measurement and Verification Protocol - Option D, Whole Building Calibrated Simulation (Method 1). Trends include electrical panel-level energy and targeted loads such as energy per air handler, lighting energy in rooms with TDDs, and plug load energy in high load spaces. Additional information and the full list of metering points is available in the project deliverable Zero Net Energy Small Commercial Retrofits Measurement and Verification Plan – Berkeley Mental Health Services. The M&V plan also included two periods of additional temporary monitoring to be installed in this workspace over two weekends, to gather more detailed thermal comfort and visual comfort data. The two monitoring periods were picked to include a range of outdoor conditions that may be considerations for visual and thermal comfort, including warmer and cooler periods, and periods with high and low seasonal sun angles.

In addition to the quantitative measurement and verification procedures, qualitative assessments were conducted to ensure that the changes made to the building did not decrease the satisfaction of the building occupants. Specifically, surveys of full-time occupants (staff) were conducted to assess if sensors are providing a realistic assessment of building comfort and to evaluate how occupants are interfacing with building systems.

Commercial Building Energy Savings

Implementation of New Features and EEMs

New features and energy conservation measures were implemented in CBES to enable small commercial office ZNE retrofit analysis. Overall, the simulation is based on EnergyPlus and OpenStudio, and the implementation is using Ruby and the OpenStudio Software Development Kit (SDK) as the development languages.

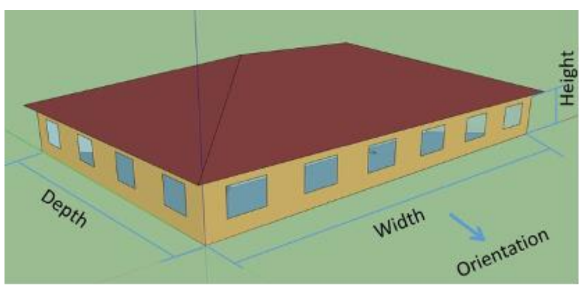
Four new features, including rooftop PV system, electric battery, solar shading, and the Time Dependent Valuation (TDV) energy metric, were implemented in CBES to enable the ZNE retrofit analysis.

A list of new EEMs were proposed by the research team to provide more retrofit options to achieve the ZNE goal. The estimated unit costs of these measures were compiled from a few sources (e.g., RSMeans, the Database for Energy Efficiency Resources (DEER)) and added to the CBES EEM database. The users can either use the default costs or adjust the costs according to their project needs.

Demonstration of Path to ZNE using CBES

An example case study was conducted to demonstrate the applications of the new features and EEMs for an existing building to achieve ZNE. The example building, shown in Figure 3, is a one-story prototype office building built in 1977, located in San Francisco. The gross floor area is 10,000 ft2. The energy use intensity (EUI) is 56.7 kBtu/ft2. Benchmarking was first performed on the building to evaluate its performance compared with its peer buildings. An EnergyStar score of 38 was obtained, which infers that the building had substantial potential for improvement.

Figure 3: The 3D Model of the Example Building



Three dimensional drawing of an example small commercial building

Source: LBNL

Two major efforts were made to achieve ZNE for the building: (1) improve building performance to reduce basic energy use, and (2) install a PV system to generate and supply electricity to the building. A list of EEMs were selected and first evaluated individually on energy savings and payback years. Based on single measure analysis results, three EEM packages were compiled with different optimization purposes, including high energy savings, short payback year, and comprehensive. A new PV system of 52kW capacity, which covers about 35 percent of the roof area, was added to the building. TDV energy was selected as the energy metric to evaluate ZNE since this building is in California.

Validation of Simulation Accuracy

Measured data from the FLEXLAB experiments was used to validate the simulation accuracy of the CBES tool. An equivalent building model was developed using CBES to represent the FLEXLAB chamber, by customizing the Small Office prototype in CBES. The layout of the FLEXLAB chamber can be found in Appendix C. The model's shape was refined in CBES by adjusting the length and width to align the floor areas of selected zones. Two of the perimeter zones were selected to represent the window space and intermediate space in the FLEXLAB experiment, and the core zone is selected to represent the TDD space in the experiment. EUI was calculated and compared in the validation.

The validation was performed in two parts: (1) validation of the TDD measure performance, (2) validation of performance of the full ZNE package implemented in the FLEXLAB experiment, where two key subsystems, lighting and HVAC, were validated separately, and the entire system was validated as a whole.

Results

ZNE Package Development

Baseline Building Model Development and Calibration

To enable ZNE analysis of the developed packages in each of the Northern and Southern California climates, an initial step was taken to develop a prototypical building in each climate to represent the baseline condition, and to calibrate those models to the average small commercial office building energy use in those regions. The Commercial Building Energy Saver (CBES) tool was used to develop the two existing building baseline models. The two buildings were set up to be a typical 'theoretical' two-story, 50,000 sf commercial office buildings built in 1980 in either a Southern California (SoCal Baseline Model) or Northern California (NorCal Baseline Model) climate zone.

Southern California Benchmark Data

Data from the 2006 California Commercial Energy End-Use Survey (CEUS) Table 10-8 Small Office Electric EUIs and Table 10-9 Small Office Natural Gas EUIs for Southern California Edison (SCE) were used to calculate the benchmark for the typical small office building in the SoCal region. For a 50,000 square foot building, this equated to 615,500 kWh/yr of electricity and 8,085 therms/yr of natural gas, resulting in an EUI of 58 kBtu/sf-yr (Figure 4). To calibrate the SoCal Baseline Model, the model inputs were adjusted within the CBES tool until the electric and natural gas outputs were in line with the benchmark data. After calibration, the baseline energy model used 660,300 kWh/yr of electricity and 10,800 therms/yr of natural gas for an EUI of 67 kBtu/sf-yr.

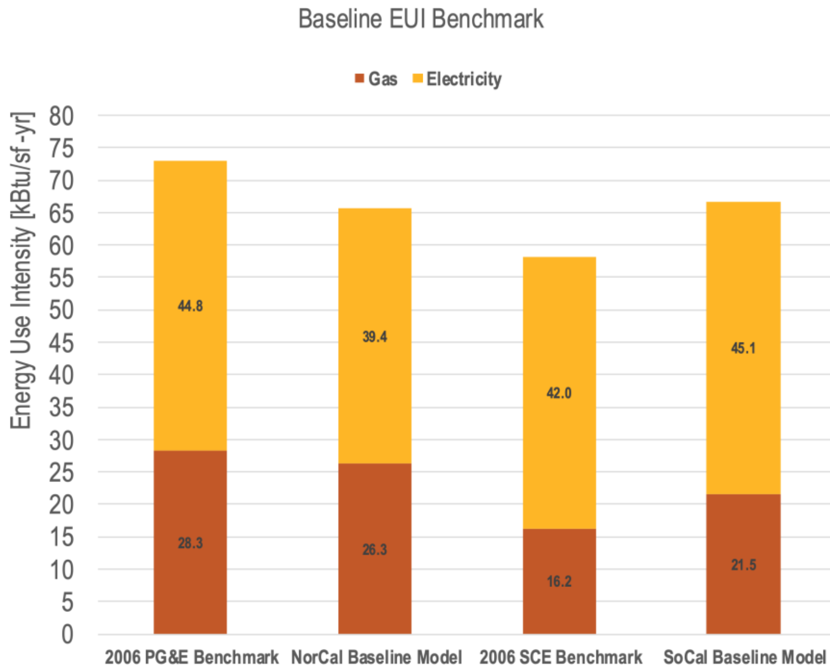
Northern California Benchmark Data

The 2006 CEUS Table 9-8 Small Office Electric EUIs (PG&E) and Table 9-9 Small Office Natural Gas EUIs for Pacific Gas & Electric (PG&E) were used to calculate the benchmark for the typical small office building in the NorCal region. For a 50,000 sf building, this equated to 656,500 kWh/yr and 14,130 therms/yr, for an EUI of 73 kBtu/sf-yr (Figure 4). To calibrate the NorCal Baseline Model, the model inputs were adjusted within the CBES tool until the electric and natural gas outputs were in line with the benchmark data. After calibration, the baseline energy model used 577,500 kWh/yr and 13,100 therms/yr for an EUI of 66 kBtu/sf-yr (Figure 4).

Baseline Model Calibration

The SoCal Baseline and NorCal Baseline models were then brought into OpenStudio software (created in collaboration with NREL, LBNL, ANL, ORNL, and PNNL) to model outside of the CBES tool and study the impacts of new EEMs. Several changes were made to schedules and HVAC specifications to better align the models with older building stock, as well as with the CEUS data. Results are presented in Figure 4 as annual EUI values which is a measure of the annual total energy use per gross square foot of building area.

Figure 4: Energy Use Intensity for Baseline Model Calibrations



Comparison of the calibrated Baseline building models with the benchmark data from the 2006 California Commercial Energy End-Use Survey.

Source: LBNL Small Office ZNE Report: Northern & Southern California Prototype Buildings

After the baseline models were calibrated, packages were developed and modeled in OpenStudio for each building to see if ZNE could be achieved using the identified measures and packages. The following simulations were modeled for both SoCal and NorCal Prototype Buildings.

- Baseline Model
- Title 24-2016 Code Baseline
- Standard Package A
- Standard Package B
- ZNE Package 1 - Envelope Focused
- ZNE Package 2 - Lighting/Daylighting Focused
- ZNE Package 3 - HVAC System Focused
- ZNE Package 1 + 2 - Envelope and Lighting/Daylighting Focused
- ZNE Package 2 + 3 - Lighting-Daylighting and HVAC System Focused
- ZNE Package 1 + 2 + 3 - Envelope, Lighting/Daylighting, and HVAC Systems

Full descriptions of all ZNE Packages are provided in Appendix A: ZNE Packages.
All ZNE Packages contained some common elements which represented the minimum upgrade for each area of the building. Specifically:

Common Measures

- HVAC: Single zone rooftop packaged heat pump (VAV fan, heat pumps COP: 3.3, without heat recovery)
    - Temperature setpoints and hours of operation are same as Baseline.
- DHW: Replace with electric instantaneous (efficiency 95 percent) and install low-flow fixtures
- Lighting:
    - Replace exterior lighting with 50 bulbs at 50 W each
    - Replace interior bulbs with LEDs or de-lamp fluorescent lighting (LPD: 0.8 W/sf). 0.8 W/sf is connected load with peak operating diversity at 90 percent of capacity (due to not all of the lights in the building being on at the same time), resulting in 0.72 W/sf max operating load.
    - Install Wall-Mounted Occupancy Sensors
- Plug Loads: reduce by 30 percent from 0.77 W/sf to 0.539 W/sf. 0.539 W/sf is connected load, 90 percent peak operating diversity, 0.485 W/sf max operating load.

All of the ZNE packages and package combinations achieved the ZNE goal, with the exception of Package 3 (HVAC focus) alone as shown in Figure 5. Package 3 did not focus on reducing the building loads, it was primarily focused on upgrading the HVAC systems beyond what was outlined in the Common Measures. This suggests that load reduction – either envelope loads and/or interior lighting loads – is critical to achieving ZNE.

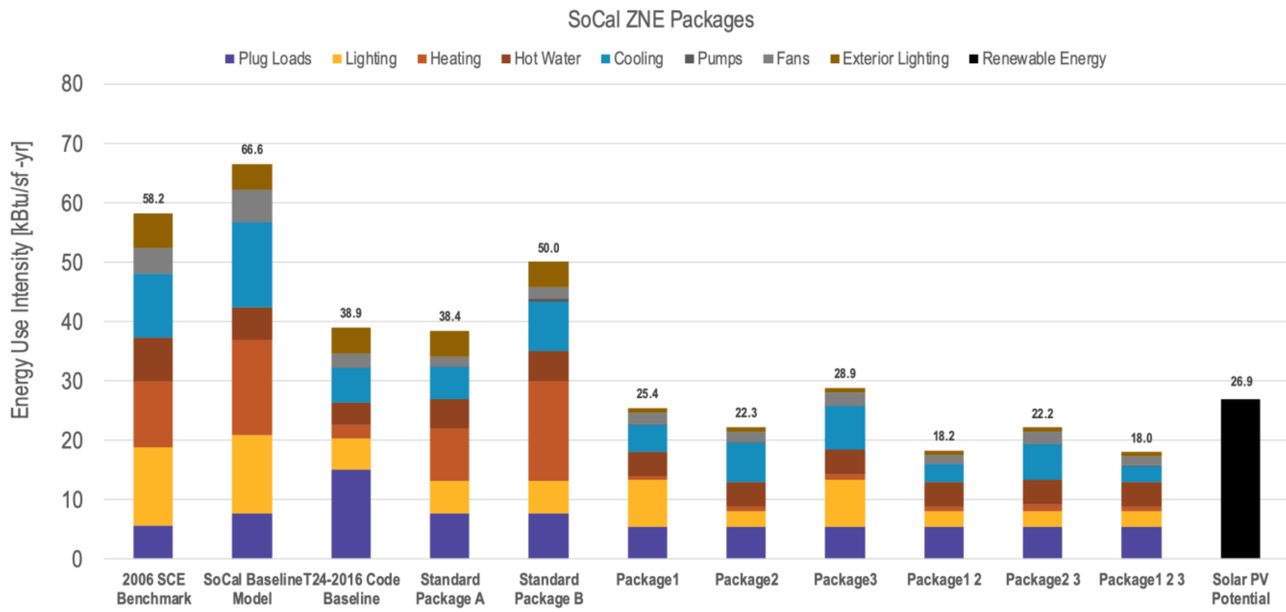
The development of the packages relied on existing, commercially available technologies and as such cost effectiveness of the packages relied on current market pricing of these technologies. The packages were costed out in late 2019, and as such it is expected that these prices, as well as energy costs, would be higher using more current pricing due to the effects of inflation and supply chain issues. Overall, the team would expect the lighting and HVAC packages to still be cost effective when compared to a similar retrofit using energy code minimally compliant technologies. The envelope measures would still have a much longer payback period and means to reduce cost for these upgrades would be highly valuable for the broader commercial buildings market.

ZNE Package Analysis

Energy Consumption

Energy consumption results for each ZNE package were compared against the calibrated baseline. The simulated annual energy end-use consumption for the SoCal Baseline Model is shown below in Figure 5, as well as the end-use consumption for all modeled ZNE packages. Additionally, the annual solar production potential is plotted as a comparison to show which packages are below the ZNE threshold. Table 1 provides the same information in a tabular format.

Figure 5: SoCal ZNE EEM Packages Energy Use Intensity and Economics



	Package1	Package2	Package3	Package1 2	Package2 3	Package1 2 3
% Incremental Cost over Standard A Retrofit	24%	-6%	-27%	39%	-5%	32%
% Incremental Cost over Standard B Retrofit	17%	-12%	-31%	31%	-11%	24%
IRR - Over Standard A Retrofit	4%	CAPITAL POS	CAPITAL POS	2%	CAPITAL POS	6%
IRR - Over Standard B Retrofit	11%	CAPITAL POS	CAPITAL POS	5%	CAPITAL POS	11%

The SoCal EEM packages focus on different categories of EEMs to achieve ZNE. Package 1 focuses on envelope improvements, Package 2 on lighting and daylighting, and Package 3 on HVAC improvements.

Source: LBNL Small Office ZNE Report: Northern & Southern California Prototype Buildings

Table 1a: SoCal ZNE EEM Packages Annual End Use Consumption – Part 1

SoCal ZNE (Area = 50,000 sqft)						
Packages	2006 SCE Benchmark	SoCal Baseline Model	T24-2016 Code Baseline	Standard Package A	Standard Package B	Package 1
Detailed Breakdown	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr
Plug Loads	278,089	386,099	754,522	386,099	386,099	270,270
Lighting	660,248	654,768	262,783	275,303	275,303	396,165
Heating	562,239	808,194	117,264	437,721	839,671	27,988
Hot Water	363,979	267,199	187,109	250,679	250,650	208,048
Cooling	532,293	717,303	290,885	270,526	418,656	230,615
Pumps	0	2,161	2,218	2,161	21,761	2,161
Fans	223,495	276,393	116,312	83,926	93,802	99,186
Exterior Lighting	288,325	216,228	216,228	216,010	216,010	37,276
Renewable Energy	0	0	0	0	0	0
Total Energy (kBtu/yr)	**2,908,668**	**3,328,345**	**1,947,320**	**1,922,425**	**2,501,953**	**1,271,710**

Table 1b: SoCal ZNE EEM Packages Annual End Use Consumption – Part 2

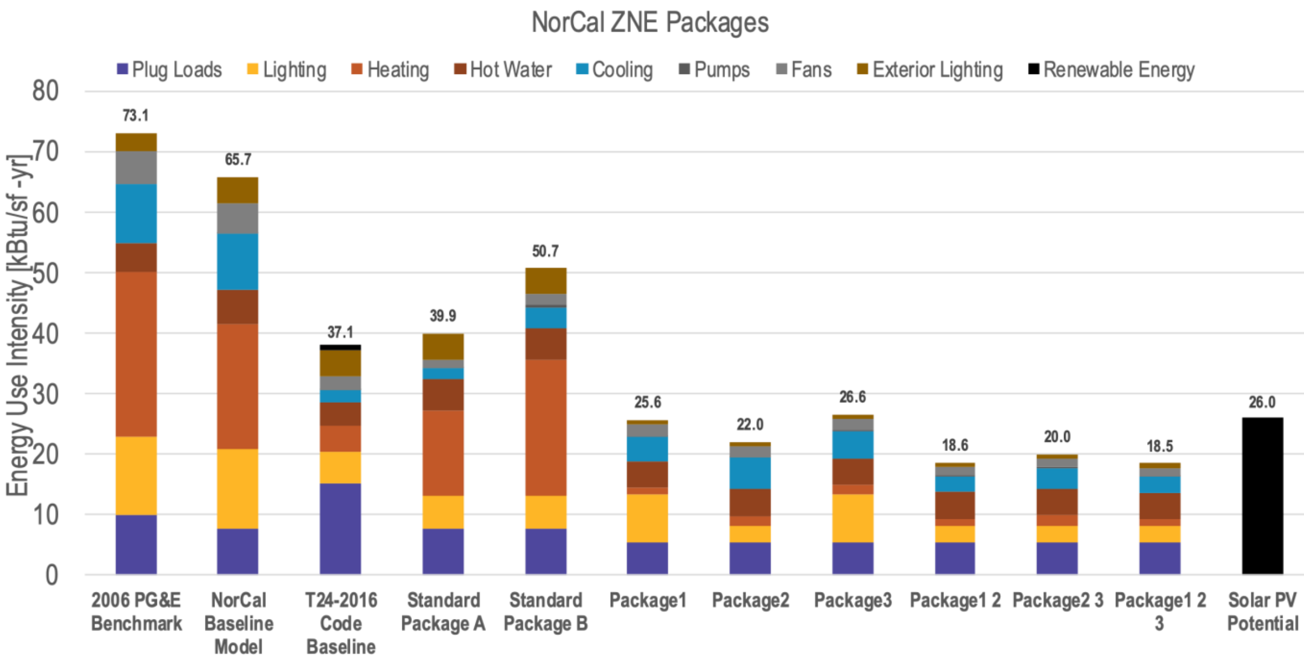
SoCal ZNE (Area = 50,000 sqft)						
Packages	Package 2	Package 3	Package 1+2	Package 2+3	Package 1+2+3	Solar PV Potential
Detailed Breakdown	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr
Plug Loads	270,270	270,270	270,270	270,270	270,270	0
Lighting	138,680	396,165	138,680	137,647	138,680	0
Heating	34,405	47,550	31,921	51,285	30,206	0
Hot Water	208,020	208,238	208,067	208,209	208,067	0
Cooling	333,865	367,627	149,390	303,187	138,680	0
Pumps	2,161	2,161	2,161	2,161	2,161	0
Fans	97,246	115,639	74,268	97,347	74,809	0
Exterior Lighting	38,224	37,248	37,276	37,248	37,276	0
Renewable Energy	0	0	0	0	0	1,344,998
Total Energy (kBtu/yr)	**1,122,872**	**1,444,899**	**912,035**	**1,107,355**	**900,150**	**1,344,988**

These two tables show the annual energy by end use (kBtu/yr) for each of the measure packages for Southern California.

Source: LBNL Small Office ZNE Report: Northern & Southern California Prototype Buildings

Similarly, the energy end-use simulation and package cost economics results for the NorCal Baseline Model are shown in Figure 6 and Table 2.

Figure 6: NorCal ZNE EEM Packages Energy Use Intensity and Economics



	Package1	Package2	Package3	Package1 2	Package2 3	Package1 2 3
% Incremental Cost over Standard A Retrofit	44%	7%	-26%	60%	-2%	45%
% Incremental Cost over Standard B Retrofit	36%	2%	-30%	52%	-7%	38%
IRR - Over Standard A Retrofit	-5%	54%	CAPITAL POS	-4%	CAPITAL POS	1%
IRR - Over Standard B Retrofit	-3%	182%	CAPITAL POS	-3%	CAPITAL POS	3%

The NorCal EEM packages focus on different categories of EEMs to achieve ZNE. Package 1 focuses on envelope improvements, package-2 on lighting and daylighting, and package-3 on HVAC improvements.

Source: LBNL Small Office ZNE Report: Northern & Southern California Prototype Buildings

Table 2a: NorCal ZNE EEM Packages End Use Consumption – Part 1

NorCal ZNE (Area = 50,000 sqft)						
Packages	2006 PG&E Benchmark	NorCal Baseline Model	T24-2016 Code Baseline	Standard Package A	Standard Package B	Package 1
Detailed Breakdown	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr
Plug Loads	496,466	386,099	263,162	386,099	386,099	270,270
Lighting	648,306	654,768	754,522	274,488	274,488	396,165
Heating	1,360,453	1,036,855	219,704	698,077	1,120,936	54,355
Hot Water	233,388	277,625	193,866	260,451	260,422	219,156
Cooling	489,641	464,510	97,802	93,926	169,720	205,196
Pumps	0	2,161	3,962	2,161	24,443	2,161
Fans	274,677	247,059	107,375	62,213	81,595	95,101
Exterior Lighting	150,134	215,744	215,744	216,019	216,019	37,201
Renewable Energy	0	0	0	0	0	0
Total Energy (kBtu/yr)	**3,653,065**	**3,284,821**	**1,856,138**	**1,993,433**	**2,533,723**	**1,279,605**

Table 2b: NorCal ZNE EEM Packages End Use Consumption – Part 2

NorCal ZNE (Area = 50,000 sqft)						
Packages	Package 2	Package 3	Package 1+2	Package 2+3	Package 1+2+3	Solar PV Potential
Detailed Breakdown	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr
Plug Loads	270,270	270,270	270,270	270,270	270,270	0
Lighting	137,780	396,165	137,780	137,239	137,780	0
Heating	81,273	81,841	59,748	88,135	53,720	0
Hot Water	219,137	218,967	219,166	218,967	219,166	0
Cooling	268,352	226,663	131,050	173,255	129,629	0
Pumps	2,161	2,161	2,161	2,161	2,161	0
Fans	85,623	95,992	72,856	71,908	73,662	0
Exterior Lighting	37,201	37,248	37,201	37,248	37,201	0
Renewable Energy	0	0	0	0	0	1,299,998
Total Energy (kBtu/yr)	**1,101,797**	**1,329,307**	**930,232**	**999,184**	**923,588**	**1,299,998**

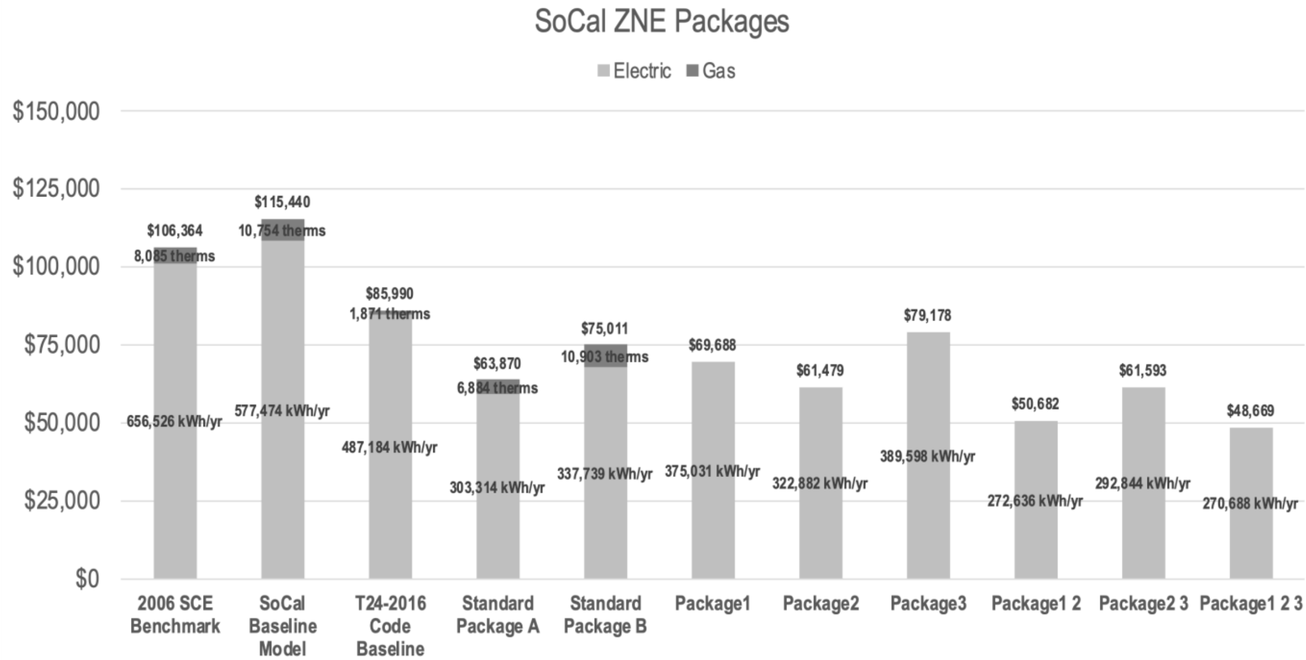
These two tables show the annual energy by end use (kBtu/yr) for each of the measure packages for Northern California.

Source: LBNL Small Office ZNE Report: Northern & Southern California Prototype Buildings

Energy Costs

Energy cost results for each ZNE package were developed and compared against the calibrated baseline (SoCal Baseline Model). The simulated energy cost (electricity and natural gas) for the SoCal Baseline Model can be seen in Figure 7. Note that all ZNE packages utilize an all-electric design.

Figure 7: SoCal ZNE Packages Annual Energy and Energy Cost



Electric and annual gas costs of the different packages using the SCE TOU-GS-2 Option A Rate and SoCalGas G-10 gas rate. The gas rate assumes a mid-tier use rate.

Source: LBNL Small Office ZNE Report: Northern & Southern California Prototype Buildings

The simulated energy cost (both electricity and natural gas) for the NorCal Prototype Building can be seen in Figure 8. Note that all ZNE packages utilize an all-electric design.

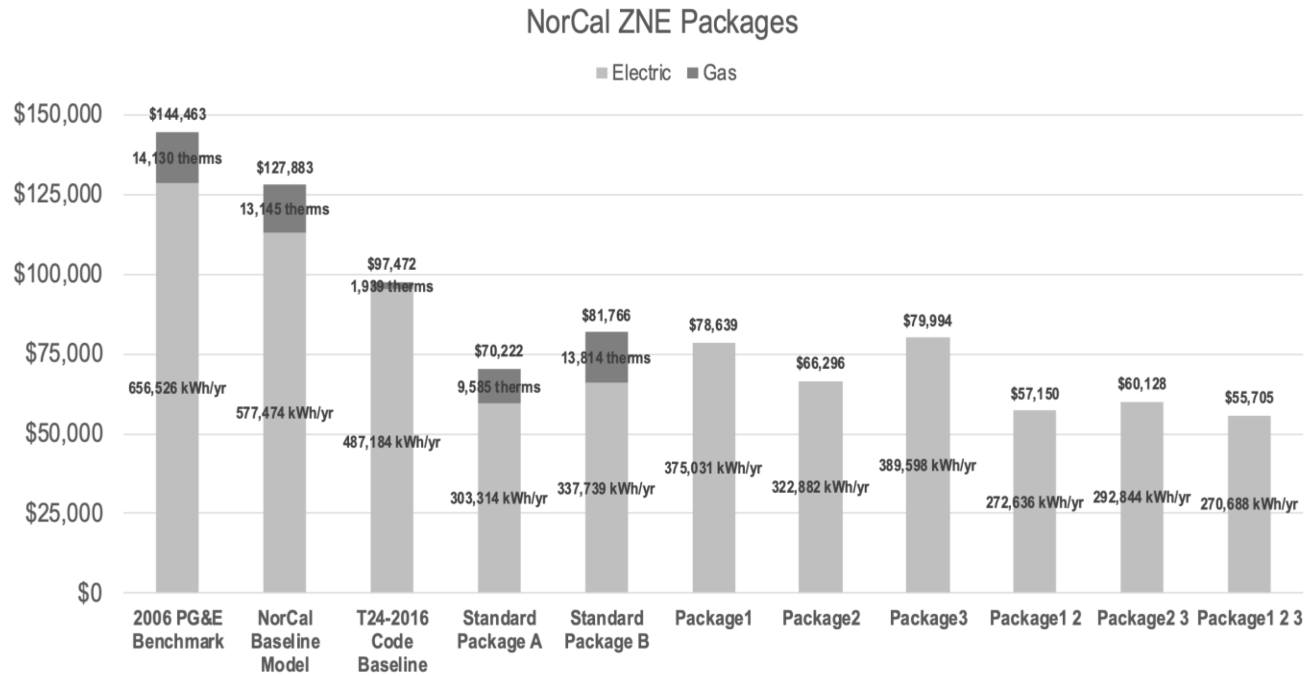
ZNE Package and Measure Validation

FLEXLAB Testing

FLEXLAB testing was conducted to validate the ZNE package energy savings, as well as visual and thermal comfort performance. Overall, the ZNE packages reduced energy use significantly without measurable impact on visual comfort and moderate impacts on thermal comfort. Façade orientation had measurable but minor energy use impact.

TDD-only FLEXLAB tests were also conducted to validate their daylighting provision, as well as visual and thermal comfort aspects. FLEXLAB tests showed no significant energy performance differences between dome and diffuser types. Savings were lower for smaller-diameter TDDs. All TDD configurations maintained acceptable visual comfort.

Figure 8: NorCal ZNE Packages Annual Energy and Energy Cost



The electric and annual gas costs of the different packages using the PG&E A-10 Time-of-Use rate and G-NR1 gas rate. The gas rate assumes the winter gas rate, when most gas consumption occurs.

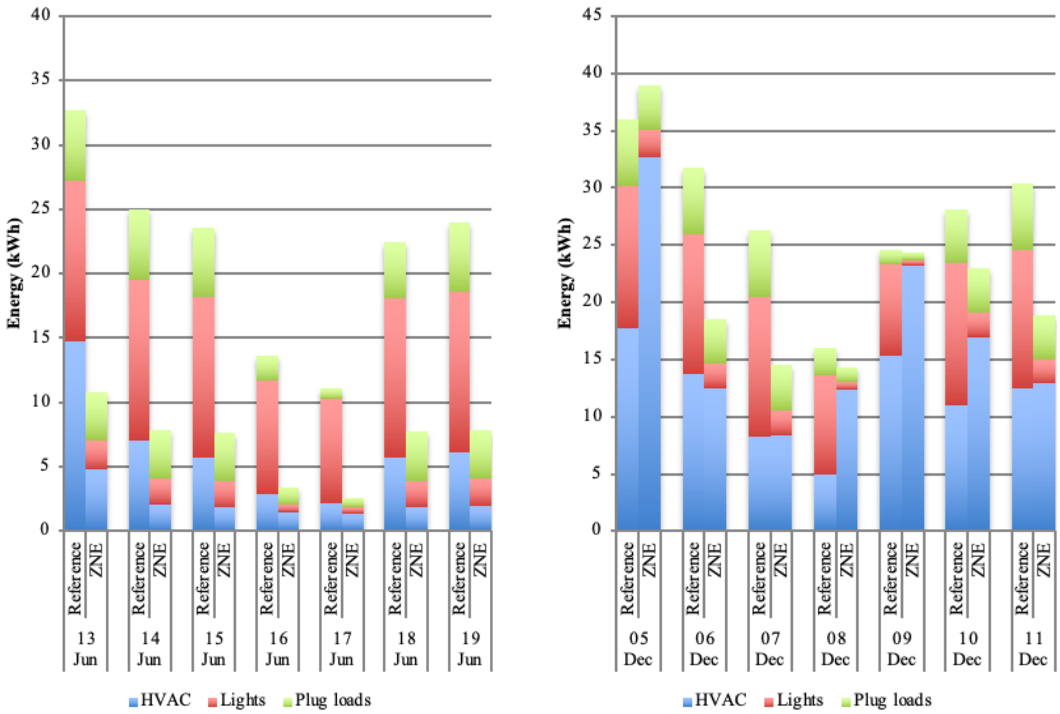
Source: LBNL Small Office ZNE Report: Northern & Southern California Prototype Buildings

ZNE Packages

The proposed ZNE package provided significant energy savings during cooling- (59 percent-69 percent) and heating-prevalent (22 percent-25 percent) periods, despite a HVAC energy penalty during the latter (Figure 9). Lighting energy savings was 85 percent and plug load energy savings was 31 percent, independently from façade orientation. These internal load savings matched the differences in plug load and lighting power densities between baseline (reference) and ZNE FLEXLAB cells. During cooling-prevalent periods, total energy savings were 65 percent and 68 percent for south and west orientation, respectively; similarly, during heating-prevalent periods total energy savings was 22 percent and 25 percent. During cooling-prevalent periods, measured HVAC thermal energy (sum of cooling and heating loads, and fan energy) savings were 79 percent- and 81- percent facing south and west, respectively; corresponding values for heating-prevalent periods are -25 percent and -49 percent. These differences between the cells result cumulatively from reduced internal heat gains, more efficient HVAC operation, and presence of MSDs in the ZNE cell.

No differences were measured in visual comfort between the cells. Regarding thermal comfort, the ZNE cell tended towards a wider range in thermal sensation levels and tended to be warmer than the reference cell during the cooling season and cooler during the heating season. Thermal comfort was generally comparable in the interior spaces of the cells. Regarding the window space, the reference cell was slightly too cool during the cooling season and the ZNE cell slightly too cool during the heating season; this could be mitigated by improving the windows/shading devices, which was outside the scope of this experiment.

Figure 9: FLEXLAB ZNE Package Energy Savings



Energy use in ZNE package and baseline (reference) cells during cooling- (*left*) and heating-prevalent (*right*) periods in 2018. Results shown are for tests with the façade due south.

Source: ZNE Package and Tubular Daylighting Device (TDD) FLEXLAB Test Results Report

Tubular Daylight Devices

TDD-specific tests showed potential annual lighting energy savings of 27-69 percent for 22”-diameter TDDs and 22-32 percent for 14”-diameter TDDs, without negative visual comfort impacts. Note that these values do not account for the fact that sky cover could vary significantly between tests with different configurations. For TDDs of the same diameter, tests did not show clear differences in lighting energy and visual comfort performance across dome/diffuser types.

Field Demonstration

The Berkeley Mental Health Services building, located at 2640 Martin Luther King Jr Way, Berkeley, CA 94704 was selected to provide a field demonstration and validation of the ZNE package approach, including study of the package technology performance, and occupant comfort and acceptance of the retrofit. The building was a one-story office building of approximately 8,800 square feet.

ZNE Retrofit

The Berkeley Mental Health Services building, was selected to provide a field demonstration and validation of the ZNE package approach, including study of technology performance and occupant comfort and acceptance of the retrofit. The rendering of the completed building retrofit appears in Figure 10.

Figure 10: Berkeley Mental Health Services Building Rendering

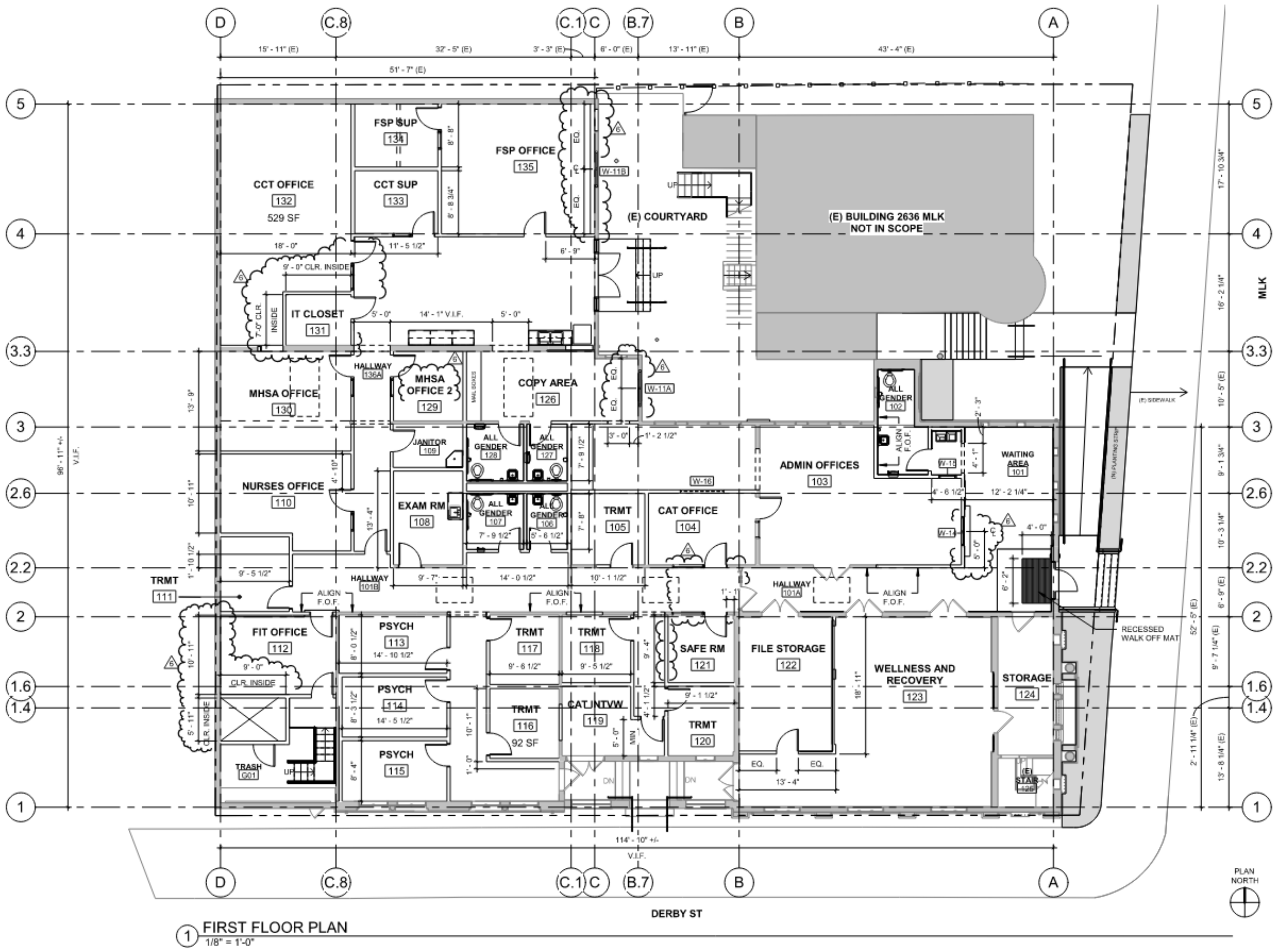
Rendering of the field demonstration site, the Berkeley Mental Health Services Building.

Source: ELS Architecture and Urban Design

The building includes a historic portion of the building, with clay roof tiles, exposed wood beams and other architectural features such as stained glass windows. This posed a number of challenges for the ZNE retrofit in that photovoltaic panels could not be installed on the historic roof; the historic windows and walls could also not be retrofit to improve thermal performance either. While this was a challenge, it also represents the very real constraints in small commercial buildings. The reduction in available roof area for onsite PV was seen as a realistic constraint found in many small commercial buildings which might not have significant access to viable solar producing roof area, such as shading by adjacent building structures or trees. An additional substantial issue for the retrofit was that the building was built right up to the property line on two lot edges, meaning that it was not possible to have windows on those walls. A goal of the project was to improve daylight availability to building occupants, which ultimately was achieved through the retrofit of tubular daylighting devices and skylights, both mounted at the roof. While this did achieve the goal of improving daylight availability, it also resulted in a further reduction of roof area for photovoltaic panels.

Figure 11 provides a layout of the building interior, which consists of a variety of open and enclosed office spaces, a lobby area, a large meeting room in the historic part of the building and multiple enclosed treatment rooms.

Figure 11: Berkeley Mental Health Services Building



Floor plan for the field demonstration site, the Berkeley Mental Health Services Building.

Source: ELS Architecture and Urban Design Drawings for Mental Health Services project 10.11.2019

The design process started with the set of measures available through CBES and developed several different retrofit packages for analysis and costing. The initial packages included:

Package 1a: DOAS + VRF (Dedicated Outside Air System + Variable Refrigerant Flow), No Window Replacement
Package 1b: DOAS + VRF, Window Replacement [only in non-historic locations]
Package 2a: Heat Pump
Package 2b: Heat Pump with ERV (Energy Recovery Ventilator)

More detailed information regarding the initial ZNE Retrofit packages for the field demonstration is provided in Appendix B: Field Demonstration. The project team selected Package 2b as their basis of design. However, throughout the design process changes were made to the design which impacted the EEM selections, as documented in Appendix B. The energy efficiency measures implemented for the ZNE retrofit were as follows:

- Envelope:
  - Reroof and add R-19 roof insulation.
  - Add crawlspace insulation (R-13 cavity insulation).
  - Added batt insulation to 2x6 wall (R-19 cavity insulation)
- Lighting and Daylighting:
  - Installed 35 Tubular Daylighting Devices
  - Replaced existing lighting with LED upgrade (0.6 W/sf): 0.6 W/sf is connected load, 65% diversity, 0.39 W/sf max operating load.
  - Installed daylighting sensors for interior lighting control.
  - Installed wall-mounted occupancy sensors
- Plug Loads: reduce by 30 percent from 0.7 W/sf to 0.49 W/sf*. 0.7 W/sf is connected load, 90 percent diversity, 0.63 W/sf max operating load.
- Domestic Hot Water (DHW): replace with electric instantaneous (efficiency: 0.98) and install low flow fixtures.
- HVAC: Heat Pump with ERV (Energy Recovery Ventilator)
  - Cooling Coefficient of Performance (COP) of 3.28 (11.2 Energy Efficiency Ratio (EER)) and Heating COP of 3.58 (12.2 EER).
  - Energy Recovery Total Enthalpy wheel @ 60 percent effectiveness.

Simulation of the initial packages, comparison to historical site energy consumption (metered data from 2015), and comparison to a CA Title 24-2016 minimally compliant baseline were completed (results shown in Figure 12). Tables 3a and 3b details the results of the analysis, including updates to the final selected package, and its modifications as the retrofit was completed. Minor modifications to the selected package did occur during the construction phase as the result of reviewing field conditions, and submittal review and approvals for available construction products and equipment. In that process some minor variations in the design were approved, resulting in some impacts to the overall building energy use. Overall, the modeled energy use intensity of the building was reduced to 17.4 kBtu/sf/yr, a 61 percent reduction from the value of 44.7 kBtu/sf/yr calculated for the Calibrated Baseline Model. Additionally, the PV panels power production estimate was also updated throughout the design and construction process. Overall, the PV panels were modeled to offset 118 percent of the building's annual energy consumption. It should be noted that during the design process there were no plans to include EV charging on site, however this was added to the retrofit later on, and were not included in the ZNE goals of the project. During the measurement and verification stage, any power consumption by the EV chargers has been separated out to verify the project's original building ZNE goals.

Table 3a: Modeled Annual Energy Consumption – Part 1

Packages	Calibrated Baseline	T24-2016 Code Baseline	Package 1a DOAS + VRF	Package 1b DOAS +VRF 2/Window Replacement	Package 2a Heat Pump
Detailed Breakdown	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr
Plug Loads	90,248	106,114	43,257	43,257	43,115
Lighting	73,984	56,441	20,557	21,392	20,444
Heating	139,594	37,638	25,751	26,273	26,832
Hot Water	13,279	10,056	10,359	10,359	10,350
Cooling	13,572	20,302	12,350	9,402	4,815
Pumps	0	0	0	0	0
Fans	61,663	94,864	2,796	2,540	6,919
Renewable Energy	0	0	0	0	0
Total Energy (kBtu/yr)	**392,341**	**325,414**	**115,071**	**113,222**	**112,474**

Table 3b: Modeled Annual Energy Consumption – Part 2

Packages	Package 2b Heat Pump + HRV	100% DD Design	Construction Phase Updates	Solar PV Production
Detailed Breakdown	kBtu/yr	kBtu/yr	kBtu/yr	kBtu/yr
Plug Loads	43,115	43,116	43,115	0
Lighting	20,444	18,748	19,003	0
Heating	23,998	23,657	48,403	0
Hot Water	10,350	10,037	10,037	0
Cooling	3,696	8,966	7,810	0
Pumps	0	0	0	0
Fans	7,270	15,838	25,458	0
Renewable Energy	0	0	0	182,757
Total Energy (kBtu/yr)	**108,872**	**120,363**	**153,826**	**182,757**

This table shows the annual energy by end use (kBtu/yr) for each of the measure packages.

Source: LBNL Small Office ZNE Report: Berkeley Mental Health Clinic

Figure 12: Annual Energy Use Intensity

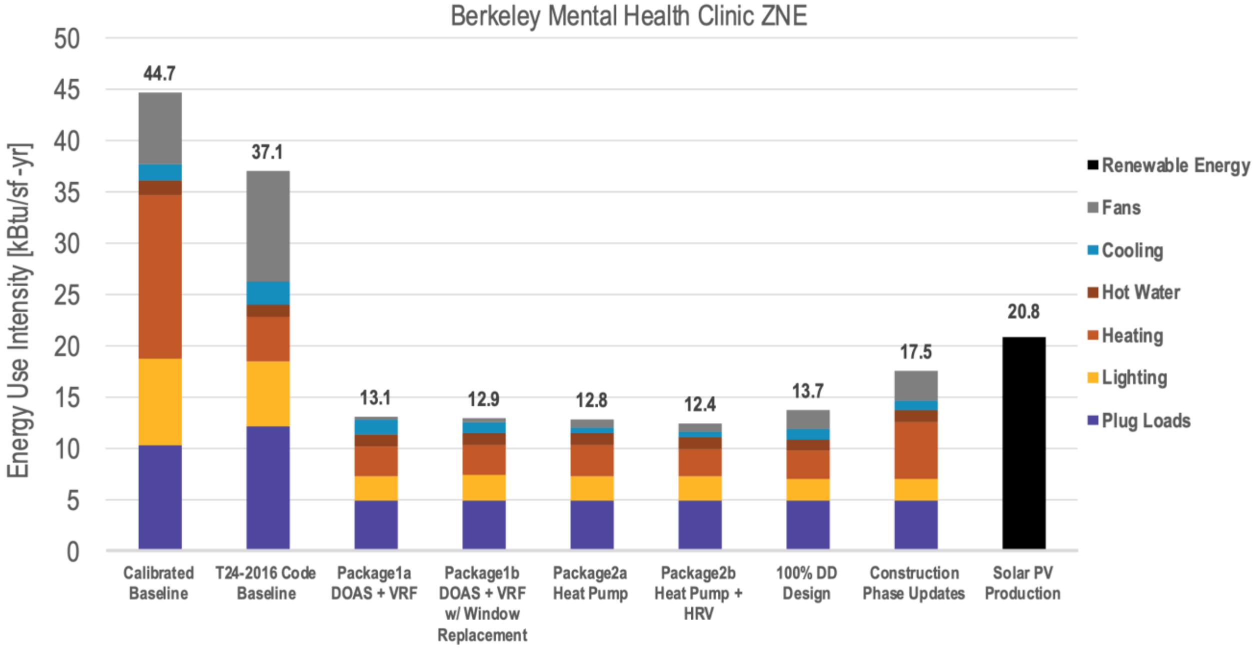


Chart showing the annual Energy Use Intensity for each of the measure packages.

Source: LBNL Small Office ZNE Report: Berkeley Mental Health Clinic

Images of the completed retrofit are provided in Figures 13, 14 and 15, showing the completed rooftop solar, coordinated around skylights and rooftop tubular daylighting devices, and an image of the interior space with the tubular daylighting device shown at ceiling level.

Figure 13: Installed Rooftop PV System

Photograph of the Installed PV System on the Berkeley Mental Health Services building.

Source: City of Berkeley, Billy Hustace

Figure 14: Interior Breakroom with Installed Tubular Daylighting Devices

Photograph of the Break Room, with Overhead Lighting and Tubular Daylighting Devices at the Berkeley Mental Health Services building.

Source: City of Berkeley, Billy Hustace

Figure 15: Updated Lobby with Historic Features

Photograph of the Main Lobby, with Overhead Suspended Lighting, Wood Panel Doors and Walls at the Berkeley Mental Health Services Building.

Source: City of Berkeley, Billy Hustace

Measurement and Verification

A measurement and verification plan was developed to verify that the building was performing as expected and to assist in optimizing energy performance over the lifetime of the building. As part of this plan, twelve months of post-occupancy trend data has been collected and compared to the energy model per the International Performance Measurement and Verification Protocol - Option D, Whole Building Calibrated Simulation (Method 1). Trends include electrical panel-level energy and targeted loads for example energy per air handler, lighting energy in rooms with TDDs, and plug load energy in high load spaces. Additional information and the full list of metering points is available in the project deliverable, Zero Net Energy Small Commercial Retrofits Measurement and Verification Plan – Berkeley Mental Health Services.

To support the ongoing ZNE operations of the building and allow operators to analyze the energy use of the building and identify areas where performance may be emerging outside of intended operations, an Energy Analysis Template was created to compare monthly energy consumption and solar PV generation against the modeled data for the building and provided to the building owner for their use. Additionally, this tool can be used to perform Hourly Meter Analysis by comparing the actual metered data against weekly energy profiles generated by the energy model simulations. Screenshots of this tool along with some analysis of selected results have been provided in Appendix D.

In addition to the quantitative measurement and verification procedures, qualitative assessments were conducted to ensure that the changes made to the building did not decrease the satisfaction of the building occupants. Specifically, surveys of full-time occupants (staff) were conducted to assess if sensors are providing a realistic assessment of building comfort and to evaluate how occupants are interfacing with building systems. Additionally, periodic detailed measurements of occupant thermal and visual comfort-related parameters and high dynamic range (HDR) photographs were taken and analyzed.
Historical utility data (from 2003 – 2017) for both the electricity and natural gas consumption was used to calculate the average monthly consumption (Figure 16). This data was used to calibrate the pre-retrofit baseline model. Based on the design decisions a 64 percent reduction in total energy, 43.9 kBtu/sf/yr to 15.7 kBtu/sf/yr, was anticipated during the design phase. This predicted EUI was updated to 17.5 kBtu/sf/yr based on changes made in the construction phase. Note that the building retrofit included the removal of all natural gas based HVAC and DHW, with an aim for a net zero carbon annual operation, offsetting electricity use through onsite PV generation.

Figure 16: Demonstration Site Historic Energy Consumption vs Modeled Consumption

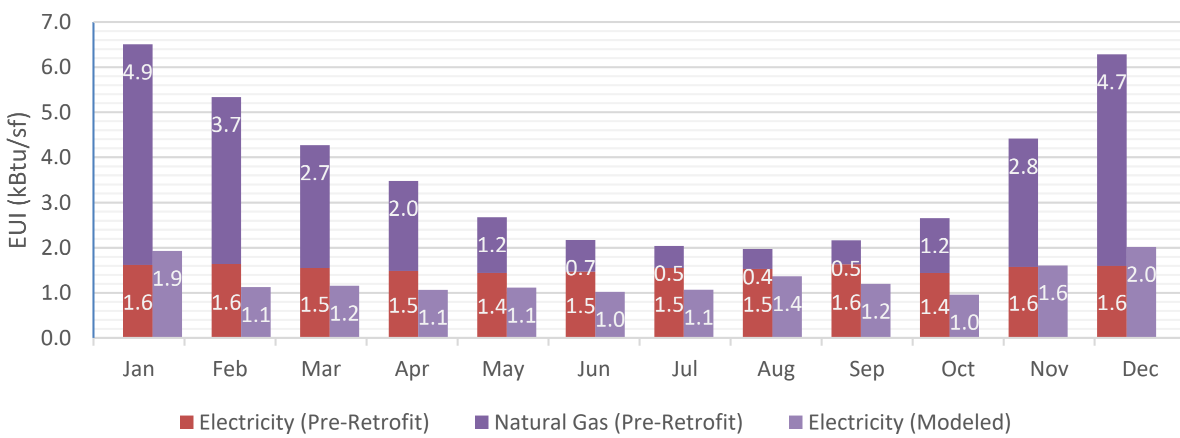


Chart showing the historic monthly gas and electric data compared to the modeled consumption.

Source: Berkeley Mental Health Services Measurement and Verification Report

A complete accounting of the demonstration site M&V assessment is documented in the report "Berkeley Mental Health Services Facility – Measurement and Verification Report". Overall, metered data showed the reduction in energy consumption between the historical building averages and the metered energy consumption for the building (without EV charging) is 79 percent (43.9 kBtu/sf/yr to 9.0 kBtu/sf/yr), exceeding the 64 percent savings previously predicted, as shown in Figure 17. The reduction in annual energy costs over the same period was 49 percent from an average of approximate $11,114/yr to $5,649/yr. While the reduction in energy costs is less than the reduction in energy consumption, due to the difference in pricing between natural gas and electricity, it is expected that once the PV system is enabled, the reduction in annual energy cost will increase, as it is predicted that zero net energy will be achieved.

Figure 17: Demonstration Site Historic Energy Consumption vs Metered Consumption

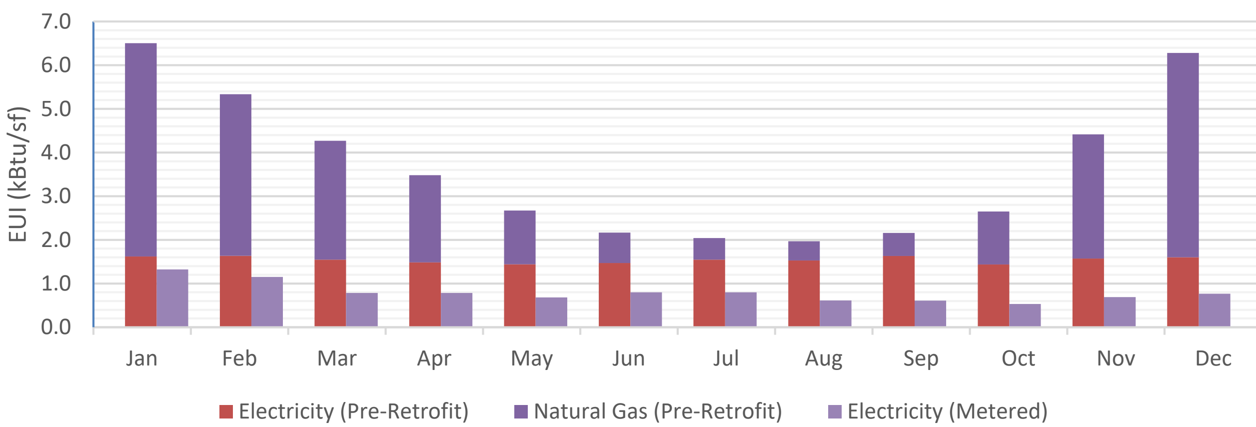


Chart showing the historic monthly gas and electric data compared to the measured consumption.

Source: Berkeley Mental Health Services Measurement and Verification Report

Occupant Engagement

The team received 16 survey responses, which represents less than half of the regular number of building occupants. A number of the building occupants (staff) are working in a hybrid fashion and may not have felt they had significant enough experience with the building to respond. The survey indicated that 50 percent occupants are satisfied or have a neutral response and 50 percent are dissatisfied with the level of thermal comfort at their workspace. The survey respondents have mentioned that they are either too hot or too cold but a direct correlation between these complaints and any design strategies such as the proximity of windows or thermal comfort controls cannot be ascertained. It is notable that there was no distinct trend in the dissatisfaction pointing to a consistent issue with either heating or cooling the building, indicating that the cause of the dissatisfaction may have less to do with the central system operation, and may have more to do with the specific individual conditions at a given work area, or individual personal comfort preferences or needs. Fifty percent of the occupants have said that the discomfort is in the morning. Thirty-five percent of occupants are dissatisfied with air quality, the predominant complaint being that the air feels stuffy or stale. All respondents except two have access to a lighting control such as a light switch, light dimmer or a task light. Close to 90 percent occupants are satisfied with overall lighting and electric lighting but close to 35 percent feel that there is not enough daylight.

Commercial Building Energy Saver Tool

Implementation of New Features and EEMs

Four new features, including rooftop PV system, electric battery, solar shading, and the Time Dependent Valuation (TDV) energy metric, were implemented in CBES to enable ZNE retrofit analysis. A summary of the new features is described.

Feature 1: Rooftop PV System

Renewable energy is essential to achieve the ZNE goal. Therefore, a new "Renewables" section was added, including PV system and electric battery, under the "Detailed Retrofit Analysis" feature.

For different application purposes, the team implemented two methods by which a PV system can be added: (1) by capacity for modeling a new PV system, and (2) by panel details for modeling an existing PV system, where the users can enter the detailed characteristics of their installed PV system. In case the users don't have access to PV module specifications, CBES provides default settings, which are compiled from several manufacturers' products on the market.

Feature 2: Electric Battery

The users can define an electric battery system by specifying the characteristics of the battery modules. Similar to the PV system, this information is usually available in the manufacturer's specifications. In case where the users don't have access to the above data, CBES provides default settings, which are compiled from several manufacturers' products on the market. CBES automatically links this electric battery to the PV system in the building.

Feature 3: Shading Objects

Three types of solar shading objects were implemented in CBES: neighbor buildings, trees, and rooftop equipment or structure. The new feature allows the users to describe the shape of the shading objects via parameters like height, length, width, and distance from the building edge. CBES will take the user inputs and calculate the coordinates of the shading surfaces, which are used to generate the shading objects in EnergyPlus models.

Feature 4: Time Dependent Valuation (TDV) metric

CEC uses TDV energy to set the target energy budgets for newly constructed buildings, and to value the design trade-offs during the development and construction of those buildings. TDV is the metric adopted in the CEC's Integrated Energy Policy Report for the measurement of zero net energy (ZNE) buildings. For this reason, the TDV metric was added in CBES for evaluating ZNE buildings in California. Multiple years (2013, 2016, and 2019) of TDV data were available for selection. When the TDV metric is selected in CBES, the retrofit analysis results will present the TDV energy as "source energy".

Twelve new EEMs were implemented in CBES. The detailed table can be found in Appendix C Table C-1.

Demonstration of Path to ZNE using CBES

Based on single measure analysis results, three EEM packages were compiled with different optimization purposes, including high energy savings, short payback, and comprehensive. Table 4 illustrates the package analysis results. The high energy saving package can achieve ZNE from the annual perspective. The comprehensive package is near ZNE. Though the short payback package can't achieve ZNE, it largely reduces the basic energy use with a very attractive payback of 2.8 years. The test case demonstrates that the new features and EEMs enable CBES to evaluate ZNE potentials for small and medium-sized commercial buildings.

Table 4: Simulation Results of the Measure Packages (in TDV energy - MWh)

	Electricity Use	Natural Gas use	Electricity generated by PV	Total Net TDV energy	Payback years
Baseline	1328	24.2	N/A	1352	N/A
Package 1: High energy saving	591	10.4	629.6	-28.2	14.0
Package 2: Short payback	723	57.0	637.3	142.7	2.8
Package 3: Comprehensive	627	42.4	641.6	27.8	5.7

The energy metric of "TDV-MWh" refers to the TDV energy in MWh, which is different from the traditional MWh.

Source: Commercial Building Energy Saver (CBES) Update Report

Validation of CBES Simulation Accuracy

Validation results were developed for two perspectives: (1) the TDD measure performance, (2) the full ZNE package performance, where two key subsystems, lighting and HVAC, were validated separately, and the entire system was validated as a whole as well.

In summary, the simulated results match well with the measurement data on lighting energy use, HVAC energy use, and whole building EUI. More details of the validation results can be found in Appendix C. Therefore, it is reasonable to conclude that the accuracy of CBES is validated through experimental data and that CBES has the capability to provide suitable assessments of ZNE measures and packages.

Outreach Activities

This project engaged stakeholders through multiple in person events held in California, as well as some virtual events. This included selection to present at AEE West's conference, ACEEE Summer Study for Energy Efficiency in Buildings (presented in 2018 and 2020), Greenbuild (2021), the EPIC Symposium (2018, 2019), Zero Net Energy conference (2021), and NBI's Getting to Zero Forum (2019). In addition, LBNL published and publicized the work through several press releases and newsletters (publicized through Building Technologies and Urban Systems Division newsletter and FLEXLAB newsletter). CBES was also recognized as an R&D 100 winner in 2019, which included additional press release and newsletter features. Last, two websites were developed to promote the project – the first hosts the CBES online tool (https://cbes.lbl.gov/) and the second promotes the work of the project overall (https://buildings.lbl.gov/cbs/zero-net-energy-small-commercial-retrofits).

Conclusion

ZNE Package Development

Package 2, which focused on lighting power reduction and automated controls in response to daylighting was independently most impactful when compared to other packages independently. This reduction in lighting loads subsequently reduced the cooling loads which had a substantial impact on the overall building energy consumption. In a similar way, Package 1 focused on reducing the envelope thermal loads. In this case, through increased insulation and improved windows as opposed to lighting power reductions. These reduced loads had a synergistic effect with the HVAC system to provide a reduction in total building energy. Package 3, which focused on HVAC energy efficiency strategies, was unable to meet the ZNE goals on its own. This shows the importance of focusing on passive design strategies early in the design process so that buildings-active-systems such as HVAC can be optimized to use less energy. In both climates studied Packages 2 and 3 are shown to be cost effective, with internal rates of return well exceeding the goal of 5% within 10 years when compared with an equivalent standard retrofit. Package 1 also had the result of achieving ZNE, however the increased costs associated with envelope retrofits resulted in longer payback periods.

FLEXLAB Testing

ZNE Packages

Experimental results show that the ZNE packages developed in this project can provide significant savings both during cooling- (59-69 percent) and heating-prevalent (22-25 percent) periods. This is roughly on the order of the magnitude of savings (versus business as usual) that is involved in achieving ZNE performance. This indicates that this type of package is suitable for wide deployment for a broad range of California climates, especially in coastal areas with relatively mild climate. These packages aren't expected to negatively impact visual comfort. In some combinations of climate, building, and interior space, moderate impacts to thermal comfort may occur.

Tubular Daylight Devices

Due to the deep floor plate in the prototype building design, the perimeter daylighting (side-lighting) is unable to provide sufficient energy reductions to truly meet the ZNE goals. The FLEXLAB testing showed that the TDD were able to provide significant lighting power reductions across the entire occupied area without negative impacts on visual comfort. When looking at the individual energy efficiency measures, the TDD were one of the most effective measures applied to both the Northern and Southern California baseline models.

Field Demonstration

The experimental evaluation confirmed that the ZNE packages developed in this project can provide significant year-round energy savings in a Northern California climate, with minimal impact on occupant comfort. The magnitude of the savings is such that it enables standardized ZNE retrofits of small commercial buildings throughout the state. Irrespective of dome/diffuser type, TDD can significantly reduce lighting energy use in spaces without windows, with larger diameter units providing greater energy benefits. Based on the collected electrical consumption data over the 12-month monitoring period, the modeled electrical generation of the PV system should have been sufficient to meet ZNE criteria.

Occupant Experience and Engagement

Due to the deep floor plate in the building design of the demonstration site, the perimeter windows do not directly contribute to thermal discomfort. It is also difficult to ascertain if the TDD are causing hot patches. From the survey, the team learned that the occupants do not perceive TDD as a source of daylight and seem to recognize those as artificial lights due to its opaque cover, which appears similar to a light fixture. For future projects, clerestories or skylights with clear glazing are recommended over TDD with opaque covers.

Commercial Building Energy Saver

Four new features and 12 new EEMs were implemented in CBES to enable the capability of ZNE retrofit analysis and deep retrofit analysis with advanced technologies. A case study was performed to demonstrate CBES's capability to explore ZNE pathways. The measured data from FLEXLAB experiments was used to validate the simulation accuracy of the CBES tool. Overall, the simulated results match well with the measurement data on lighting energy use, HVAC energy use, and whole building EUI.

From January 2019 to February 2023, there are a total of 5,690 user visits and 23,527 pageviews to the CBES website, according to Google Analytics (see Appendix C Figure C-4). Starting from August 2020, we added a feature of registration and login to track and collect users' basic information. Within the last two years, CBES has a total of 125 registered users.

In 2019, the CBES API, which is the underlying simulation engine for the CBES web app, was expanded for the needs of two projects: one funded by CEC project EPC-17-035 titled "Building Healthier and More Energy-Efficient Communities in Fresno and the Central Valley", the other funded by California Strategic Growth Council titled "CAL-THRIVES: A California Toolkit for Heat Resiliency in Vulnerable Environments". New building types (single family homes, multi-family homes) and new EEMs (e.g., duct sealing, window film, precooling, electric vehicles, radiant barriers, mini-split heat pump, etc.) were added to CBES API to enable the simulation capability of residential buildings, electrification, and heat resilience. In addition, the team has also been exploring opportunities to promote the adoption of CBES. For example, the team is having ongoing discussions with U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy Advanced Manufacturing Office industry assessment centers about using CBES as the tool to perform energy audits and retrofit analysis.

General Conclusions

Scaling in the Small Commercial Market

Results from this study show that the packages developed and evaluated in this project are suitable for wide deployment in small commercial buildings throughout a wide swath of California. While the availability of CBES serves as an enabler, achieving such scale in a timeline commensurate with the urgency of reducing carbon emissions, as well as meeting California's emissions targets, will probably require a multitude of incentives to spur action. This could include a mixture of 1) updating energy codes, at state and local level, to require ZNE levels of performance in small commercial buildings that undergo major retrofits would provide a performance floor, 2) utilities providing incentives through their rebate programs and targeted outreach and assistance specifically tailored for small commercial buildings in their territory, 3) energy-as-a-service providers developing financing and/or other products based on this type of ZNE retrofit package, or 4) government (state and/or local) programs to identify financing for ZNE retrofits or other approaches to improve access to capital and reduce this as a barrier to conducting ZNE retrofits or all of them.

Acknowledgments

This work was supported by the California Energy Commission's Electric Program Investment Charge (EPIC) under Contract Number EPC-16-004, and the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

The FLEXLAB component of this work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

The California Energy Commission provided primary funding to make this project possible, and we would like to thank the following Energy Research and Development Division staff for providing their support and project stewardship:

Laurie ten Hope, Former Deputy Director
Virginia Lew, Office Manager
Dustin Davis, Commission Agreement Manager

The authors thank the City of Berkeley, particularly the Mental Health Services Department for their participation as a demonstration site for the Zero Net Energy Retrofit, and the Public Works Department for their collaboration on the demonstration site. Particular thanks are given to City of Berkeley staff Nick Cartagena, Alice LaPierre and Yvette Katuala.

Thanks to our collaborators and our partners for their enthusiastic participation in this research: Integral Group, and the San Francisco 2030 District.

Thanks to the many industry professionals who shared their ideas and feedback for this project. They came from utilities, public agencies, energy companies, nonprofits, consultants, other national laboratories, the US Department of Energy, and the California Energy Commission.

Thanks, also, to the reviewers for their generosity and time improving this report.
Thanks to the many individuals who contributed to this work including Lawrence Berkeley National Laboratory (LBNL) staff, especially Ari Harding, Josh Brown, Gari Kloss, Janie Page, Sang Hoon Lee, Jordan Shackelford, and Joshua Mouledoux.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
API	Application program interface
Btu	British thermal unit
CBES	Commercial Building Energy Saver
CEC	California Energy Commission
CPUC	California Public Utilities Commission
DOE	United States Department of Energy
EEM	Energy efficiency measure
EPIC	Electric Program Investment Charge
ESCO	Energy Services Company
EUI	Energy use intensity
GHG	Greenhouse gas
GWh	Gigawatt hours
HVAC	Heating, ventilation, and air-conditioning
IOU	Investor-Owned Utility
kW	Kilowatts
kWh	Kilowatt-hours
LBNL	Lawrence Berkeley National Laboratory
LED	Light-emitting diode
MSD	Modulating supply diffuser
MUSH	Municipalities, universities, schools and hospitals
M&V	Monitoring and verification
sf	Square feet
TDD	Tubular daylight device
VAV	Variable air volume
ZNE	zero net energy

References

Greenblatt, J.B. (2013). Estimating Policy-Driven Greenhouse Gas Emissions Trajectories in California: The California Greenhouse Gas Inventory Spreadsheet (GHGIS) Model. LBNL Report LBNL-6451E.

International Living Future Case Study. IDEAS Z2 Design Facility. http://living-future.org/case-study/ideasz2

Osborn, J., C. Goldman, N. Hopper, T. Singer. (2002). Assessing the US ESCO Industry: Results from the NAESCO Database Project, Lawrence Berkeley National Laboratory. LBNL-5030

Page, J. S. Kiliccote, J. Dudley, M. Piette, Al Chiu, B. Kellow, E. Koch, and P. Lipkin. (2011). Automated Demand Response Technology Demo for Small and Medium Commercial Buildings. LBNL-4982E.

Reducing Costs for Communities and Businesses Through Integrated Demand-Side Management and Zero Net Energy Demonstrations Grant Funding Opportunity. CEC. (2015)

C. Regnier, P. Mathew, A. Robinson, J. Shackelford, T. Walter. (2020) System Retrofit Trends in Commercial Buildings: Opening Up Opportunities for Deeper Savings, Lawrence Berkeley National Laboratory.

Regnier, C., A. Harding, A. Robinson. (2015). Achieving a Net Zero Retrofit in a Hot, Humid Climate—Lessons from the University of Hawaii at Manoa. U.S. Department of Energy, Commercial Building Partnerships. LBNL Report LBNL-189802.

Regnier, C., K. Settlemyre. (2015). The Business of High Performance: The USC Darla Moore School of Business. U.S. Department of Energy, Commercial Building Partnerships. LBNL Report LBNL-6904E.

Stuart, E., P. Larsen, C. Goldman, D. Gilligan. (2013). Current Size and Remaining Market Potential of U.S. ESCO Industry. (2013) LBNL Report LBNL-6300E.

U.S. Department of Energy, Commercial Building Partnerships. "Achieving a Net Zero Retrofit in a Hot, Humid Climate—Lessons from the University of Hawaii at Manoa." (2015) LBNL-189802. "The Business of High Performance: The USC Darla Moore School of Business." LBNL-6904E.

Project Deliverables

The following project deliverables are available through the project's website (https://buildings.lbl.gov/cbs/zero-net-energy-small-commercial-retrofits):

- Zero Net Energy Retrofits for Small Commercial Offices: Northern & Southern California Prototype Building ZNE Packages
- Zero Net Energy Retrofits for Small Commercial Offices: Berkeley Mental Health Clinic Demonstration Package
- Commercial Building Energy Saver (CBES) Update Report
- Zero Net Energy Retrofits for Small Commercial Offices - FLEXLAB Test Plan
- ZNE Package and Tubular Daylighting Device (TDD) FLEXLAB Test Results Report
- Zero Net Energy Retrofits for Small Commercial Offices - Demonstration Site Test Plan
- Zero Net Energy Retrofits for Small Commercial Offices - Demonstration Site (Berkeley Mental Health Services) Measurement and Verification Plan
- Zero Net Energy Retrofits for Small Commercial Offices - Demonstration Site (Berkeley Mental Health Services) Measurement and Verification Report
- Zero Net Energy Retrofits for Small Commercial Offices - ZNE Best Practices Report
- Zero Net Energy Small Commercial Retrofits Measurement and Verification Plan – Berkeley Mental Health Services
- Final project fact sheet

Appendix A: ZNE Packages

The starting point for the ZNE package development was from the Benchmark Building Models. Both the SoCal and NorCal Benchmark Building Models were modeled using the same parameters.

Baseline Building Models

- Envelope
  - Roof Insulation R-value: 8
    - 14" Metal ceiling joist with R-25 Batt cavity Insulation.
    - ¾" roof sheathing with TPO roof membrane.
  - Roof Solar Reflectance: 0.63
  - External Wall Metal Frame R-value: 9
    - 6in Metal Stud Wall with R-19 Batt Cavity Insulation
    - Interior Gypboard, painted.
  - Ground Floor Insulation R-value: 0
  - Window, 24.7% WWR on all façades,
  - Window U-value: 1.02 (includes frame),
  - Window SHGC: 0.82, VT: 0.89; single pane, clear glass, aluminum frame
- Internal Loads
  - Occupant Density (ft²/person): 200
  - Lighting: 1.19 W/sf 90% diversity, 1.07 W/sf max operating load, 3,233 annual full load hrs
  - Equipment: 0.77 W/sf is connected load, 90% diversity, 0.70 W/sf max operating load
  - Infiltration (cfm/ft² ext wall area): 0.2 (0.05 with 25% schedule fraction)
  - Infiltration Schedule: 0.25 during HVAC operation, 1.0 otherwise
  - OA/occ (cfm/person): 15; OA/SF (cfm/sf): 0.15
- External Lighting
  - Lighting Power per Fixture (W): 145; Number of Fixtures: 100
- Setpoints and Operating Schedule
  - 75°F Cooling, no setback; 70°F Heating, no setback
  - Always ON HVAC operation, ventilation 7am-midnight Mon-Fri, 7am-7pm Sat, 7am-6pm Sun
- HVAC
  - System Type: PVAV with Gas Furnace per Floor

- Cooling COP: 2.7; Cooling Supply Air Temp: 55 °F
    - Heating Efficiency: 80 percent; Heating Supply Air Temp: 95 °F
    - Fan Efficiency: 60 percent; Fan Motor Efficiency: 85 percent
    - Supply Fan Pressure Rise: 5.0 in. w.g.; Exhaust Fan Pressure Rise: 4.5 in. w.g.
    - Economizer Type: None; Demand Control Ventilation: No
    - Energy Recovery Type: None
- Water Heater
    - Type: Gas Storage; Efficiency: 75 percent; Temperature: 135 degF
    - Tank Volume: 50 gallons; Use Rate: 3.25 gpm peak

After modeling the benchmarks, two packages of typical EEMs were modeled, Standard Package A and Standard Package B. For all modeled parameters, if not called out below they have been modeled identically to the Baseline building case.

Standard Package A

- HVAC: Packaged rooftop units with DX cooling and natural gas heating, single-zone VAV fan
    - Single-speed DX Cooling EER: 10.8 EER (Title 24 minimum)
    - Supply Fan Pressure Rise: 4 in. w.g.
    - Economizer Type: Airside economizer with fixed dry bulb control (75F maximum limit temperature)
    - Demand Control Ventilation: For spaces ≥ 0.025 people/sf per Title 24
- DHW: same as Baseline, with 80% efficiency (Title 24 minimum efficiency)
- Lighting:
    - Replace interior bulbs with LEDs or de-lamp fluorescent lighting (LPD: 0.8 W/sf). 0.8 W/sf is connected load, 90% diversity, 0.72 W/sf max operating load.
    - Add occupancy sensors
    - Install daylighting sensors for interior lighting control (per Title 24)

Standard Package B

Standard Package B is the same as Standard Package A except for the following adjustments.

- HVAC: Packaged rooftop units with DX cooling and no heating, multi-zone VAV with hot water reheat terminal units
    - Two-speed DX Cooling EER: 9.8 EER (Title 24 minimum); Supply Fan Pressure Rise: 5 in. w.g.
    - Natural Gas Boiler (for hot water reheat) Efficiency: 80% (Title 24 minimum)

The developed ZNE packages are described in greater detail as follows. All packages include the following common measures:

Common ZNE Package Measures

- HVAC: Single zone rooftop packaged heat pump (VAV fan, heat pumps COP: 3.3, without heat recovery)
  - Temperature setpoints and hours of operation are same as Baseline.
- DHW: Replace with electric instantaneous (efficiency 95 percent) and install low-flow fixtures
- Lighting:
  - Replace exterior lighting with 50 bulbs at 50 W each.
  - Replace interior bulbs with LEDs or de-lamp fluorescent lighting (LPD: 0.8 W/sf). 0.8 W/sf is connected load, 90 percent diversity, 0.72 W/sf max operating load.
  - Install Wall-Mounted Occupancy Sensors.
- Plug Loads: reduce by 30 percent [12] from 0.77 W/sf to 0.539 W/sf W/sf. 0.539 W/sf is connected load, 90 percent diversity, 0.485 W/sf max operating load. Strategies include:
  - Utilize "smart" occupancy-controlled plug strips at workstations (in the demonstration site these were implemented as controlled outlets).
  - Use laptops instead of desktop computers.
  - Replace equipment/appliances with high efficiency (such as EnergyStar) models.
  - Consolidate printers, or fax machines to a common branch panel and enable branch panel security system power off control.
  - Virtualize servers or use offsite servers.

In addition to these common measures, the following energy efficiency measures were specifically included in the following ZNE packages:

Package 1: Envelope focused

- Envelope: add insulation to walls, roof, replace windows, reduce infiltration
  - Apply top floor ceiling insulation (R40)
    - Apply 6.5in of Polyisocyanurate insulation over the top of roof sheathing. Add protection board and apply roofing membrane over protection board.
  - Apply wall insulation (R20)
    - Apply 4.5in of rigid mineral wool board continuous insulation over exterior weather resistant barrier. Use 5" Greengirt z-girts attached to wall

[12] Previous plug load studies done by Integral Group were used as the basis for potential 30% savings estimates.

sheathing and extending through the continuous insulation to support new cladding material. Attach new cladding system to greengirts.

- Replace windows: U-factor (0.29) and SHGC (0.27) and VLT (0.6 min) aluminum windows with thermal break. Solarban 70xl
- Add air sealing to seal envelope leaks, 30 percent reduction from 0.15 cfm/ft² ext to 0.105 cfm/ft² ext; Aero-barrier can be used to achieve this.
- Add exterior shading to windows. Shading is two opaque surfaces, one at the top of the window and one 2.5 ft from the top of the window, each at 1 ft depth.

Package 2: Lighting-daylighting focused

- Lighting: replace lights with LEDs and add occupancy and daylighting controls
  - Replace interior lighting with LED upgrade (0.4 W/sf). 0.4 W/sf is connected load, 90 percent diversity, 0.36 W/sf max operating load.
  - Install daylighting sensors for interior lighting control
  - Add tubular daylighting devices to provide daylight to interior spaces

Package 3: HVAC system focused

- HVAC: Install DOAS energy recovery ventilator with VAV fan and VRF (with heat recovery)
  - Install dedicated outside air system (DOAS) energy recovery ventilator (enthalpy wheel) with VAV fan
  - Install variable refrigerant flow (VRF) rooftop heat pump with indoor refrigerant fan coils (with heat recovery)
  - Add Demand Controlled Ventilation with CO2 sensors
  - Implement unoccupied room temperature setbacks
  - Widen zone temperature deadband (cooling: +2F; heating -2F)
  - Reduce HVAC equipment runtime (shutoff when unoccupied)

Package 1+2: Envelope and Lighting-daylighting focused

- Lighting: replace lights with LEDs add occupancy and daylighting controls
  - Replace exterior lighting with 50 bulbs at 50 W each
  - Replace interior lighting with LED upgrade (0.4 W/sf). 0.4 W/sf is connected load, 90% diversity, 0.36 W/sf max operating load.
  - Install daylighting sensors for interior lighting control
  - Add tubular daylighting devices to provide daylight to interior spaces
- Envelope: add insulation to walls, roof, replace windows, reduce infiltration
  - Apply top floor ceiling insulation (R40) and wall insulation (R20)
  - Replace windows: U-factor (0.29) and SHGC (0.20) aluminum windows with thermal break.

    - Add air sealing to seal envelope leaks, 30% reduction from 0.15 cfm/ft² ext to 0.105 cfm/ft² ext
    - Add exterior shading to windows. Shading is two opaque surfaces, one at the top of the window and one 2.5 ft from the top of the window, each at 1 ft depth.

Package 2+3: Lighting-daylighting and HVAC focused

- HVAC: Install DOAS energy recovery ventilator, VAV fan and VRF (with heat recovery)
    - Install dedicated outside air system (DOAS) energy recovery ventilator (enthalpy wheel) with VAV fan
    - Install variable refrigerant flow (VRF) rooftop heat pump with indoor refrigerant fan coils (with heat recovery)
    - Add Demand Controlled Ventilation with CO2 sensors
    - Implement unoccupied room temperature setbacks
    - Widen zone temperature deadband (cooling: +2F; heating -2F)
    - Reduce HVAC equipment runtime (shutoff when unoccupied)
- Lighting: replace lights with LEDs add occupancy and daylighting controls
    - Replace interior lighting with LED upgrade (0.4 W/sf). 0.4 W/sf is connected load, 90% diversity, 0.36 W/sf max operating load.
    - Install daylighting sensors for interior lighting control
    - Add tubular daylighting devices to provide daylight to interior spaces

Package 1+2+3: Envelope, Lighting-daylighting, HVAC focused

- HVAC: Install DOAS energy recovery ventilator with VAV fan and VRF (with heat recovery)
    - Install dedicated outside air system (DOAS) energy recovery ventilator (enthalpy wheel) with VAV fan
    - Install variable refrigerant flow (VRF) rooftop heat pump with indoor refrigerant fan coils (with heat recovery)
    - Add Demand Controlled Ventilation with CO2 sensors
    - Implement unoccupied room temperature setbacks
    - Widen zone temperature deadband (cooling: +2F; heating -2F)
    - Reduce HVAC equipment runtime (shutoff when unoccupied)
- Lighting: replace lights with LEDs add occupancy and daylighting controls
    - Replace interior lighting with LED upgrade (0.4 W/sf). 0.4 W/sf is connected load, 90% diversity, 0.36 W/sf max operating load.
    - Install daylighting sensors for interior lighting control
    - Add tubular daylighting devices to provide daylight to interior spaces
- Envelope: add insulation to walls, roof, replace windows, reduce infiltration
    - Apply top floor ceiling insulation (R40) and wall insulation (R20)

- Replace windows: U-factor (0.29) and SHGC (0.20) aluminum windows with thermal break.
- Add air sealing to seal envelope, 30% reduction from 0.15 cfm/ft² ext to 0.105 cfm/ft² ext
- Add exterior shading to windows. Shading is two opaque surfaces, one at the top of the window and one 2.5 ft from the top of the window, each at 1 ft depth.

Appendix B: Field Demonstration

Existing Conditions

Site visits were conducted to determine the existing conditions and historic energy data was gathered from utility meters from the year 2015 and used to develop the Baseline energy model. The existing conditions prior to the ZNE retrofit are listed below:

Description & Inputs

Envelope

- Roof Solar Reflectance: 0.63 — Roof Insulation R-value: 4.29
- External Wall Insulation R-value: 4 — Ground Floor Insulation R-value: 4.29
- Window U-value: 1.0, SHGC: 0.82, VT: 0.81
- Infiltration (cfm/ft² exterior surface area): 0.085

Internal Loads

- Occupant Density (ft²/person): 200
- Lighting (W/sf): 1.0
- Equipment (W/sf): 0.7 + 0.8 W/sf of Electric Space Heaters November - March

External Lighting

- Lighting Power per Fixture (W): 30 — Number of Fixtures: 10

Setpoints and Operating Schedule

- 78°F Cooling, no setback
- 68°F Heating 7am-7pm, 65°F setback, off July 1st – Sept 30th
- HVAC units are always ON

HVAC

- System Type: Packaged Rooftop AC
- Cooling COP: 2.7 — Cooling Supply Air Temp: 55 degF
- Heating Efficiency: 0.8 — Heating Supply Air Temp: 95 degF
- Constant Volume Fan — Fan Efficiency: 0.6
- Fan Motor Efficiency: 0.85 — Fan Pressure Rise: 2.5 in. w.g.
- Economizer Type: None — Demand Control Ventilation: No

Domestic Water Heater

- Type: Gas Storage
- Efficiency: 0.78
- Tank Volume (gallon): 30

Temperature: 135 degF

Use Rate (gal/min): 0.05

ZNE Packages

After the Baseline model was calibrated to 2015 monthly utility data, packages were developed and modeled in OpenStudio to see if ZNE could be achieved. Tubular Daylighting Devices with daylight sensors were added to model the lighting impact of this measure. The prior ZNE study is included and consists of packaged rooftop heat pumps with heat recovery and tubular daylighting diffusers. Changes to the HVAC are assumed to add ventilation to the building, as the majority of the current building is unventilated, and to eliminate the need for electric space heaters. Lighting use is higher in this ZNE package than in the proposed packages below, because the prior ZNE study assumed 0.8 W/sf of lighting while the following packages assume 0.6 W/sf of lighting and occupancy sensors.

For the Berkeley Mental Health Clinic, four ZNE packages are suggested with the only difference being the HVAC system type and window replacement. Below is a description of each package. In addition, after receiving the updated construction drawings, Integral Group updated the energy efficiency measures to match the drawings to understand the impacts of the modifications. The results are provided in this section. Model inputs are the same as the baseline building, including envelope, internal loads, thermostat setpoints, hours of operation, HVAC system, and domestic hot water inputs except where noted.

Package 1a: DOAS (Dedicated Outside Air System) + VRF, No Window Replacement

- HVAC: DOAS with VAV fan, Energy Recovery Ventilator (enthalpy wheel), no economizer, and VRF (with heat recovery)
  - Cooling COP of 3.96
  - Total energy recovery effectiveness of 75 percent
  - Operating schedule 6am-midnight Mon-Fri, 6am-7pm Sat, 6am-6pm Sun
  - Temperature setpoints are same as Baseline.
- DHW: replace with electric instantaneous (efficiency: 0.95) and install low flow fixtures
- Lighting:
  - 38 tubular skylights
  - Replace existing lighting with LED upgrade (0.6 W/sf): 0.6 W/sf is connected load, 65 percent diversity, 0.39 W/sf max operating load.
  - Install daylighting sensors for interior lighting control
  - Install wall-mounted occupancy sensors
- Envelope:
  - Reroof and add R-25 roof insulation

    - Add crawlspace insulation (R-13 cavity insulation)
- Plug Loads: reduce by 30 percent from 0.7 W/sf to 0.49 W/sf*. 0.7 W/sf is connected load, 90% diversity, 0.63 W/sf max operating load.

Package 1b: DOAS + VRF, Window Replacement

- HVAC: same as Package 1a
- DHW: same as Package 1a
- Lighting: same as Package 1a
- Envelope:
    - Reroof and add R-25 roof insulation
    - Add crawlspace insulation (R-13 cavity insulation)
    - Replace all windows with SB70XL (U-factor 0.40 and SHGC 0.28) including aluminum frames with thermal break.
- Plug Loads: same as Package 1a

Package 2a: Heat Pump

- HVAC: Packaged Rooftop Units with Heat Pump, multi-zone VAV fan, 100 percent outdoor air (maximum airflow sized for peak ventilation condition), demand controlled ventilation, no economizer
    - Operating schedule 6am-midnight Mon-Fri, 6am-7pm Sat, 6am-6pm Sun
    - Temperature setpoints are same as Baseline.
- DHW: same as Package 1a
- Lighting: same as Package 1a
- Envelope: same as Package 1a
- Plug Loads: same as Package 1a

Package 2b: Heat Pump with ERV (Energy Recovery Ventilator)

- Same as 2a, adding Energy Recovery (enthalpy wheel)
- DHW: same as Package 1a
- Lighting: same as Package 1a
- Envelope: same as Package 1a
- Plug Loads: same as Package 1a

The project team selected Package 2b as their basis of design. However, throughout the design process changes were made to the design which impacted the EEM selections. The following changes were made.

Package 100% Design Development (100 percent DD): Heat Pump with ERV (Energy Recovery Ventilator)

- HVAC: System type is the same as 2b, with the following modifications:
  - Reduce Cooling Coefficient of Performance (COP) to 3.28 (11.2 EER) and 3.58 (12.2 EER)
  - Reduce Cooling Supply Air Temp from 55 degF to 50 degF
  - Reduce Heating Supply Air Temp from 95 degF to 82 degF
  - Increase supply fan total static pressure to 3.3 in. w.g. and 2.7 in. w.g.
  - Reduce total energy recovery effectiveness to 59% and 64%, and sensible energy recovery effectiveness to 60% and 65% for each enthalpy wheel
- DHW: same as Package 1a, with the efficiency changed from 0.95 to 0.98
- Lighting: same as Package 1a, except the number of tubular skylights changed from 38 to 35 and 5 existing skylights remain
- Envelope:
  - Reroof and add R-19 roof insulation
  - Add batt insulation to 2x6 wall (R-19 cavity insulation)
  - No window replacement
- Plug Loads: same as Package 1a

Package Construction Phase Updates: Heat Pump with ERV (Energy Recovery Ventilator)

- HVAC: System type is the same as 2b, with the following modifications from the 100% Design Development Package to match parameters in the approved equipment submittal:
  - Occupancy Schedule changed to 7am-10pm M-F; 11:30am – 10pm Saturdays, Sundays and Holidays.
  - Increase Cooling Coefficient of Performance (COP) to 3.43 (11.7 EER) and 3.69 (12.6 EER)
  - Add electric resistance heating coils in AHUs to operate, instead of heat pump DX heating, when outside air temperature below 45 deg F.
  - Increase Cooling Supply Air Temp to 53.3 deg F and 57.4 deg F.
  - Decrease AHU-2 heating supply air temp from 82 deg F to 78.4 deg F.
  - Increase AHU-2 supply fan total static pressure from 2.7 in. w.g. to 3.0 in. w.g.
  - Increase total energy recovery effectiveness to 64% and 65%, and sensible energy recovery effectiveness to 65% and 67% for each enthalpy wheel.
- DHW: same as Package 100 percent DD
- Lighting: same as Package 100 percent DD
- Envelope: same as Package 100 percent DD
- Plug Loads: same as Package 100 percent DD

- Energy Simulation Model Update: Air handler operating hours in the model were revised to match occupancy schedule described above and to provide morning warmup as needed during weekdays.

Appendix C:
Commercial Building Energy Saver

Implementation of new features and EEMs

Table C-1 lists all the new EEMs that were implemented in CBES.

Table C-1: List of new EEMs in CBES

Measure Name	Category
Apply Demand Response Strategy of Thermostat Reset	Demand Response
Add Tubular Daylighting Device	Envelope - Skylight
Upgrade to VRF heat recovery type with DOAS Energy Recovery Ventilator plus Demand Control Ventilation system	HVAC - Whole System
Upgrade to VRF heat recovery type coupled with DOAS Enthalpy Wheel plus Demand Control Ventilation system	HVAC - Whole System
Upgrade to Packaged Heat Pump with thermafuser	HVAC - Whole System
Add Window Film	Envelope - Window
Add Exterior Storm Window Layer	Envelope - Window
Add Interior Storm Window Layer	Envelope - Window
Add Exterior Overhang Shades	Envelope - Window
Efficiency Upgrade to Electric Instantaneous Water Heater and low-flow fixtures	Service Hot Water
High efficiency exterior light fixture	Exterior Lights
Add detailed measure for plug load energy use reduction	Plug load

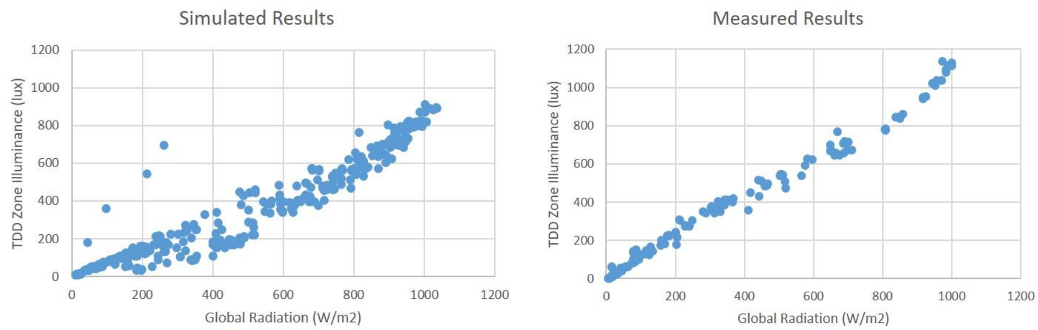
Detailed Results in Validating CBES With FLEXLAB Test Data

(1) Tubular Daylighting Device EEM Performance Validation

TDD performance was validated for two main factors - illuminance provided to the space, and the resulting lighting energy use reduction. The illuminance levels under daylight only mode (without lights on) were compared between simulation and FLEXLAB test in Figure C-1. From the comparison, the simulated and measured illuminance levels on the working plane (0.8 meter above the ground) both vary with the global horizontal radiation in a very similar trend.

Figure C-2 shows that the energy use was reduced due to harvested daylight from TDD. The higher the global horizontal solar radiation is, the more energy the TDD can save. When the solar radiation rises above a certain level, the harvested daylight reaches the illuminance setpoint for maximum dimming setting, thus the energy trend turns horizontal as it can't be reduced further. The coefficient of variation of the root mean square error (CVRMSE) between simulated results and measured data was 25.3 percent, which met the calibration criteria of 30 percent CVRMSE using hourly data according to ASHRAE Guideline 14 (ASHRAE, 2014).

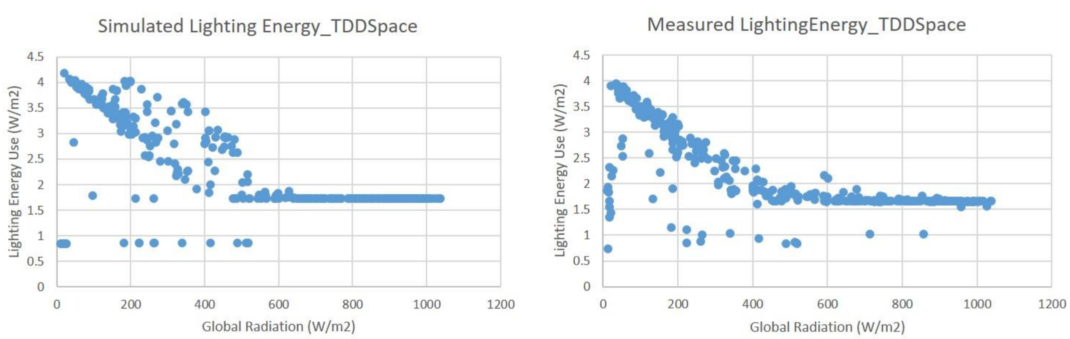
Figure C-1: Illuminance Variation With Global Radiation - Simulated vs. Measured



This is a side-by-side comparison containing two figures, with left figure showing the simulated results, and right figure showing the measured results. The x-axis is global radiation with unit of W/m2, the y-axis is the illuminance of the TDD zone with unit of lux. Both figures are showing monotonically ascending trend.

Source: Commercial Building Energy Saver (CBES) Update Report

Figure C-2: Lighting Energy Use With Global Radiation - Simulated vs. Measured



This is a side-by-side comparison containing two figures, with left figure showing the simulated results, and right figure showing the measured results. The x-axis is global radiation with unit of W/m2, the y-axis is the lighting energy use with unit of W/m2. Both figures are showing the trend of decreasing linearly at x-value between 0 to 450W/m2, then stay constant when x is larger than 450W/m2.

Source: Commercial Building Energy Saver (CBES) Update Report

(2) Full ZNE Package Validation

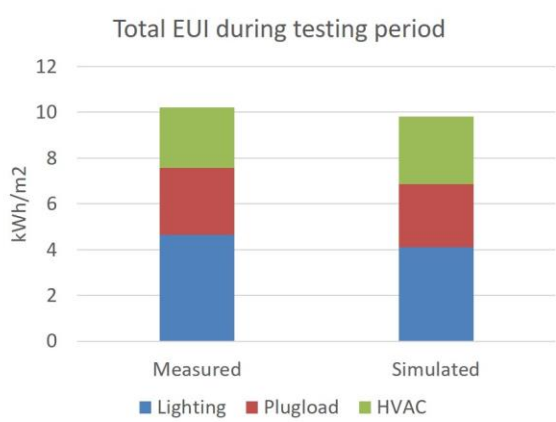
The full ZNE package includes a retrofit of multiple aspects of the building, including envelope, lighting, plug load and HVAC. In the validation of the ZNE package, two key subsystems, lighting, and HVAC, were validated separately. Finally, the entire building with the ZNE package was validated as well.

The lighting retrofit was performed in three parts: (1) installation of the TDD in the core zone; (2) add daylighting control in the perimeter zones; (3) reducing LPD from 1.19 to 0.4W/ft2. The results indicate that the lighting energy use was reduced with the higher the global horizontal solar radiation is, the more energy the daylighting controls save. The CVRMSE between simulated results and measured data was 27.7 percent, which met the calibration criteria of 30 percent CVRMSE using hourly data according to ASHRAE Guideline 14 (ASHRAE, 2014).

The HVAC retrofit implemented in FLEXLAB includes a widened temperature deadband, setbacks during unoccupied hours, and advanced control logic. Specifically, the 100 percent outdoor air system, uses integrated control logic to control the VAV thermafusers by modifying the thermafuser valves based on indoor temperature as well as adjusting the static pressure via AHU fans. Both cooling and heating thermal energy and electricity consumption were compared and overall, the hourly and daily simulation results align well with measured data. Meanwhile, some discrepancies are observed, such as a few cooling peak hours in June and the underestimated startup heating energy in early mornings of May and December in 2018.

For the whole building, the discrepancy between simulated and measured total EUI during the testing period is -3.8 percent, as shown in Figure C-3. This is less than 5 percent, which is the calibration criteria defined by ASHRAE Guideline 14.

Figure C-3: Total Energy Use Intensity During the Testing Period



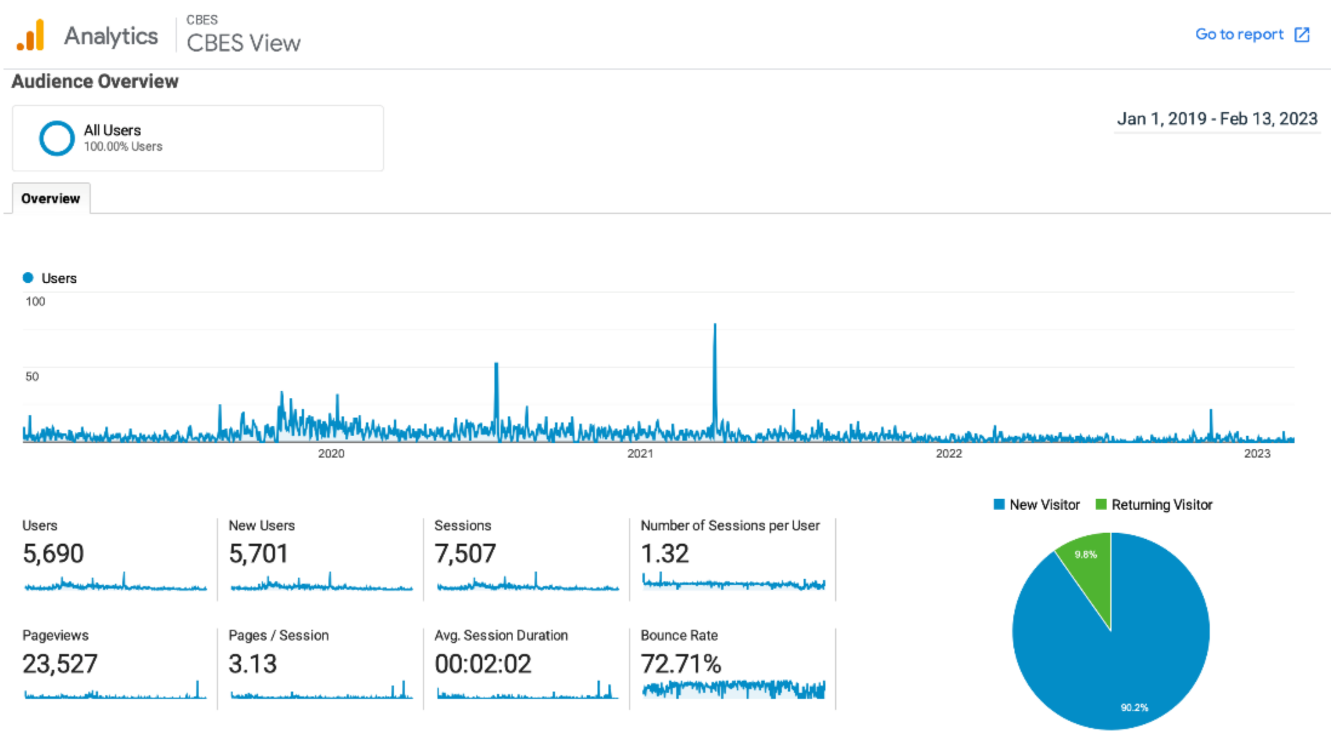
This figure compares the breakdown end uses between simulated results and measured data. There are two columns, left column being the measured data, right column being the simulated results. Y-axis is energy use intensity (EUI) with unit of kWh/m2. For each column, three end uses are displayed, including lighting, plug load, and HVAC. The end uses of measured and simulated results are very close.

Source: Commercial Building Energy Saver (CBES) Update Report

In summary, the simulated results match well with the measurement data on lighting energy use, HVAC energy use, and whole building EUI. Therefore, it is reasonable to conclude that the accuracy of CBES is validated through experimental data and that CBES has the capability to simulate ZNE measures and packages.

CBES website statistics

Figure C-4: CBES website audience overview statistics data since the project started

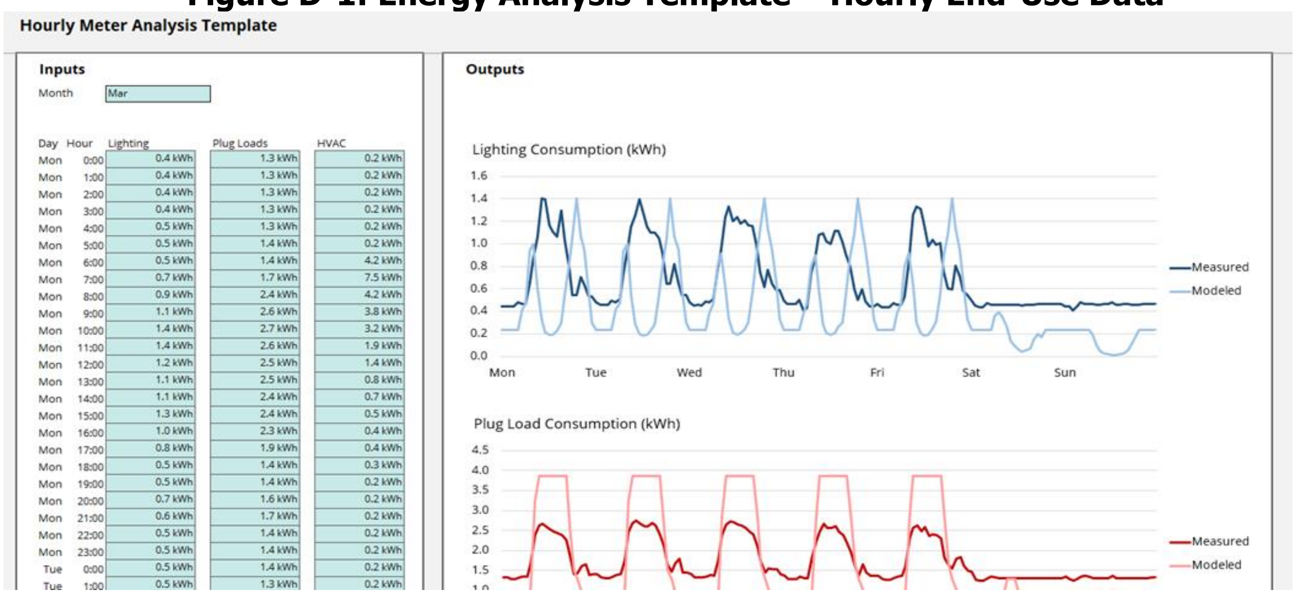


This is the Google Analytics summary of the CBES website. In the middle, there is a figure showing the daily number of users from Jan 1, 2019 to Feb 13, 2023. On the bottom left, there are statistical numbers of the website usage, including 5690 total users, 5701 new users, 7507 sessions, 1.32 number of sessions per user, 23527 page views, 3.13 pages/session, 00:02:02 average session duration, 72.71% bounce rate. On the bottom right, there is a pie chart showing 90.2% of new visitor and 9.8% returning visitor.

Appendix D: Measurement and Verification Energy Analysis Tool

To support ongoing ZNE operations, the project developed an Energy Analysis Template for the Berkeley Mental Health Services ZNE Retrofit project as part of the overall M&V plan (Figure D-1). This tool was preloaded with data from the calibrated energy model to use as a comparison against the measured data generated after the building re-opened. Using such a tool will allow facility operators to potentially identify operational issues, such as unscheduled after-hours energy use, lighting and plug load energy use increases, decreases in photovoltaic energy production and so forth. To compare the energy end-use consumption, the user chooses a month for analysis (in this case, March of 2022), calculates the average consumption for the month for each end-use by day of the week as well as hour of the day and enters the data in the table as shown below.

Figure D-1: Energy Analysis Template – Hourly End-Use Data


Hourly Meter Analysis Template

Inputs

Month: Mar

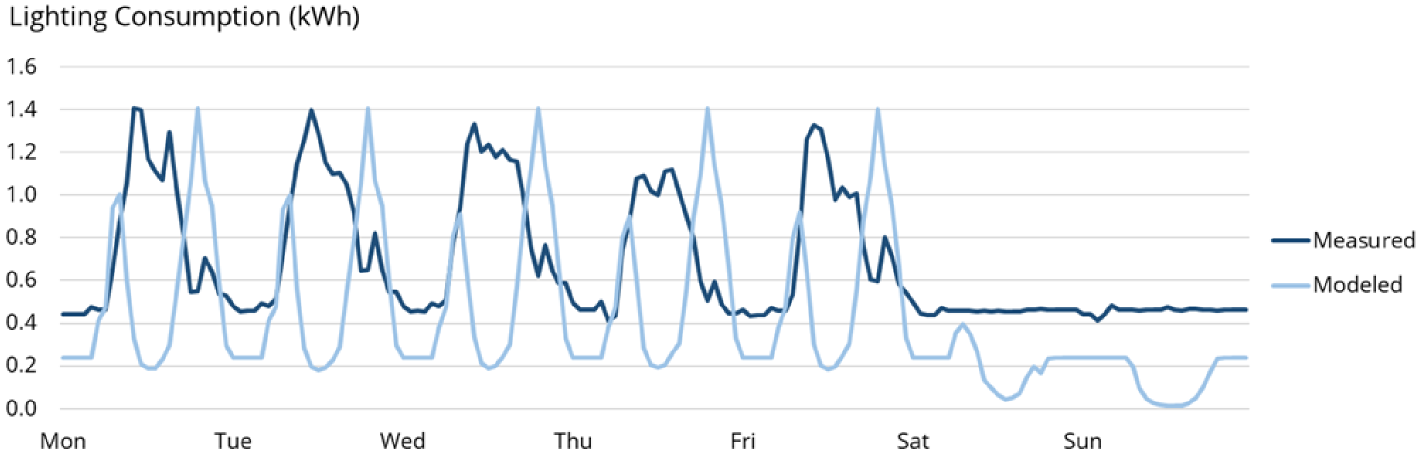
Day	Hour	Lighting	Plug Loads	HVAC
Mon	0:00	0.4 kWh	1.3 kWh	0.2 kWh
Mon	1:00	0.4 kWh	1.3 kWh	0.2 kWh
Mon	2:00	0.4 kWh	1.3 kWh	0.2 kWh
Mon	3:00	0.4 kWh	1.3 kWh	0.2 kWh
Mon	4:00	0.5 kWh	1.3 kWh	0.2 kWh
Mon	5:00	0.5 kWh	1.4 kWh	0.2 kWh
Mon	6:00	0.5 kWh	1.4 kWh	4.2 kWh
Mon	7:00	0.7 kWh	1.7 kWh	7.5 kWh
Mon	8:00	0.9 kWh	2.4 kWh	4.2 kWh
Mon	9:00	1.1 kWh	2.6 kWh	3.8 kWh
Mon	10:00	1.4 kWh	2.7 kWh	3.2 kWh
Mon	11:00	1.4 kWh	2.6 kWh	1.9 kWh
Mon	12:00	1.2 kWh	2.5 kWh	1.4 kWh
Mon	13:00	1.1 kWh	2.5 kWh	0.8 kWh
Mon	14:00	1.1 kWh	2.4 kWh	0.7 kWh
Mon	15:00	1.3 kWh	2.4 kWh	0.5 kWh
Mon	16:00	1.0 kWh	2.3 kWh	0.4 kWh
Mon	17:00	0.8 kWh	1.9 kWh	0.4 kWh
Mon	18:00	0.5 kWh	1.4 kWh	0.3 kWh
Mon	19:00	0.5 kWh	1.4 kWh	0.2 kWh
Mon	20:00	0.7 kWh	1.6 kWh	0.2 kWh
Mon	21:00	0.6 kWh	1.7 kWh	0.2 kWh
Mon	22:00	0.5 kWh	1.4 kWh	0.2 kWh
Mon	23:00	0.5 kWh	1.4 kWh	0.2 kWh
Tue	0:00	0.5 kWh	1.4 kWh	0.2 kWh
Tue	1:00	0.5 kWh	1.3 kWh	0.2 kWh

Overview of the Energy Analysis Tool showing input data and output comparison graphs.

Source: Energy Analysis Template developed for Berkeley Mental Health Services ZNE Retrofit

This allows for easy visual analysis of the building operation against the modeled data which can be used as a measurement and verification tool to determine if systems are behaving as expected. Some example analysis has been presented in Figure D-2. When comparing the measured data against the modeled lighting energy it can be seen that the peak lighting consumption is roughly the same as the modeled value, as expected. However, on weekdays, it is noted that the peak energy consumption is happening much earlier in the day than anticipated. This could be due to a number of factors. For example, the location of the daylighting sensors may be different than the modeled location which is causing the dimming of the lights to occur at different times than predicted. Alternatively, the building occupancy schedule may differ from that modeled with higher occupancy in the morning than the evening, resulting in the lights turning on due to the occupancy sensors in the spaces.

Figure D-2: Hourly Lighting Electricity Consumption – Measured vs Modeled

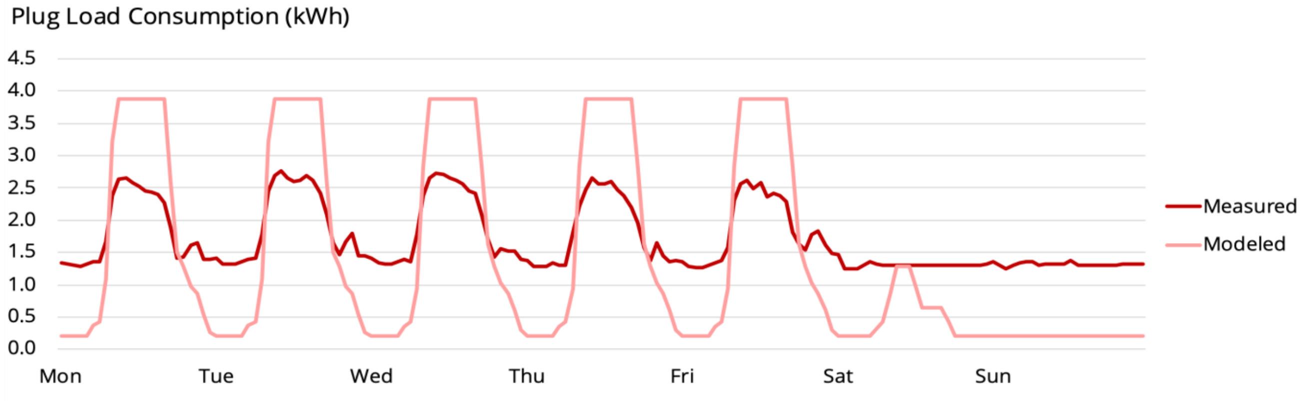


Comparison of the modeled lighting energy consumption versus measured data from March 2022.

Source: Energy Analysis Template developed for Berkeley Mental Health Services ZNE Retrofit

Additionally, there is a noticeable difference in the minimum lighting energy consumption which is happening throughout the week with the measured data being approximately twice the level of the modeled minimum. This could be for a few reasons. For example, the lighting control system programming may be requiring lights to stay on longer than intended, or possibly the occupancy sensors are mistakenly requiring lighting when the spaces are unoccupied. Alternatively, it could be that the levels of lights being left on for emergency lighting are higher than anticipated. When comparing the measured plug load consumption (Figure D-3,) against the modeled data it is noted is that there is much less variation between the lows and highs. When looking at the measured high-end hourly plug loads for Monday (2.7 kWh), it is noted that these are averages for all Mondays in the month of March which may help smooth peak demand values. It also appears that the diversity in the use of the installed plug load equipment is lower than anticipated, further reducing the daily plug load peak demand.

Figure D-3: Hourly Plug Load Electricity Consumption – Measured vs Modeled



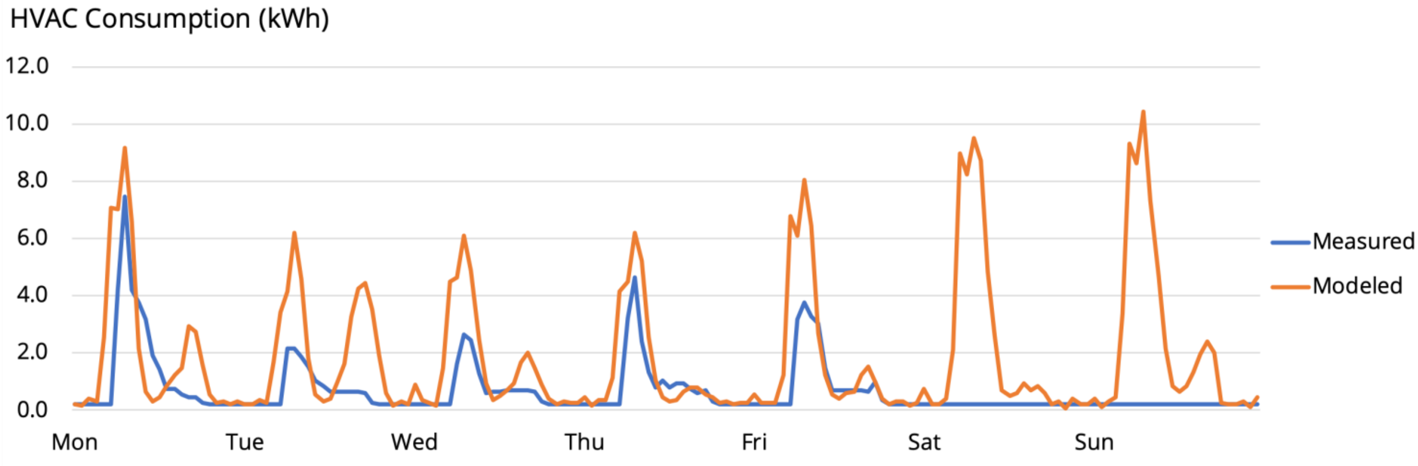
Comparison of the modeled plug load energy consumption versus measured data from March 2022.

Source: Energy Analysis Template developed for Berkeley Mental Health Services ZNE Retrofit

When examining the daily minimum plug load consumption in the modeled data, it appears that some of the plug load reduction strategies are not delivering the expected results. Looking at the unoccupied period over the weekend, the measured plug load use is approximately six times higher than the modeled consumption. Additionally, during the overnight periods when the loads are expected to be minimal, the measured plug loads are similarly higher than the modeled values. This could be due to the occupancy-controlled plug strips not being used or possibly the isolated branch panel set-aside for printers, fax machines, and similar devices is not being powered off by the system when the building is unoccupied. Site visits did show that additional plug strips had been put in place to avoid the use of the controlled outlets in some locations, which would have the effect of increasing the minimum power draw.

HVAC energy comparisons are presented in Figure D-4. When comparing HVAC measured data versus modeled data, care must be taken as the largest variations are likely to occur due to the differences between the real-world weather and the typical meteorological year data used for the simulation. Nevertheless, a couple of trends can be seen from these results.

Figure D-4: Hourly HVAC Electricity Consumption – Measured vs Modeled



Comparison of the modeled HVAC energy consumption versus measured data from March 2022.

Source: Energy Analysis Template developed for Berkeley Mental Health Services ZNE Retrofit

First, there is a spike in the measured and modeled data on Monday mornings. This appears to be due to the morning warm-up cycle to heat the building back up after being empty on the weekends. For the rest of the weekdays, while the consumption varies a bit between the measured data and the modeled values, the overall shape of the energy consumption is similar which indicates that there isn't a significant disconnect between the modeled hours of operation and the actual operation of the HVAC system in the building. According to the measured data, it appears that the HVAC system is turned off entirely on the weekends, which differs from the modeled schedule of operations. Previous understanding of the operation of the facility was that there would be open operating hours over the weekends, however it may be that the facility reduced operating hours or relies on remote work instead on weekends. If interior space conditions on the weekends are within the building's operating requirements (for both temperature and relative humidity), and if the building can meet the desired setpoint when occupied conditions resume, this operating strategy may help reduce the annual building energy consumption. The thermal conditions of the space should be monitored to verify that they are maintained within the operating requirements of the space.